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A research platform for investigating human position sense in altered gravity conditions for space applications and beyond

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With ever increasing complexity and distance of space exploration missions, telerobotics will continue to play an important role. By pairing more capable multi-modal user interfaces with teams of dexterous intelligent robotic assets, astronauts are able to perform a wide variety of remote tasks in the space environment on orbit or celestial surface.

In several telerobotics technology demonstration missions carried out on the International Space Station (ISS) such as Haptics 1 [28] and 2 [29], Kontur-2 [3], SUPVIS Justin, Analog-1 [28], and Surface Avatar [11], we have continuously advanced the capabilities in commanding complex robotic assets and teams. In these experiments, different modalities of user interfaces, including intuitive graphical user interfaces, a joystick and kinesthetic interfaces were deployed to examine their effectiveness in microgravity conditions for direct motion control of robotic assets.

The immersive robot command with force-reflection is a valuable command modality for non-repetitive exploratory tasks, or in other unknown situations. However, we also observed proprioceptive performance degradation of astronauts when teleoperating on board the ISS. These performance erosions are believed to originate from a degraded sensory state in the human user's limb. In order to study the effects of altered gravity on the human's position sensing systematically, a research platform was designed allowing test subjects to perform the standard test procedures for measuring human limb position sense in micro- and hypergravity conditions as experienced during parabolic flight.

This paper details and discusses the research platform designed to fulfill requirements resulting from precautions for parabolic flights and quality standards in proprioceptive test procedures. The mechatronic requirements, challenges and solutions for such a test setup are specified and described. The developed research platform enables the investigation of the human's position sensing and the physiological mechanisms in altered gravity conditions. As such, the research platform will play a key role in our user interface design for future space telerobotic applications.

1 Introduction

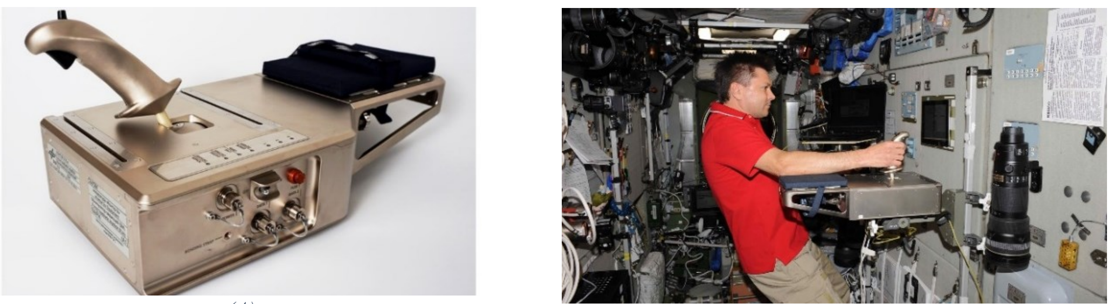
To reduce risks and cost of future space missions, robots are planned to be deployed on planetary surface, while astronauts stay on orbiting spacecraft. Robots will not work completely autonomously in the short term. Hence, the astronauts will be equipped with interfaces enabling the remote control of the robotic assets on ground. Also, in the long term, teleoperation capabilities will be crucial as a fallback solution in case of autonomy failures. Therefore, high-fidelity teleoperation interfaces will be required to guarantee the success of those robotic space missions.

A variety of projects focused on interaction via graphical user interfaces for supervised autonomy. One current project, Surface Avatar Experiment, is an ISS technology demonstration telerobotic mission led by the German Aerospace Center (DLR) in partnership with the European Space Agency (ESA) [11]. The idea is to investigate how an astronaut can control a team of robots from a space capsule in close orbit around the surface. The goal of this analogue mission is to build a habitat on a planetary surface. The analogue setup depicted in Fig. 1 presents the interaction of DLR's dexterous bimanual mobile robot Rollin' Justin [6], quadruped Bert [5], Robotic lander Enhanced LAnder Functional AssistaNT (ELAFANT) and ESA's Interact Rover [9] while being telecommanded by NASA astronauts Tracy "TC" Dyson and Jeanette Epps on board the ISS.

Figure 1 Surface Avatar ISS Telerobotic Technology Demonstration Mission, Prime Session 2

Besides high-level commands from the graphical user interface (GUI) based on knowledge driven approaches [27], the astronaut is able to directly control the robots using a joystick and a force-reflective input device located on the ISS. These variations of the control system enable the astronaut to have a control and feedback unit suitable for the task. Direct control via kinesthetic motions of the astronaut (and haptic input device) allows for particularly delicate interactions. But this limits the astronauts to one singular controllable device. The advantage of this is that kinesthetic control helps to immersing in the work and in combination with force feedback it helps to reduce the cognitive load, investigated in [12] and in [4]. The problem in integrating kinesthetic control are twofold. Firstly, the delay in the communication channel [22, 23, 24] reduces the operator's immersion into the robot's environment. Secondly, and the focus of this work, the operator in an orbiting spacecraft is exposed to microgravity which negatively affects the human's proprioception, the human sense of limb position [17] and thus the control of input devices.

Humans can be exposed to altered gravity in different means ranging from studies on the ISS [21, 19, 20], underwater [21] or in parabolic flights [18]. As part of the Kontur-2 mission [3], DLR, in cooperation with the ROSKOSMOS, RSC Energia, RTC St. Petersburg, brought a force-reflecting joystick, shown in Fig. 2 to the ISS. The cosmonauts performed basic aiming and tracking tasks in a simulation with a joystick [15, 19, 20]. Due to enormous costs, the necessary preparation time and limited access to test subjects, studies on the ISS are comparably difficult to realize. Although parabolic flights only allow short phases of altered gravity, they offer the only opportunity to carry out user studies under real microgravity conditions, whereas underwater studies only simulate weightlessness through neutral buoyancy. Another



(A) *(B) Credit:ROSKOSMOS/O. Kononenko*

Figure 2 The Kontur2 Joystick (A) used at the ISS from Oleg Kononenko(B) advantage of parabolic flights is the possibility of testing microgravity as well as hypergravity conditions. In this work, we present the requirements and development of a research platform enabling the study of state-of-the-art experiments of human position sense research in parabolic flight campaigns performed by the NOVESPACE [1].

2 Requirements

In this section we detail the requirements to ensure a safe setup and the conducted experiments on [26]. We also the stages and procedures in a parabolic flight, the challenges it imposes, and our considerations to tackle them and to achieve comparability with the previous experiments.

2.1 Parabolic Flight

The purpose of a parabolic flight is to generate conditions of microgravity. This is achieved by a special flight maneuver, the parabola. The pilot alternates between a climb and a dive in quick succession. The parabola can be divided into 5 phases, as shown in Fig. 3. In the different phases of the parabola the airplane flies through 2 gravitational conditions: Hypergravity (i.e. 1.8 g) in phases 2 and 4 (both lasting ~20 sec) and microgravity (0 g, lasting 20-22 sec) in phase 3 [14]. For our experimental setup, this means that all functions have to work at 0 as well as 1.8G, and we only have small time windows in which to perform experiments. In phases 1 and 5, i.e. during steady horizontal flight gravity is nominal (1 g).

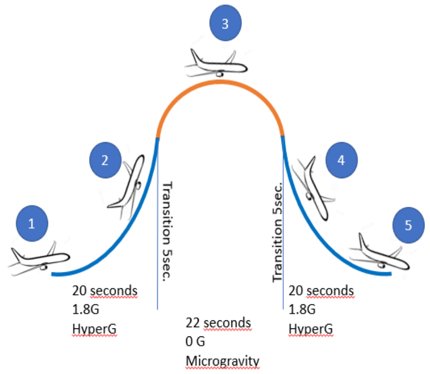


Figure 3: Typical parabolic flight manoeuvre, (redrawing from [16])

2.2 Technical and Safety Requirements

A catalogue of safety requirements (e.g. mechanical, electronical, procedural aspects) defined by NOVESPACE [1] must be fulfilled, to be allowed to participate in the parabolic flight campaigns. NOVESPACE released multiple design guidelines they regulate the hardware structure and basic architecture of the experimental rack. They describe the structure, maximum weight and mechanical load capacity of experimental racks. For example, the structure must be able to withstand an emergency landing with accelerations of up to 9g. It is defined, how to install the experiment inside the aircraft and how to attach experimental payload (e.g. PCs) in the racks. Also, they define the electronic interface to the aircraft, the installation of the electronic components, there wiring, the fuse design and thermal handling, to avoid overheating. Also, the general safety instruction for the flights and the work of the operator are defined. Besides others, it required that the experimenter and test subjects must be able to leave the setup in less than 60 seconds. All these safety guidelines are checked and thoroughly reviewed by NOVESPACE.

2.3 Scientific Requirements

There are various methods to examine the human sense of limb position [26]: Methods such as two-arm matching or pointing, in which the position of one reference arm is matched with the other arm. Both arms are typically positioned on paddles that can be moved around a rotatable joint so that the arms on the paddles can be moved from a fully extended position to a fully flexed position. Usually, the experimenter executer moves the reference arm to a certain test angle without the subject being able to see it. In two-arm matching, the blindfolded test subject is asked to match the angle perceived as identical with the other arm. In pointing, the angle should not be indicated with the arm, but the visible paddle should be moved to the corresponding angle. In the clinical field, repositioning is also frequently used, in which the same arm is first brought to the test angle and then the remembered position is indicated with this arm at the same time, of course without sight. In this study, these three methods were to be implemented.

This means that paddles must be designed in a way that their rotational joint is aligned with the elbow joint and can move from 0° (horizontal) - 90° (vertical position). It must be possible to fix the arm, to achieve a stable position on the paddle. When indicating the perceived angles, the paddles should be able to be moved freely without significant friction or inertia, as this could have affect position sense. An additional requirement arises from the fact a so-called co-conditioning must be carried out before each test run (to ensure a defined initial state of the muscle receptors involved); here, the paddle in vertical position had to be pulled and pressed against briefly to generate muscle activity.

Figure 4: Picture of the paddle design concept generated with "Adobe Firefly"

All these requirements resulted in an initial design concept, see Fig. 4.

3 Design

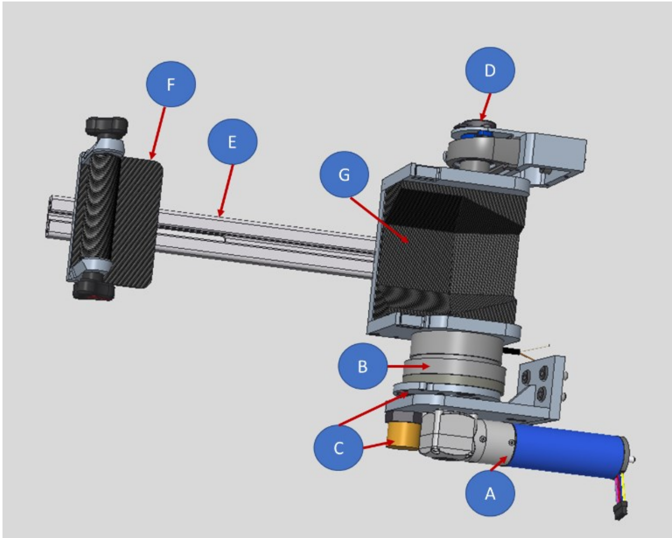
The following describes how the system requirements defined above were met in the implementation of the mechanics, electronics and the communication infrastructure.

3.1 Mechanical System

The general setup was designed such that two test subjects could carry out the experiment simultaneously, with two pairs of paddles attached to either side of the experimental rack. For the purpose of comparison with our earlier ISS studies [19-21], the experiments were to be conducted in an upright position and not in a sitting position, see Fig. 5.

Figure 5: Illustration of the structure with two test subjects

contrast to the terrestrial implementations of the experimental setups for measuring the sense of position, e.g. [26], the setup had to be implemented in such a way that the procedure could be automated to the second due to the very narrow experimental time windows with the desired gravity conditions. For this reason, the test angles were not set manually by an experimenter, as in previous studies, but were approached automatically by the motorized levers. The motor needed to be sufficiently strong enough and precise to accurately move the paddles under conditions of hypergravity, i.e., it needed to lift at least a 2 kg mass on the tip of the lever at 1.8G. Additionally, the motor must also fast enough to move the paddle in less than 2 seconds to the desired position. In general, the paddles' weight has to be as low as possible to not exceed the structures' limits of mechanical loading in case of an emergency landing. To ensure the safety of the test subjects, it was also decided that the maximum speed of the motors should be limited to 30 rpm. For this reason, a direct drive with a suitable transmission ratio was selected. The maximum speed is reduced in favor of torque increase, which suits the experiment objectives. As a result we chose the eci-42.40-b00-k1.ecp42.3.85 [7] from EBM-Pabst, with 10 Nm and a maximum of 47.8 rpm at a maximum power consumption of 49 W. The gearbox is integrated at the paddle as shown on Fig. 6 (Motor labelled as "A"). The disadvantage of a motor with gear reduction is the higher friction and inertia, which reduces measurement sensitivity, as moving the paddle with the motor coupled to it leads to frictional resistance. This could have an impact on position sensing precision To avoid this, we decided to use a clutch to separate the motor from the paddle when not in use. The clutch had to handle the maximum torque of the motor and the external forces. Therefor, a fully active system which can act fast and with high position resolution was required. We chose the Moenninghof Typ558 [13], an electromagnetic spring-loaded tooth break ("B" in Fig. 6). Furthermore, a locking mechanism was implemented, to hold the paddle at a specified angle, e.g. to accurately fix the paddle even in case of unintended external forces applied by the test subject. Because the angles were defined beforehand, a solenoid activated locking could be used. We built a perforated disk with the planned positions, which is locked with the pin of the solenoid (Fig. 6, "C"). The motor break BFK551-03 which has a rated brake torque of 0.5 Nm [10] was chosen as potential alternative; it was attached at the motor side, so the paddle had a rated brake torque of 42.3 Nm. The break can hold around 100 N on the tip of the lever. The current angle of the paddles was measured using a rotational potentiometer (Fig. 6 "D"). The handle's position (Fig. 6 "F") could be adjusted individually on the rail (E). For the elbow support ("G"), we designed a 3D printed structure which was printed in Thermoplastics Polyurethane (TPU) with a shore hardness of 85.



3.2 Electrical System

The aircraft provided 230V-AC/50Hz with a current limit of 8 A_{RMS} and 19 A_{Peak} for the complete system. For the paddle setup we used a stepdown to 24V. To avoid interference from one paddle to the other, they were isolated into differ electric cycles as shown in Fig. 7. There are two cles for the paddles. One is for the real-time data face described in the next section. If on one set o ror occurs, it is possible to switch off each paddle vidually, without interfering the other set of padd paddles we estimated a power consumption of 20 isfy this power budget, a 24V 10A power supply same was also utilized for the real-time control cy need of multiple different spare parts. As described in [1] all

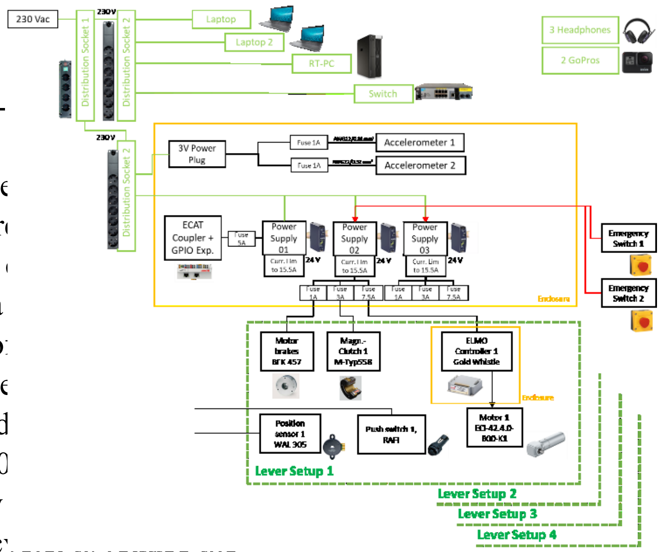
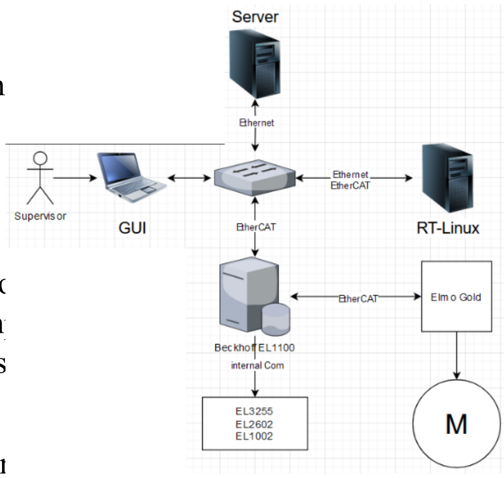


Figure 7: Electrical overview

cables longer then 20cm or free movable ones, had to be individually implemented with non-self-resetting fuses. The dimensioning is close to DIN EN ISO 10133. For easier maintenance, power supplies and the controller are separated from the fuses in the fuse box. For motor control, the ELMO Gold Twitter was used [8]. It comes with an EtherCat interface that enable real-time workflow. The control of the clutch, brake and solenoid were realized via a Beckhoff relay module. The potentiometer was read out by a Beckhoff EL3255. A push bottom was read out with an EL1002 from Beckhoff. All those modules were coupled with a Beckhoff EL1100, a real time EtherCat coupler, so that all parts of a paddle are running in the same real time domain. Thus, measured data had all the same timestamp.

3.2 Data Infrastructure

The data infrastructure, presented in Fig. 8, is divided in components: the graphical user interface (GUI, non-real-time), and the control framework (real-time). The GUI provided information on system and task states to the supervisor. Furthermore, the task order was implemented in and organized by the GUI software. The cc ware was executed on a RT-Linux system at a1kHz sam The realtime sytem communicated via an EtherCAT bus Beckhoff bus terminals and the Elmo.



Figur8 Communication interface

Both real-time and non-real-time portions of the setup ai connected via an Ethernet switch to a server for all software and data during system startup. The DLR middleware, Links and Nodes [25], was executed on the GUI laptop to manage all processes. The experimental data is logged automatically after each task onto the server and stored on a separate data storage after each flight day.

4 Pre-flight Piloting

Figure 9 Testing paddle with 5 kg at tip

Prior to flight, the experimental setup (shown in Fig. 9) procedures (shown in Fig. 10) were intensively tested. Due to the short experimental phases during flight, the timing of the pre-recorded audio instructions was optimized. As the solenoid locking mechanism was stuck multiple times during testing, , the motor brakes were used instead. After multiple testing the entire setup was brought to Bordeaux, France for the parabolic flight as shown in Fig. 11).

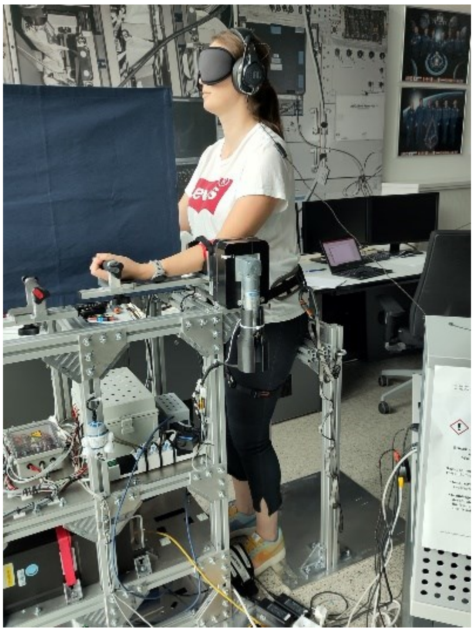


Figure 10 Testing's at the institute

5 Result and Conclusion

Figure 11 Pictures from the campaign

The experiment was successfully carried out over three days with 91 parabolas. Of these were without technical issues. With this flight campaign, shown in Fig. 11, we demonstrated that all hard- and software components of setup functioned reliably. The setup was designed so that a series of tests could be carried out to test the positional sense of the human limbs under changing gravity conditions. as could be experienced during space flight. The setup was able to provide stable and reliable human subject limb positioning with timely response due to its stable real-time system, and its powerful motors. The experiment thus represents the first successful attempt to use different methods to measure the human sense of position under conditions of altered gravity induced by parabolic flights. The results actually indicate that the human sense of position changes is affected in non-nominal gravity, but also that these effects vary depending on the method used [17]. These findings are crucial to better predict human performance during space missions, to better understand the underlying physiological mechanisms and thus to design suitable countermeasures.

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