Master thesis

Evaluation of Augmented Reality and Robot-assistance in Spacecraft AIV

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Declaration of academic honesty

I hereby declare that the master thesis ”Evaluation of Augmented Reality and Robot-assistance in Spacecraft AIV” is my own work, that I have not presented it elsewhere for examination purposes and that I have not used any sources or aids other than those stated. I have marked verbatim and indirect quotations as such. Further declarations which have to be signed within the context of the examination regulations of the University of Bremen can be obtained from the appendix A. Larger quantities of data and the software scripts developed are not appended due to unreasonable spatial requirements but made available on the institute server.

Place & Date	Torsten Raupach

Abstract

The prototype nature combined with the necessary high requirements towards quality make spacecraft Assembly, Integration and Verification (AIV) operations highly complex tasks that impart high workloads onto the operators. Implementing assistance systems like head-mounted Augmented Reality (AR) devices and industrial robots into the workflow could result in significant decreases in workload. Opening up the third dimension for information transport can lead to a more meaningful display of information. This can enable the operator to re-allocate cognitive capacities towards the task rather than understanding subpar presented information. Handling a spacecraft in six degrees of freedom within the work area is one of the major improvements that an industrial robot brings to the AIV environment. Current jigs and Mechanical Ground Support Equipment (MGSE) lack in flexibility and the individual adaption to the operator. Workload reduction and improved ergonomics could be the result of using the robot.

This thesis aims to evaluate the impact of these two assistance systems with regards to workload and ergonomics. The current AIV environment was analyzed and test cases determined. Subsequently tools and test procedures were developed to evaluate the usage of AR and robot. The result was a test setup that analyzed the subjective workload using NASAs TLX questionnaire and the body posture with the help of an AI-based video analysis. Furthermore the time for task completion and the mistakes made are tracked and assessed.

First test showed promising results. Body posture with regards to the torso angle showed an improvement after the robot was introduced. Mistakes made while using the traditional paper instructions were reduced significantly once the head-mounted AR device was used. A limited data set of six subjects however does not allow to produce statistically valid results. Once the digital clean room laboratory in the DLR Institute of Space Systems is operational this can however be remedied.

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List of Acronyms

OVP	Operation and Verification Procedure
EU:CROPIS	Euglena Combined Regenerative Organic Food Production in Space
CAD	Computer aided design
CAM	Computer aided manufacturing
ESD	Electro-Static-Discharge
PA	Product Assurance
GSE	Ground Service Equipment
PDF	Portable Document Format
QR	Quick Response
API	Application Programming Interface
NCR	Non-conformance report
MGSE	Mechanical Ground Support Equipment
MExR	Modular Experiment Rig
MTBF	Mean time between failure
DLR	Deutsches Zentrum für Luft- und Raumfahrt
COBOT	Robot designed for direct interaction/collaboration with humans
AIV	Assembly, Integration and Verification
ReFEx	Reusability Flight Experiment
MMX	Mars Moon Explorer
LOCO	Locomotion

NASA	National Aeronautics and Space Agency
TLX	Task Load Index
DGUV	Deutsche Gesetzliche Unfallversicherung
MPEG	Moving Picture Experts Group
GNC	Guidance, Navigation and Control
RLV	Reusable Launch Vehicle
AR	Augmented Reality
VR	Virtual Reality
JARVIS	Joint Assembly Robot for Versatile Integration of Spacecraft
CAST	Core Avionics Systems Testbed
HMD	Head mounted display
PA	Product Assurance
ENIGMAS	Engineering Information and Ground Operations Management System
COOPERANTS	Collaborative Processes and Services for Aeronautics and Space
HRC	Human Robot Collaboration
S/C	Spacecraft
DIN	Deutsches Institut für Normung
KIP	Key Inspection Point
EOIP	End of Operation Inspection Point
AI	Artificial intelligence
IPA	Isopropyl-alcohol
RGB	color space using red, green and blue additive primaries
IOP	Internal Operating Standard
DPL	Declared Processes List
SME	Small and Medium Sized Enterprise

1. Introduction

Digitalization and the development of new tools and processes are the focus of multiple projects and theses in the Institute of Space Systems of the DLR in Bremen. Using augmented reality systems and flexible robot MGSEs as assistance systems is one of the projects of the system engineering and project office. It is aimed towards improving the work of operators and decrease the workload. To study the applicability of these tools and develop a test setup to evaluate them is the focus of this thesis.
The motivation and goals are explained in Chapter 2. The technologies applied and current research done in the field are outlined in Chapter 3. The current and an ideal future AIV environment are depicted and analyzed in Section 4.1 to work out possible applications of the assistance systems proposed. Section 4.2 highlights the development of a complexity factor model to determine the complexity of a task which can be used to evaluate if an operation would benefit from assistance systems. The test setup developed to assess benefits towards the workload of the operator of the proposed systems is described in Chapter 4.3. Initial tests using this setup are done and the results shown in chapter 5. Discussion of the outcomes and future improvements can be found in Chapter 6. Finally an outlook towards future experiments and developments in the field of assistance systems is given in Chapter 8.

1.1. Spacecraft Assembly, Integration and Verification

Understanding the concept of assembly, integration and verification is of key importance to analyze its processes. The European Cooperation for Space Standardization [1] has normed the terms as follows:

- Assembly: Physically combining parts, components, equipment or segment elements to form a larger entity
- Integration: Functionally combining lower-level functional entities(hardware or software) so they operate together to constitute a higher-level functional entity.
- Verification: Process which demonstrates through the provision of objective evidence that the product is designed and produced according to its specifications and the agreed deviations and waivers, and is free of defects.

Main task of AIV is the verification that the hardware will perform the desired mission.[2] This is done through planning and conduction of the entire assembly, integration and test campaign as well as meticulous documentation of each step. The system AIV activities begin already in Phase 0/A with the definition of the system model philosophy and the AIV schedule. During phase B these include the preparation of AIV plans and verification control documents. In phase C the assembly and integration of qualification models as well as the planning and surveillance of tests and inspections are some of the tasks. In phase D the system acceptance campaign and the assembly, integration and test of the flight model are done. These are then concluded by qualification and acceptance reviews and the preparation of the launch campaign and logistics. Phase E concludes the AIV activities on the system integrator side by conducting the launch campaign and preparing the launch readiness review.[3]
Spacecraft or space systems are highly complex and are comprised of multiple subsystems. These are, for example, power, propulsion, GNC or payload. All of those are again built out of many different components and parts. Each part, component, subsystem and finally the whole system is tested to verify correct functionality under the expected environments during the mission but also if they work together as required to perform a higher-level functional task. Operators therefore have to manage complex assembly workflows with high numbers of parts while maintaining very high requirements on the quality. Furthermore the documentation of each step done has to be absolutely meticulous. For the individual worker this can lead to a high workload and stress.

2. Motivation and Goals

This thesis aims to answer the question of how Augmented Reality (AR) and robot-assistance can aid in the reduction of workload of the individual operator. A test setup to analyze the applicability of these assistance systems in spacecraft AIV is developed. The project is part of the on-going digitalization and optimization efforts of the DLR Institute of Space Systems in Bremen in the field of AIV activities. Improving the work environment for the individual operator during assembly and integration is the main focus here. The high complexity of spacecraft and space systems combined with the prototype production characteristic lead to challenging and unique tasks. Factors like information load, physical work or high quality requirements are contributing to the operators workload.

Using assistance systems, like a head-worn augmented reality system, could lead to a better overview, more concise and relevant information load and less errors due to excessive workload. These systems however impose an additional complexity through their usage onto the operator. Therefore, the complexity of the task has to justify the effort of implementing and using them. Finding the boundary beyond which the complexity of the task justifies the usage of augmented reality is the goal of the complexity factor developed. The model aims to quantitatively evaluate the complexity of a task using three indicators with up to five dimensions.

Additionally, the unique geometry, size and weight of spacecraft can make the assembly and integration unwieldy and unergonomic. Standard mechanical ground support equipment (MGSE) are usually not flexible enough in the individual positioning in relation to the operator. The usage of an industrial 6-axis type robot could improve the handling and ergonomics of spacecraft AIV and also enable additional use cases.

3. State of the Art

The following sections provide an overview over previous and on-going research in the field of assistance systems inside and outside the institute. Furthermore key terms and concepts are highlighted and explained.
Industries which involve a high degree of repetitive tasks during assembly, for example the automotive industry, have been using industrial robots for handling tasks for decades. During spacecraft assembly almost solely traditional MGSE are used which are described in more detail in section 3.5. Within the space industry the prototype nature of most space systems lead to highly complex and unique tasks and systems to be handled. This imposes high information load and stress onto the operator resulting from the delicacy and artisanal nature of the activities. Using AR for AIV operations to reduce the workload is however rarely implemented in the workflow of the space industry. Research done on the applicability of AR in other industries is presented in section 3.1. Also some studies for the implementation of augmented reality in astronaut training or on the ISS are briefly discussed. No work on the implementation of Augmented Reality (AR) during AIV activities in the space sector could be found. Due to the high workload environment implementing an AR system and a robot may aid in the reduction of the workload and improve operator performance.

3.1. Research

Augmented Reality and its application have been subject to research since the 1990´s. The use of augmented reality in industrial processes is the focus of many articles and papers. Only a small fraction is showcased here. De Pace et.al. looked at the applications of AR in enhancing user understanding of robot movement.[4] This is especially valuable in collaborative work with large robots. Maintenance of technical systems assisted with augmented reality instructions has been studied by Fiorentino et.al. [5]. They demonstrated the use of a Head mounted display (HMD)-less AR instruction system to display instructions on large screens. Re et.al showed the benefits of augmented reality when providing instructions for manual industrial operations with regards to workload and time.[6] A different application showing the versatility of the concept is indoor navigation as proposed and researched by Rehman and Cao.[7] The use of the MS HoloLens 2 for remote support of workers by experts is another application that could improve the effectiveness of maintenance

and servicing in the field. This has been studied by Bun et.al..[8]
Initial studies on the applicability of AR in operations on the ISS have shown that using a HMD system mostly reduces the subjective workload.[9] Implementing augmented reality in the environment of long duration spaceflight missions to reduce training time and increase crew autonomy has been researched by Karasinski et al.[10] Work with regards to AIV activities in the space industry could not be found and is therefore focus of the research in the institute. Fischer developed an augmented reality application for the use in spacecraft AIV which laid the base for this thesis and the research on this topic in the department.[11]

3.2. Digitization vs Digitalization

The terms digitization and digitalization are often mixed and misused. However they do not mean the same. To aid in the correct understanding the following definitions exist:

- Digitization is the process of changing from analog to digital form which is also known as digital enablement. [12]
- Digitalization is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business.[12]

When talking about implementing augmented reality systems to display instructions this is therefore regarded as digitalization. It is foreseen to offer new value-producing opportunities. Changing the form of work instructions from a paper-based form to a PDF and eventually a fully data-driven form is however digitization as it is the key to enable future applications like displaying the instructions on tablets, screens or head-mounted AR systems.

3.3. Advanced AIV

The assembly, integration and verification processes of spacecraft in the DLR in Bremen are under continous review. Research is done on multiple aspects. The system engineering and project office is working towards an advanced AIV concept. This is set forth to use modern technologies to aid in the various tasks that occur during the manufacturing of a spacecraft or space system. The activities are focused towards three major areas of the AIV environment: data, infrastructure and tools. They are focused on phase D for the moment. In the field of data, the creation of a comprehensive product data management system and its connections towards other systems is looked at. The field of infrastructure addresses the development,

analysis and usage of smart ground support equipment. Mainly the JARVIS and the Core Avionics Systems Testbed (CAST). In the section of tools the application of assistance systems using augmented reality as well as the development of new methods and processes is researched. A few systems and ideas are looked at in more detail in chapter 4.1.2.
The goals of the advanced AIV concept are to digitize the AIV process for ease of data usage over a wide range of applications. Being able to pull relevant data from and writing back results to a common database will enable faster work with, for example, different simulation tools, test infrastructure or external suppliers. Most importantly though, it will suffice the requirement for a single-source-of-truth. Another goal is the use of state of the art technologies to improve ergonomics, decrease workload and subsequently reduce mistakes made during the activities. The research towards new processes, methods and tools is set forth to improve the overall AIV workflow.

3.4. Augmented Reality

Augmented Reality (AR) is a system in which virtual objects are added to the real world in real-time during the user´s experience.[13] Contrary to Virtual Reality (VR), which completely immerses the user in a synthetic computer generated world, the user of an AR system is still able to see his surroundings. This makes AR the advantageous system over VR when applied to AIV activities. VR however can be used to depict environments that are not in reach for the user. The DLR is currently conducting research on the applicability to familiarize users in a new environment like, for example, a future lunar habitat using VR applications.[14]

3.4.1. Microsoft HoloLens 2

The Microsoft HoloLens 2 is a so-called Mixed Reality device. It is used as it represents the upper end of the scale of AR HMD devices and allows for the highest performance while still running independent of a PC. It also allows for entirely hands-free usage and unimpeded view of the surroundings which are essential features for efficient use in AIV activities. Other AR devices, like the RealWear HMT-1 use less powerful processing units or displays that are mounted in front of only one eye.
The term mixed reality was first defined by Milgram and Kishino in 1994.[15] They also defined the reality-virtuality continuum pictured in figure 3.1 It gives a continuous scale for the transition between virtual and real environment. The left side represents the real environment which contains solely real objects that are observable when viewing a real-world scene. The right side on the other hand depicts the virtual environment. This is comprised solely by virtual objects like conventional

computer graphics. The mixed reality environment is subsequently displaying objects from the real and the virtual world on for example, one display.
In case of the HoloLens 2 the user is wearing a head mounted display with see-through holographic lenses. It is therefore possible to see the real environment while having graphical information overlayed. This provides a more naturally perceived real world than with handheld devices like tablets or smartphones.

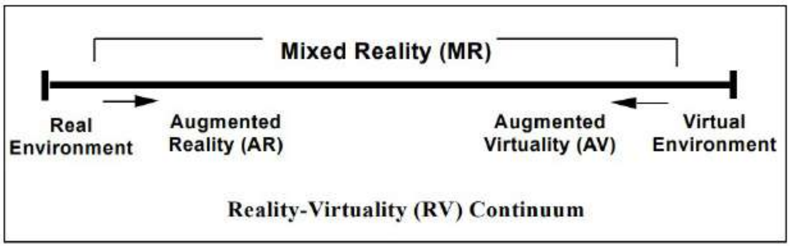


Figure 3.1.: Reality-virtuality continuum by Milgram and Kishino [15]

Augmented Reality devices are usually comprised of four major components. The display, the computer, the input devices and the tracking devices.

- Display: Is the hardware responsible for the overlay of the information on the real environment.[16]
- Computer: To process the sensor and camera information AR systems need powerful processing units. In the case of the HL this is integrated into the head mount. It can therefore run on its own without the requirement for an additional computer.[16]
- Input Devices: These are responsible for translating user input into machine-readable instructions. Speech and gesture recognition are commonly used systems.[16]
- Tracking Devices: With the help of cameras and depth sensors (in the case of the HL) a spatial map of the users surrounding is created to calculate or estimate the current position and orientation of the user at any given moment. This is then used to merge the virtual and real world. Additionally inertial measurement units are used.

Table 3.1 gives an overview of the Microsoft HoloLens 2 specifications.

Table 3.1.: Specifications of the Microsoft HoloLens 2 [17]

Display	
Optics	See-through holographic lenses (waveguides)
Resolution	2k 3:2 light engines
Holographic density	>2.5k radiants (light points per radian)
Eye-based rendering	Display optimization for 3D eye position
Sensors	
Head tracking	4 visible light cameras
Eye tracking	2 Infrared (IR) cameras
Depth	1-MP time-of-flight (ToF) depth sensor
IMU	Accelerometer, gyroscope, magnetometer
Camera	8-MP stills, 1080p30 video
Fit	
Weight	566g
Compute and connectivity	
SoC	Qualcomm Snapdragon 850 Compute Platform
HPU	Second-generation custom-built holographic processing unit
Memory	4-GB LPDDR4x system DRAM
Storage	64-GB UFS 2.1
Wi-Fi	Wi-Fi: Wi-Fi 5 (802.11ac 2x2)
Bluetooth	5
USB	USB Type-C
Audio and Speech	
Microphone Array	5 channels
Speakers	Built-in spatial sound

Figure 3.2.: Microsoft HoloLens 2[18]

3.4.2. DLR-Holo-Space-Tool

The DLR Holo-Space-Tool is an application developed by Fischer [11] during a master thesis in the DLR Institute for Space Systems in Bremen. It already features a few of the major capabilities foreseen for a future application. It is in use since the mid of 2021 and is therefore also used for the purpose of this thesis.
The app runs on the HoloLens 2 and is developed in the game engine Unity. Microsoft Visual Studio is used to write and edit Unity scripts. Visual Studio is also the prerequisite for the deployment onto the HoloLens.[11] Notable features are:

- QRCodesManager: This is responsible for the detection of QR codes. It localizes and encrypts physical QR codes and also visualizes their virtual counterparts. [11]
- HandMenu: This is the primary component to interact with the application and controls the other UI elements. It also serves as shortcut for important functions. As it is the main control interface its easy and fast accessibility is of vital importance. Therefore it can be positioned to the left of the hand by simply raising the hand vertically upwards. [11]
- 3DModel: This is an object which possesses various components and scripts to effectively manage the movement of 3D models in space. It is used to display 3D models into the visual field of the user. For this the models have to be imported into the application prior to its deployment onto the HL. [11]

While an external development partner of the DLR is working on the successor to the Holo-Space-Tool this is currently not available. For the experiments done during this thesis the features of the Holo-Space-Tool can already give insights into the applicability of Augmented Reality use in mechanical integration activities and the impact on the workload.

3.5. Ground Service Equipment - GSE

Ground Service Equipment (GSE) are critical to spacecraft AIV activities. The term describes all non-flight equipment used to support the tasks during AIV campaigns. Examples for GSE are rotation fixtures, cranes, hardware used in specialized lifts and moves but also shipping crates or ladders. Also included in the wide range of ground support equipment are electrical cables, hoses, computers, power supplies or simulation hardware for testing.[19] For the use in clean rooms these have to meet many requirements, for example, with respect to cleanliness, ESD-safety and reliable and secure handling and positioning of the delicate spacecraft. Figure 3.3 shows a typical MGSE with a spacecraft attached. This allows for the rotation of the spacecraft around its own axis and 90° of rotation to place the spacecraft upright.

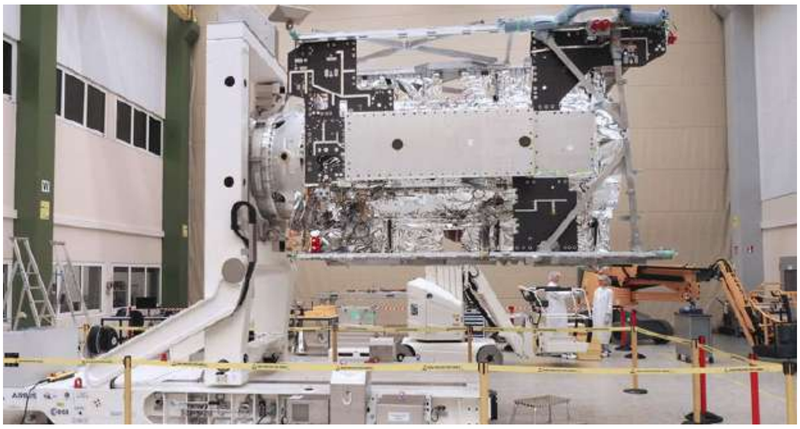


Figure 3.3.: A typical mechanical Ground Support Equipment. Image taken from [20]

4. Methodology

4.1. Workflow Analysis

To understand how the proposed assistance system can be beneficial to the operator workload the current workflow needs to be analyzed. This can then be compared to an ideal, fully digitalized AIV environment to find potential and most beneficial use cases. In a second step a test methodology and necessary tools can be developed to evaluate the assistance systems with regards to the workload improvements.

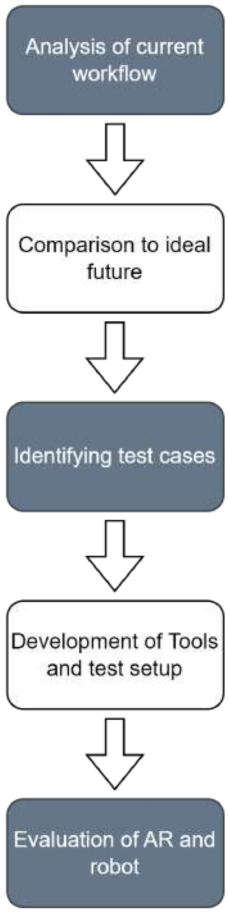


Figure 4.1.

Digitization and digitalization in industry have been ongoing for the last decades. In the aerospace industry however only 37% of suppliers have started to digitalize their processes.[21] This is mostly due to the high investment cost necessary and the supplier base being mostly Small and Medium Sized Enterprises (SMEs) which have harder times making these investments.[22] Moving from a paper-based information and documentation scheme to a fully digitized environment takes considerable financial effort but also the participation of each stakeholder beginning from the management all the way down to the employee base. Convincing the individual operator of the benefits of new digital processes and working schemes is a crucial point.

4.1.1. Depiction of the current material- and information flow

Prior to analyzing the material- and information flow within the AIV environment of the institute it has to be understood what is meant by the term. The term "material flow" according to VDI 2689 refers to: The interconnection of all processes involved in obtaining, processing, and distributing goods within defined

areas. The material flow includes all forms of the movement of work items through a system.[23]
In the frame of the of the assembly, integration and verification of spacecraft this mainly refers to hardware from part up to system level. Rarely raw materials are used. This is however becoming more relevant with the incorporation of additive manufacturing. Here the raw material is directly used by the institute staff to manufacture, for example, cover plates for the Mars Moon Explorer (MMX) rover chassis, on short notice. It is however the flow of parts and components up to systems that make up the largest amount of the material flow within an AIV environment such as the institute of space systems.

The "data or information flow" is the path that oral, written, or electronic data or information follows from its creation to storage or destruction.[24]
One could argue that the information flow is part of the material flow since both are connected via, for example, ordering processes or specifications for hard- or software. It is therefore rarely possible to view them independently. In a space project, where documentation is of highest importance, the information flow therefore has to be closely linked to the materials. Looking at AIV operations, this makes a highly reliable and centralized information and data management necessary to enable efficient and fail proof work. At the same time, the high complexity of space systems also means a large number of information sources that have to be deployed to the individual operator at the right time and linked to the respective material that is being worked on at the moment.
During this thesis the focus lies on the operational work and the analysis of the application of AR- and robot assistance. The following sections will depict and analyze the material- and information flow from this viewing angle.

4.1.1.1. Current Material- and Informationflow

Figure 4.2 shows a typical flow of hardware through an integration facility. Each step of the component, subsystem or system is tracked and documented. Once a component, part or subsystem has arrived at the integration facility it is subjected to the Incoming Quality Inspection. It is verified that it meets all requirements and is released for further assembly, integration and testing. It is then either stored or directly transferred to the integration area of the respective project. This is usually also true for fasteners, custom GSE´s and tooling.
Depending on the nature of the component this manual transfer process can have high requirements towards ESD-safety, cleanliness or minimizing environmental loads. Small parts and components are usually stored in ESD-bags and almost all parts are stored within the climate controlled environment of the clean room.
Each individual component is given an unambiguous alpha-numerical identifier dur-

ing the design phase. This is then either written onto the component or a small label taped to it once the component arrives at the integration facility. This label also includes a Quick Response (QR)-code to access the identifier fast and convenient. It is of major importance to track each item during the AIV process. All information and documents regarding the respective item will also have the identifier stated on them. Before and after transfer steps there are usually inspection points included in the OVP that accompany each operation.
Additionally the size of a component or subsystem has an impact on the flow through the integration facility. This can be easily understood when looking at complete satellite buses in comparison to a small electronic box. Size and weight dictate the number of operators, the spatial requirements within the facility and also the need for specialized GSEs.
During integration of large space systems the positioning of the system relative to the operator is also done by mechanical ground support equipment as could be seen in section 3.5 or for smaller systems they are positioned on tables. This gives only limited degrees of freedom for the positioning of the spacecraft or system and usually requires custom built GSEs and interfaces. Mounting and demounting of a system to the GSE, changing the position or moving it entirely are operations that follow specific instructions and also require documentation.

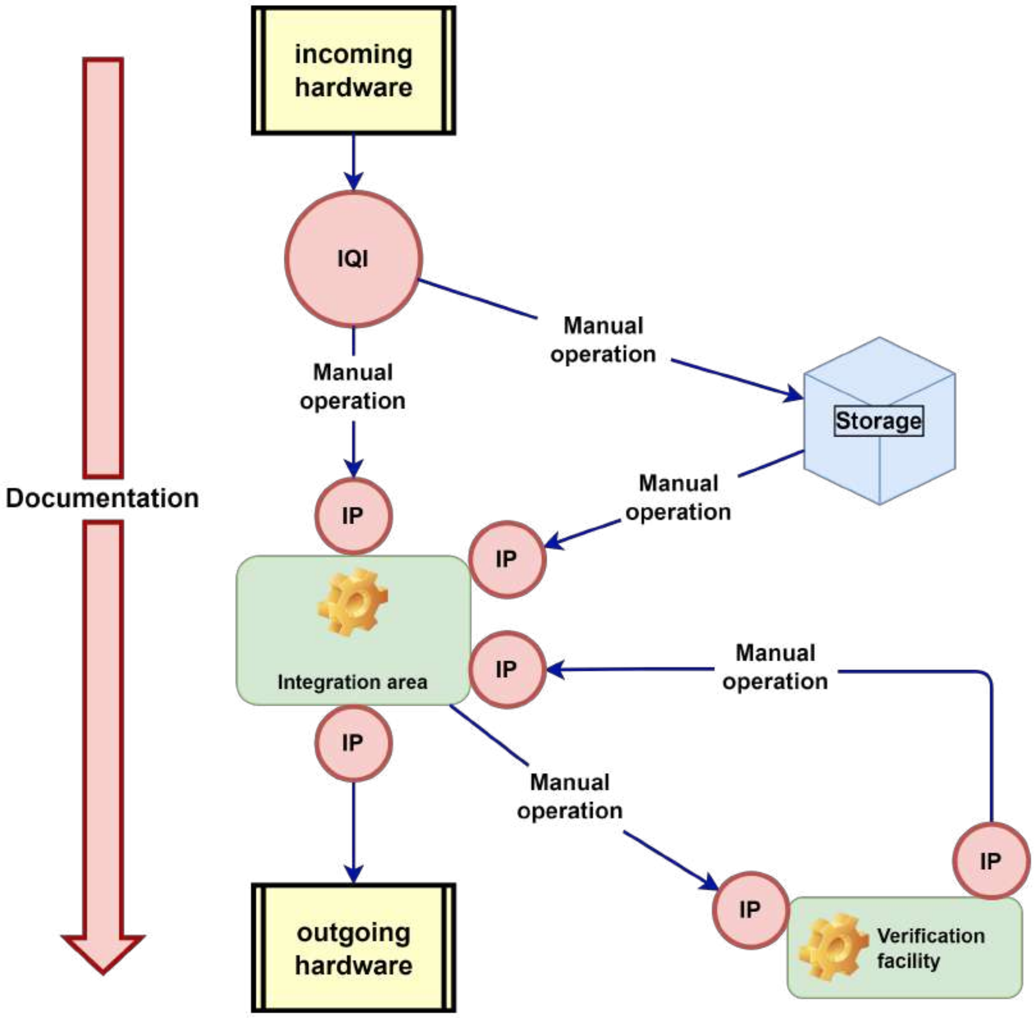


Figure 4.2.: Flow chart depicting the hardware flow through a integration facility

4.1.1.2. AIV Procedures

Documentation of each process and it's outcome are essential in the development and realization of space projects. By having detailed records through all phases, each stakeholder can justify the actions taken. This is of special importance when it comes to documenting correct assembly, integration and testing of a system. The launch provider expects complete traceability to minimize the risk of a failure during launch. Same is true, for example, for the hand-over of hardware between supplier and system integrator or integrator and a test institution. For this purpose the activities during an AIV campaign are split up into sections. These are called OVP. During this thesis these are just referred to as procedures. These are the main information source for the operator and also the main way of documentation during AIV operation.

A procedure typically describes a set of activities that are centered around a specific part or subsystem of the overall system. This can be the integration or testing of a component or subsystem, inspections of items or previous tasks or transfer and logistic operations.
These procedures always have the same general structure. At first there is information regarding the applicable documents, tools to be used and overview drawings and figures of the components or the integration envelope. Another important part is the Integration KIT list. This lists all components, assemblies, harnesses, and fasteners that are to be used during the operation at hand.

The operational information is split into operations, which are again split into processes and steps. Each operation usually covers a specific part or component or a certain set of activities that are in themselves finished after each operation. This could be, for example, the integration, torque and screw lock of a component or part into another assembly or subsystem.
It starts with preparation activities. These include the acquisition and calibration of tools, the preparation of software, making sure the workplace is electrostatically grounded and clean and the inspection of the respective components to be integrated or worked on.
Next is the part which describes the specific task or tests to be conducted. Each page in the operational, but also the preparation part, is usually split up into two main parts. Figure 4.3 shows an exemplary page of the operational part from a Reusability Flight Experiment (ReFEx) procedure.
The left side holds the description. This is again split into two halves. The left half has a step-by-step description of the tasks to be carried out as well as check boxes to document the successful execution of the respective step. The right one contains required or additional information for the steps. These can be images of components from Computer aided design (CAD) models, drawings, text-based information or anything that the operator might need during this operation.

The second part of the operation sheet holds the information part. It is a set of columns designed to be used for documentation of the operation progress. Start and end time as well as breaks are logged. Furthermore any deviations and Nonconformance report (NCR)´s that occurred are logged in this section. Additionally each page may require the signature of the operators and/or the Product Assurance (PA) engineer.

Between operations there may also be intermediate inspections and reviews which aid in quality management and make sure the operation has been correctly executed and following operations can be conducted safely. These are called End of Operation Inspection Point (EOIP). Additionally, Key Inspection Point (KIP) may be required. These are done at important and sensitive points within and also at the end of each procedure. This may be due to the respective component or subsystem not being accessible after following activities and therefore special care needs to be taken with regards to product assurance. Or the functionality of a component or subsystem needs to be tested before continuing the integration process.
Every procedure will be concluded by a part that serves as a documentation point for product and quality assurance. This includes pages for documentation of the climate within the integration facility and non-conformance records.

Additionally, each procedure has a large overhead of pages. These include document information like cover sheet, document information sheet or table of contents but also sheets important for the documentation of the progress of preparation and execution of the procedure like the procedure closeout sheet or the procedure change record. Furthermore glossaries, general remarks and summaries. In sum this is around 17-20 pages. This overhead is more or less constant in page count for all current procedures.

Operation and Verification Procedure (OVP) are currently printed out, filled out by hand and later scanned into Portable Document Format (PDF)s for final storage. Depending on the extent of the task a procedure can have between 20 and 100 pages. [25]

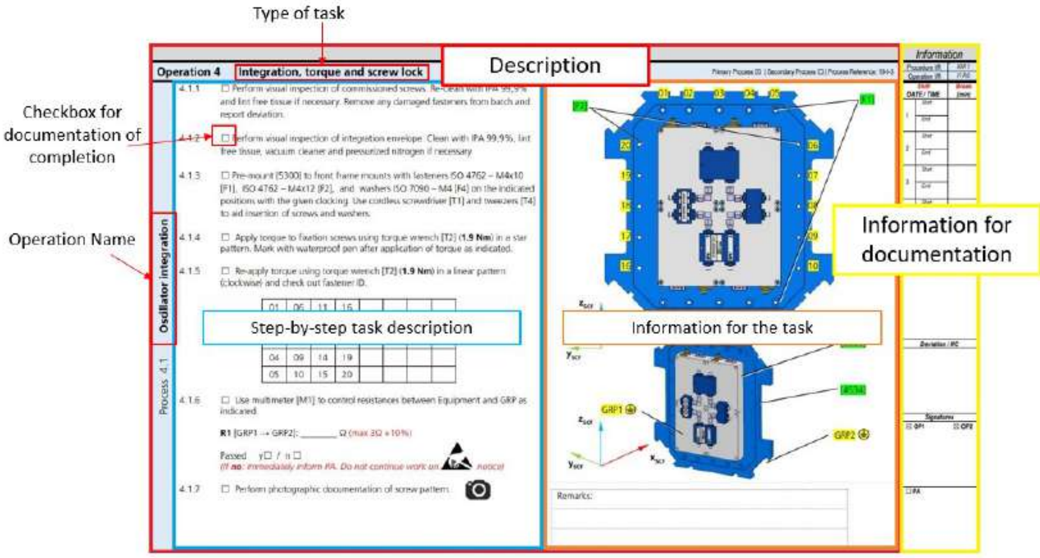


Figure 4.3.: Exemplary page of a OVP showing the main aspects

Preparation of AIV Procedures

Figure 4.4 shows the current process of OVP preparation. Currently OVP are prepared by an engineer of the system engineering and project office using a text editing software. They are then published for review by the design engineers as PDFs and enter an iterative process of review and updates. Finally an employee of the product assurance team responsible for the project signs the procedure and it is issued to the operator.

During this process the procedure is iteratively changed multiple times. Version control and maintaining a single-source-of-truth is therefore a key challenge during the preparation process but also prior in phases A-C.

Another aspect to look at are the many different sources of information that are incorporated in the preparation stage. Many different documents on multiple locations as well as 3D information out of CAD systems are used. Additionally, a multitude of file formats ranging from text files like word or PDF, lists in excel files, scanned pictures and many more are found during the process. These are stored in repositories like SVN´s, Wiki´s or teamsites and local or network hard drives. Finding the necessary information needed for the operation or task to be described in a procedure can therefore be a challenge and takes considerable amounts of time.

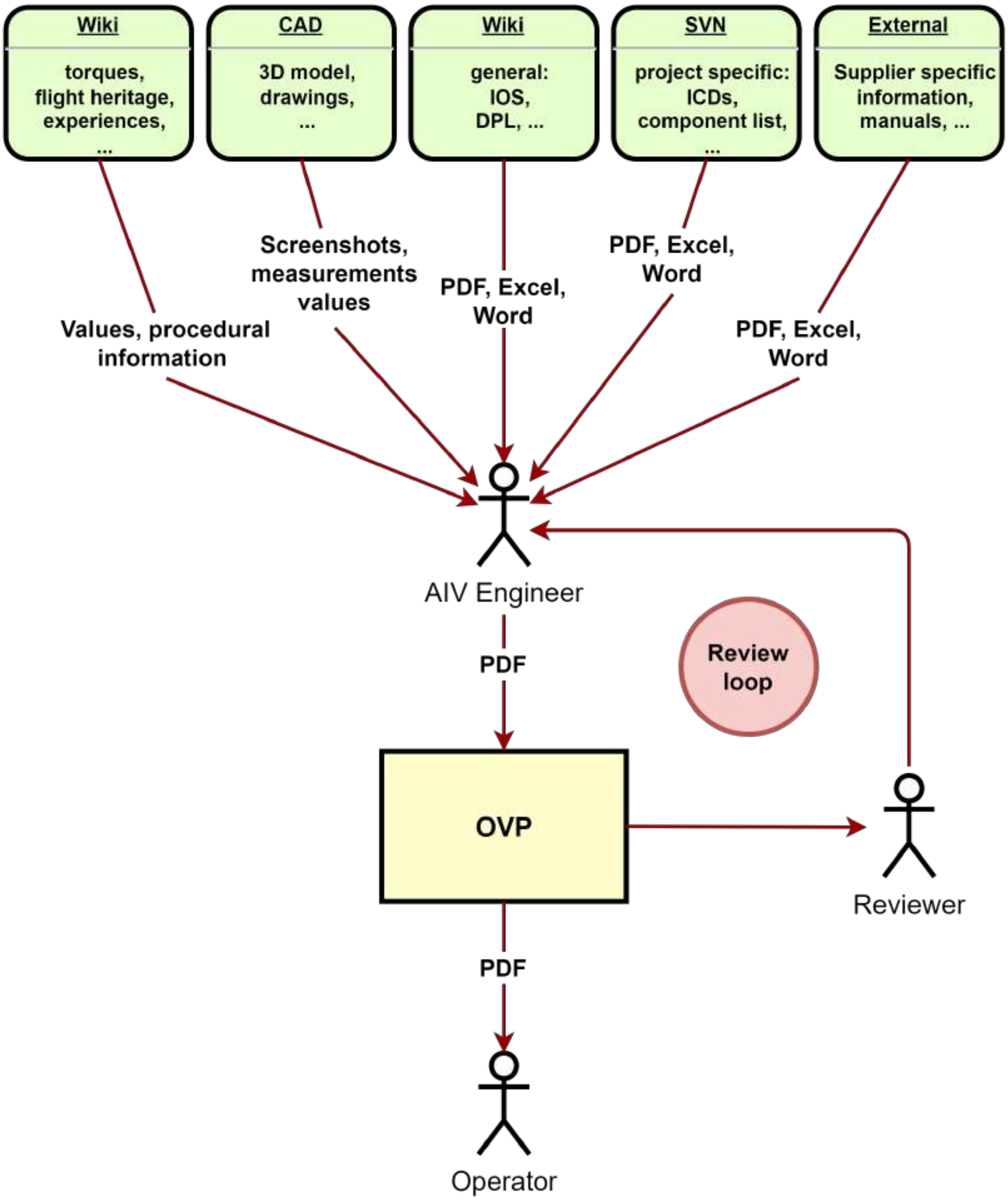


Figure 4.4.: Flow chart showing the process of OVP preparation

It can be seen from figure 4.4 that there is a certain order in where to find which type of information. The Wiki serves as source for general information while SVN repositories or Teamsites hold project specific information. 3D models, drawings and schematics are extracted directly from CAD systems. Additionally, external sources like suppliers, other institutes or stakeholder and the internet are frequently incorporated into the preparation process.

4.1.1.3. Information flow to operator

Providing the operator in the clean room with the right information at the right time is of key importance. Figure 4.5 depicts the in- and outputs of information to and from an operator. As already mentioned, the main source of information is the OVP. It describes the tasks to be carried out, lists all necessary tools and components and is used for the documentation of the AIV operation at hand. It may also include drawings, pictures of CAD models, harness schematics or connector sequence diagrams. All of these are transported via paper as 2D information from the engineer that prepared the procedure to the operator. They might be the same person but frequently are not.

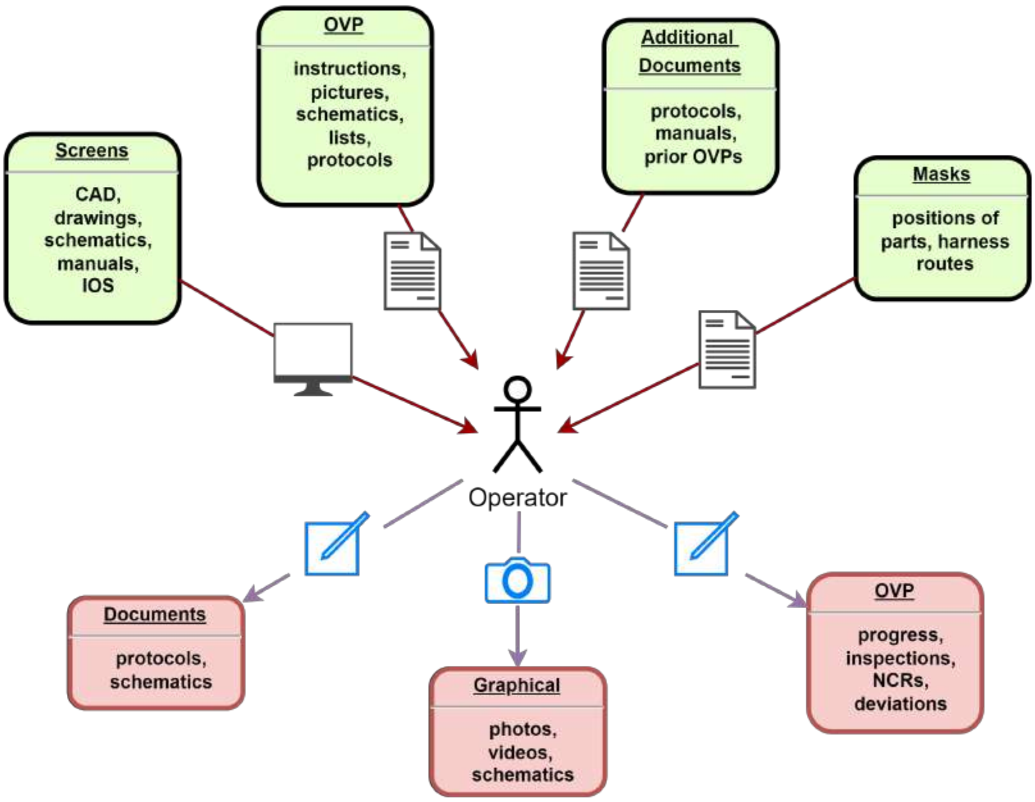


Figure 4.5.: Flow chart showing information in- and output to the operator and the means of transportation

Since every human works or processes information differently or is more or less familiar with the project or system, each operator may need different or additional information. It is therefore frequently the case that drawings, schematics or CAD models are viewed on laptops or larger screens during the operation. These offer more flexibility in the way information is shown and offer access to other additional information from internal or external sources.

For some operations it may also be necessary to design masks that can be printed out and attached to the bus or subsystem to route cables or mark positions of tie bases to be glued in. Depending on the geometry of the surface that the mask needs to be applied on or other components and harnesses already in place, this can be a tedious and lengthy task.
Furthermore additional documents like manuals, protocols or already run procedures might be necessary.

4.1.1.4. Information flow from operator back to engineering team

Equally important as the flow of information to the operator is the return of information from the operator back to the engineering team, product assurance or other stakeholders. Documenting the time of start and completion of a task is only a small fraction of information and data produced during the AIV operations.
This ranges from photographic documentation, measurement values and software versions to deviations, non-conformances and close-outs. Some of this is directly entered into the procedure by handwriting while pictures are taken with different cameras or mobile phones and automatic measurement data is saved to local hard drives or different department servers.
Deviations and non-conformances are additionally tracked and documented by the product assurance engineers in form of handwritten entries into the procedure and PA internal lists and documents. Test results may also be documented in independent protocols either written by hand or typed into a digital format. In case of hand-written documentation this usually has to be either scanned in afterwards for final storage or even transcribed manually into further analysis or software tools. This would also be necessary if information from during the operations are required by external stakeholders.

4.1.2. Ideal AIV environment

An ideal AIV environment would enable the individual operator to execute highly complex tasks very efficient, with smart tools at his or her disposal and the workload being manageable. Information is provided at the right time and additional information accessible without effort. Documentation is done paperless and stored in a single database. The limits of paper documents are overcome and instructions and other information can be made available to the operator in many different ways that are not based on standardized paper formats but maybe on new digital documentation standards.

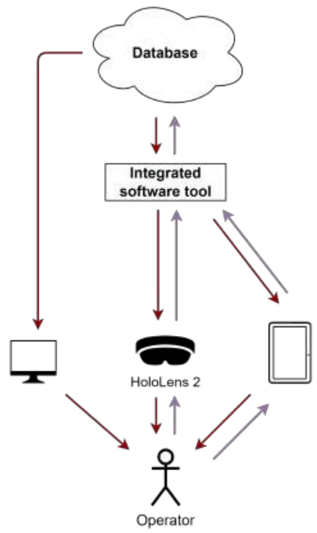


Figure 4.6.

Figure 4.6 shows the flow of information to and from the operator and the different means of transportation. Information and instructions would be made available on multiple connected devices. Tablets to display instructions, HMDs to display three dimensional information directly into the work environment or larger screens to access and show additional information from the database. Measurements, progress documentation, NCRs or photographic documentation could be made with these tools and directly linked to the procedure and stored in the common database. A closed cycle of information transport without paper documentation or handwritten information would be the result.
Figure 4.7 shows how the implementation of a database is the foundation of a digital workflow during AIV activities. A fully integrated tool to prepare, review and execute the fully digital OVP is the second major improvement. This tool will then enable the operator to make use of multiple different ways to display the instructions and information linked to the indivdual task.
The foundation lies within a database which provides all the necessary information and data to the many different front-end applications that can be thought of. The Engineering Information and Ground Operations Management System (ENIGMAS) database is in development to fulfill that role and is introduced in section 4.1.2.1. This enables the AIV engineer to access all information necessary to prepare an Operation and Verification Procedure (OVP) from one source. The already in use unambiguous identifier serves as a way to link all information to the part and access it accordingly.
The applications for AR and robot that are foreseen to reduce the operator workload are described in more detail in sections 4.1.2.2 and 4.1.2.3.

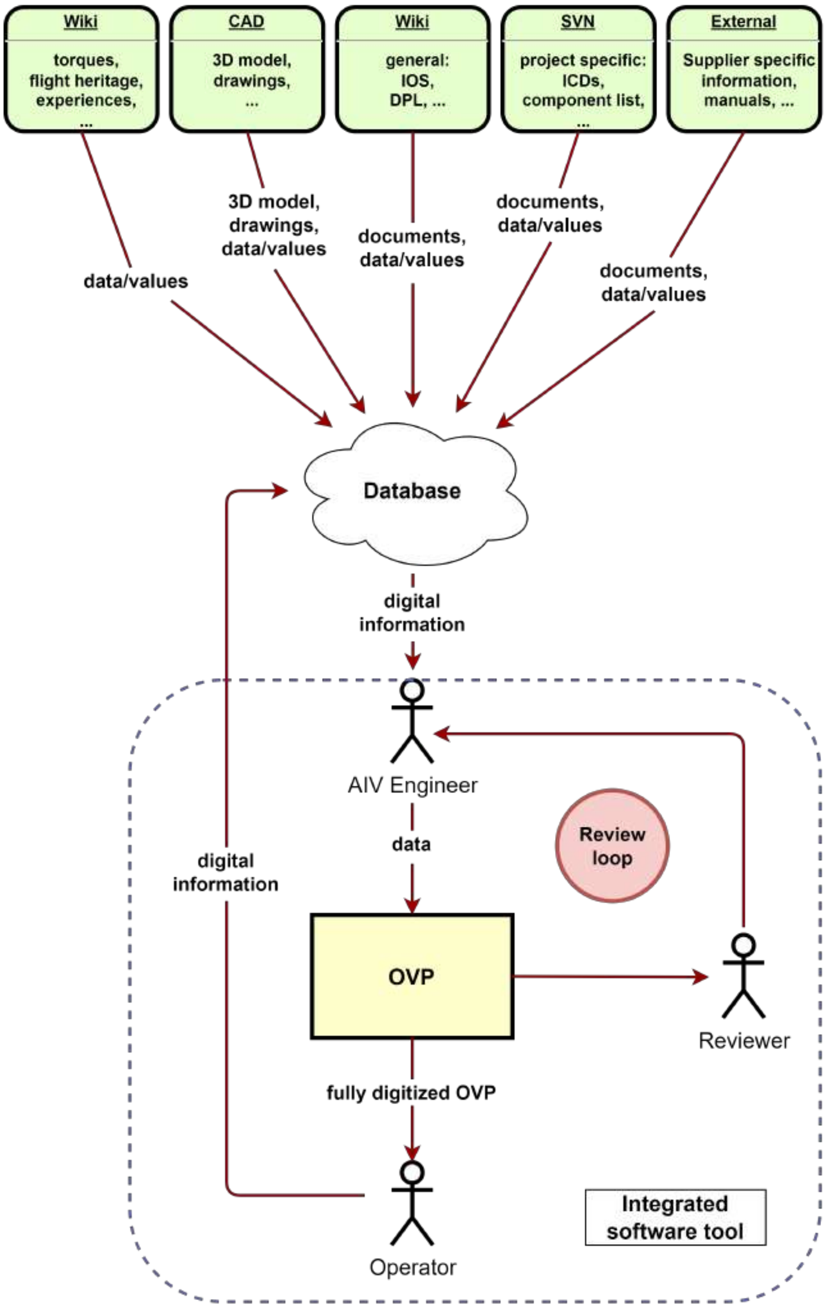


Figure 4.7.: Flow chart showing future way of preparing OVPs

More applications are developed at the moment, for example, dashboards that display process information via large screens in the integration hall. Furthermore the

DLR Institute of Space Systems is setting up the "Digital Clean Room" laboratory. This shall provide the researchers and engineers with a functionally representative laboratory. It shall be used to simulate a production environment as demonstrator for the developed applications and strategies.[26] With this laboratory the research towards new tools and applications for a fully digital AIV environment can be accelerated and streamlined. Goal shall always be to improve the workflows and processes. This requires the use of the right tool for a task and does not necessarily mean each task benefits from the use of additional tools like an augmented-reality system. Quantifying the complexity of a task and being able to determine a point at which it would be beneficial to introduce a tool like the HoloLens to the task would therefore be valuable information during AIV planning. This is the goal of the Complexity Factor developed during this thesis. It is described in more detail in section 4.2.

4.1.2.1. Engineering Information and Ground Operations Management System - ENIGMAS

To enable all the different concepts that are thought of for the fully digitalized AIV environment a common database that contains all data and information is the crucial basis.[27] The ENIGMAS database is in development right now and shall provide, in a first step, engineering information and data to the AIV engineers. It collects AIV data from the various sources in use at the moment (see 4.1.1.2) and transforms it into a structured format.[28] Future applications can then use APIs to access the necessary information from one source and also write back measurement data and other information to this single database. Providing a single source of information and data is especially important for external stakeholders developing applications.
The usage of information also needs to transform from document-based towards a data-based environment. This means that, for example, measurements are not stored within a document which is then safed to a database but each individual value can be accessed.
While the individual operator would only interact with this database via web applications or other tools it is the basis for an "ideal" AIV environment.

4.1.2.2. Augmented Reality

Due to the complex nature of spacecraft AIV activities the individual operator has to process a large number of information. This can be instructions, interface documentation, images of CAD models, tooling information and many more. Providing this information to the operator at the right time in a comprehensible amount is a key challenge to increase efficiency and reduce the workload. Using a head-mounted augmented reality system like, for example, the Microsoft HoloLens 2, can aid in many ways. It is however another tool to be used by the operator which adds complexity to the task. Section 4.1.2.2 gives an overview over possible applications of the AR and their advantages.

Applications

Augmented Reality applications are foreseen in many use cases during AIV campaigns. They range from planning activities like determining the position of GSEs beforehand and without even having the physical hardware on-site to overlaying 3D models onto the integration envelope to enhance the operators overview of the task at hand. Remote assistance by experts or back office personnel via the HMD system can also enhance the cooperative working and decrease the effort to be taken by each individual. Viewing the item or area of interest through the camera and getting displayed the same information as the operator on site can make the task of troubleshooting or assisting highly more effective. A few of the presumably most advantageous uses shall be looked at in more detail in the following sections.

Displaying 3D/CAD models

CAD systems have revolutionized the development and design of complex systems of any kind. Saving time, faster transfer of information via, for example, E-Mail and the implementation of CAD data directly into simulation tools or CAM applications are just a few of the benefits. When digitally assembling multiple components to a functionally higher system the increased overview through the usage of computer-aided design software is a major aspect of finding collisions or inhibiting features.[29] This is however still happening on a screen that is not giving an actual three-dimensional view of the model.

By displaying a 3D model directly into the visual field the operator can walk around it, increase or decrease the size and also step into the model. It also enables the positioning of components or subsystems as virtual models into the integration envelope to plan for spatial demands or position GSEs. This has already been demonstrated during tests for the alignment process of the ReFEx demonstrator. This features a cube with mirror surfaces in the front of the Hybrid Navigation System. Since the primary structure of the vehicle was not on-site a 3D-model of the ReFEx demonstrator was placed inside the integration facility relative to the robot GSE as it would be during future alignment procedures. Afterwards the theodolites, which need to be positioned rectangular to the alignment cube, could be placed in the physical world and their positions marked for the actual alignment in the future. This will safe time once the actual hardware arrives but also allowed for tests of the alignment setup in advance.

Overlaying 3D/CAD models over physical hardware

Through overlaying virtual models over physical hardware a whole new range of possibilities arise that can reduce time and workload. Many operations like, for example, fit checks, require the actual physical model of the component or a mock-up of identical shape and size. When using a 3D model of correct dimensions and overlaying it directly over or into physical hardware this is not necessary anymore. Without the need for mock-ups or the actual hardware the planning of AIV activities, fit-checks and also design of mechanical ground support equipment can be done independently. Delays due to missing hardware and additional costs by designing and building of mock-ups can be avoided.

This technique can also be implemented directly into the assembly and integration work. By displaying the next component to be integrated into the physical hardware the operator can determine the correct position and orientation of the component. This leads to a more effortless orientation within complex integration envelopes, higher confidence of the worker in the correct execution of the task and also faster determination of possible deviations and NCRs. An overall reduction of stress and workload factors would be the result.

Displaying documents

Displaying documents of any kind into the direct view of the operator is an application that is closely looked at. Enabling the worker to view and manipulate documents via gesture and without loosing focus of the current task is thought to decrease the workload and time needed for tasks but also improve ergonomics. The manipulation via gestures and without physical contact also allows for operators wearing gloves or with polluted hands to fill in documents, change pages or make annotations. These can also be done via speech, by taking pictures or videos or combinations of all of the mentioned inputs.

The increased flexibility in arranging the different information sources freely within the entire three-dimensional working environment also allows for a more organized, cleaner work space while additionally using, so far, unused space. This can lead to less focus shifts from the task at hand to, for example, a paper-based source of information but also ergonomic improvements. The classic sheet of paper that takes up space on the table, fixed in size and easily covered by tools or polluted can be replaced by an advantageous system. This is however strongly dependent on the fast and intuitive use of the application.

A head-mounted system with an integrated network access also would allow for the direct interaction with information in the database. Adding comments to procedures, documenting NCRs with pictures or videos that directly include the virtual information into the depiction of the physical world can lead to more precise and concise transport of the relevant information.

4.1.2.3. Joint Assembly Robot for Versatile Integration of Spacecraft - JARVIS

The Joint Assembly Robot for Versatile Integration of Spacecraft, short JARVIS, was introduced to the DLR clean room in 2019. It is foreseen to be used for multiple different applications during spacecraft AIV campaigns to reduce the number of re chucking operations, enable in-line verification and improve ergonomics. All would result in a decrease in workload for the operator. The robot is part of the research field of Smart Ground Support Equipment in the DLR Institute of Space Systems, in Bremen.

Specifications

JARVIS is a KUKA KR500 R2830 industrial robot that is mounted onto a base to raise it from the ground. Table 4.1 gives an overview of the technical data and figure 4.8 shows the robot on its base in the clean room of the DLR Institute of Space Systems in Bremen.

Figure 4.8.: The Joint Assembly Robot for Versatile Integration of Spacecraft mounted in the DLR clean room in Bremen.[30]

Table 4.1.: Specifications of the KUKA KR500 R2830 industrial robot [31]

Technical Data	
Maximum reach	2826 mm
Rated payload	500 kg
Maximum payload	611 kg
Pose repeatability	+- 0.08 mm
Number of axes	6
Footprint	1050 mm x 1050 mm
Weight	approx. 2385 kg

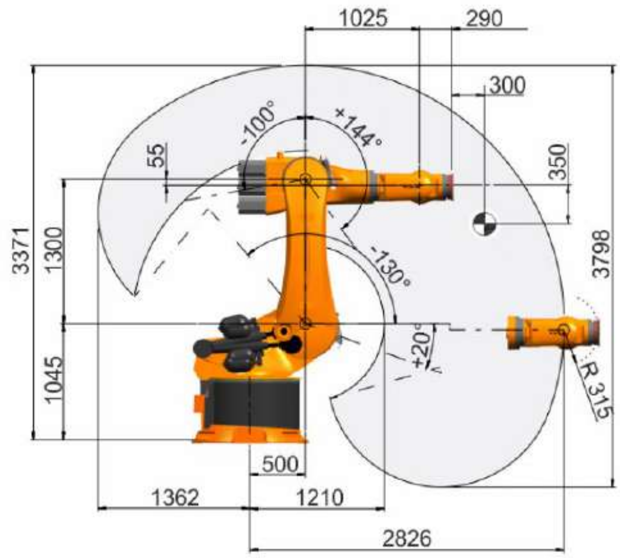


Figure 4.9.: The working envelope of the KUKA KR500 R2830 industrial robot. [31]

Applications

Multiple different applications of the robot during AIV campaigns have already been determined. Table B.3 in the Appendix B gives an overview on the foreseen applications and also on the status of development. For the purpose of this thesis the application of handling is analyzed with respect to its benefits towards time and ergonomic factors during mechanical integration activities.

To be able to use the robot in close proximity to humans without a cage, it is used exclusively in manual mode. It therefore only moves when the dead man´s switch on the handheld KR C4 remote control is depressed and only with limited speeds. The KR C4 features a 6D mouse or axis-wise buttons to control the motion of the robot. It can be used in several different modes depending on the use case. For example, axis-wise motion, relative motion in robot or flange coordinate frame or in half automatic mode with pre-programmed motions.

While the handling and positioning of a spacecraft in 6 degrees of freedom is an apparent advantage over MGSEs the robot also has drawbacks. In its current setup the JARVIS robot is fixed in place and cannot move. This makes it less flexible with regards to logistical operations within the integration hall than a traditional MGSE. Those are usually setup to be movable. Transfers to the shaker test facility or the thermal, vacuum chamber therefore require an additional mechanical ground support equipment. This can however be less sophisticated in its features.

Furthermore the KUKA KR500 is limited to in its payload. While the actual payload is larger than 500kg when used at lower speeds and in manual mode it would not be enough for large communication or reconnaissance satellites. However, the largest industrial six axis robots have payloads of 2.3t which could be enough for the dry-mass of most satellites.[32] For the purposes of the Institute of Space Systems mostly smaller and lighter systems are integrated and the KR500 is more than sufficient.

Other limiting factors for the envisioned applications are the built in safety systems of the robot. While these are necessary during automatic operations using the full capabilities with regards to speed they are hindering the use as a Robot designed for direct interaction/collaboration with humans (COBOT). The term "COBOT" comes from the combination of the english words "Collaboration" and "Robot", and describes robots designed for direct interaction/collaboration with humans. When humans and robots share a workspace without separating safety devices, it is also referred to as human-robot collaboration (Human Robot Collaboration (HRC)).[33] Traditionally force-momentum sensors on the axes of robots are used to detect contact with obstacles, like humans or walls. This is however not always feasible or wanted. A possible solution would be the combination of augmented reality with the robots controller. Increasing the safety of workers within the movement envelope of the arm by displaying its next movements as hologram into the visual field could lead to more confidence in close proximity operations.[34] Additionally, safety checks and warnings could be integrated into the procedural task description whenever a movement of the robot would be necessary. Using a head-worn augmented reality system to control, visualize and approve motion of the JARVIS robot would integrate the robot seamlessly into the workflow.

Applications like in-line verification methods have already been in development for some time within the institute. Determining the mass, center of gravity or moments of inertia using the robots motor currents would reduce mounting and demounting operations and eliminate the need for additional GSEs. Elimination of re-chucking steps saves time and decreases the risk of handling mistakes and damages to the spacecraft.

4.1.3. Comparison Traditional vs. Digital

When comparing the current and the ideal AIV environment it becomes apparent that the potential for improvement is considerable. Using a digital workflow can reduce the workload of the AIV operator significantly.

4.1.3.1. Paper vs. Digital

For the individual operator the paper-based OVP is limiting in flexibility and lacks in capability with regards to showing information. This increases workload due to less-than-ideal presentation of information and everything being confined to an A4 format. Choosing the ideal tool for displaying information and documenting, for example, progress, deviations and measurements can enhance the ability to process the high information load while maintaining a superior quality standard.
Using one integrated software tool to prepare, review and execute procedures leads to a much simpler workflow and reduction of workload and time needed by the AIV team. Additionally it enables a closed loop of information transport without the need for transcription of hand-written measurements or scanning in procedures afterwards.

4.1.3.2. Augmented Reality

Implementing augmented reality applications into the workflow of AIV activities has the potential to open up the third dimension to the operator in terms of information transport. Holographic models of the system worked on could aid in understanding the steps in spacecraft integration. The individual operator could be enabled to evaluate and, if necessary, change the planned procedures should the hologram reveal a better solution that might have not been visible while looking at a CAD model. Subsequently the workload is reduced while the individual operators participation is increased leading to a positive identification with the workplace.
Direct connectivity with the database would allow for fast and effortless information exchange between operator and experts or back office engineers leading to less work to be done. Remote assistance via a HMD device with full access to the operators view and the same information he is seeing could allow for troubleshooting without the need to actually be in the same room. This is especially helpful in cases where the two operators are not in the same building, city or even country. Not having to put on special cloths and pass a lock would decrease the effort to render assistance

to someone working in the clean room to a minimum saving time and workload.
The addition of holographic tools, like virtual lines as measuring aid or displaying the coordinate system of parts or systems can improve operator efficiency due to less physical tools to be held. The same applies to holographic instructions and information. Having them placed in a convenient position in the three-dimensional space without the need for desk space or free and clean hands to view them is believed to be one of the most valuable applications of HMD devices.

4.1.3.3. Ergonomics

Using a robot as mechanical ground support equipment has the potential to make spacecraft integration more ergonomic. It can also lead to less demounting of spacecraft from MGSE since it opens up the possibilites of in-line verification. This leads to less workload for the individual operator and decreases actvities that cost time and have the potential for failures resulting in damage. However, safety limitations have to be overcome by using smart tools and software to enable full flexibility and confidence in the COBOT application.

4.1.4. Identifying test cases

Using the HoloLens to display information and overlay 3D models as well as the robot as MGSE are applications that are already available and have the potential to decrease operator workload. Therefore, these two assistance systems are chosen to be evaluated in the following test setup. Other applications, while having high potential with regards to workload reduction, are not fully developed or require a functional database and could therefore not be considered.

Three task were envisioned for the initial experimental tests. The complexity factor was not sufficiently developed by the time the experiments had to be designed and could therefore not be incorporated into the task design. The JARVIS robot MGSE will be used in comparison to a table with rollers to evaluate ergonomic and time improvements and workload reduction.
Displaying the procedure and holographically overlay the parts to be integrated will be the applications on the HoloLens 2. Routing harnesses over a series of mounting points and placing TC105 cable tie bases are two tasks that are believed to benefit from a holographic assistance. Their positioning and orientation within a large integration envelope is hard to properly present on paper or via two-dimensional media. These exercises will therefore be used as test cases for the applicability of the proposed assistance systems.
Lastly, a task that is believed to not benefit from the use of the HoloLens is proposed. Mounting a rather simple electronic box onto a pre-existing hole pattern

is sufficiently described using a two-dimensional format of information transport. Therefore the additional time and workload overhead when using the HoloLens 2 is believed to be detrimental to the execution of this task.

4.2. Complexity Factor

During early tests with the current augmented reality application and the Microsoft Hololens 2 it was brought forward by two test subjects that the task at hand was to simple. Setup and interaction with the additional tool on the head was hindering their ability to perform this task. The complexity of the task at hand was not justifying the overhead of the additional tool. To remedy this a model for a complexity factor was developed. Using as-run-procedures from current and previous projects in the institute inputs and outputs are characterized. This factor is envisioned to be used to determine the complexity of a task beforehand and decide whether or not using tools like the HoloLens would be beneficial.

Task complexity has been researched for many decades with different focuses. Researchers have taken into account many different factors and in various scenarios to develop a framework that is usable for all applications and task. [35]
Since this factor shall be calculated prior to executing the procedure to verify the applicability of using assistance systems, it needs to take inputs that are independent from the individual operator. It is also tailored especially towards tasks in spacecraft AIV.
Complexity definitions using, for example, the amount of knowledge or the familiarity with the environment, as used by Braarud and Kirwan[36], are therefore not usable. The number and type of inputs and the amount of information needed however, are commonly applied factors in research. (see [37], [38], [35])
Additionally the physical appearance of the products are considered due to the often unwieldy but simultaneously, delicate nature of spacecraft components.

For the purpose of this study the factor is developed with the data from previously run procedures of the Euglena Combined Regenerative Organic Food Production in Space (EU:CROPIS), ReFEx and MMX projects. It therefore needed to be comprised of inputs that are commonly found in all procedures and that are discernible from the as-run-procedures without having to ask the engineers who executed them. A factor is calculated for each process within a procedure since this usually describes a closed set of instructions or tasks.

Three separate dimensions are proposed: Mental, Effort and Physical. This is done to allow for future weighting of the components and increase flexibility in the model development.
The mental complexity factor is taking into account the number of different interface groups that are encountered during the task and the accompanying information needed for the completion of the task.
The effort factor is comprised of the factor for product complexity and the tooling

complexity.
The physical factor describes the added complexity by having larger or heavier components.

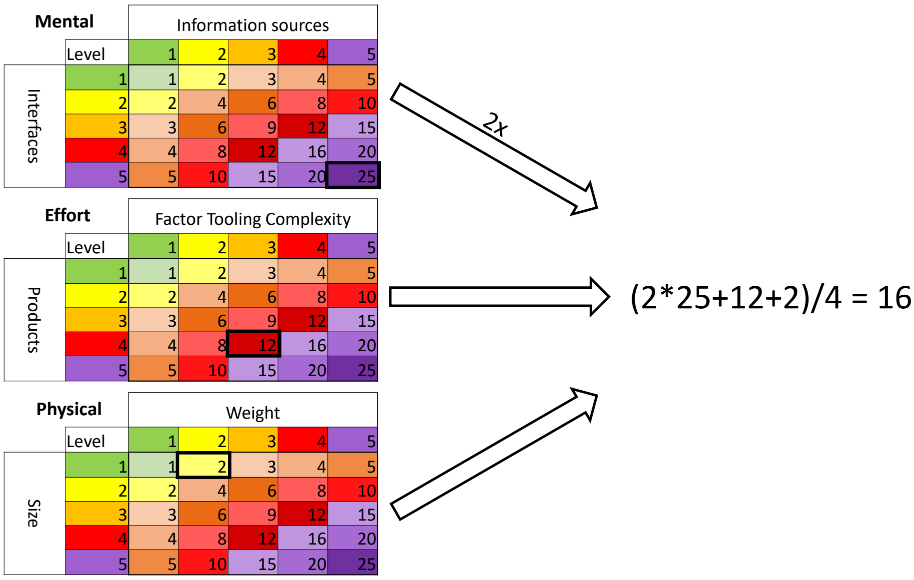


Figure 4.10.: Determination of the complexity factor on the example of MMX LOCO OVP Process 11

Each factor can have a value between 1 and 25 describing increasing complexity. They have two dimensions each, with each dimension having five levels. For the overall factor all three are summed up and divided by the input. In the present version the mental component is weighted with a factor of two and therefore the overall sum divided by four. This gives a scale ranging from 1 to 25 with one being the lowest complexity and 25 the highest. This range should allow for the determination of a discrete complexity boundary beyond which the use of an arbitrary assistance system is indicated.
To determine the range of inputs for each level five Histograms are created from 236 processes out of 28 procedures.(see Appendix) These show the number of occurrence over the number of relevant input into the model. They were then split into five sections holding as close to equal numbers of inputs as possible to then define the five levels per factor dimension. Figure 4.11 shows the process of splitting up the histogram into five levels on the example of the product types. The first level was deliberately set to also incorporate the count of two since there are only 20 processes including 1 product and these are almost exclusively inspection points and subsequently are of lesser interest for the factor at hand.

Figure 4.11.: Histogram of the product types(top) and the 5 levels it is split into(bottom)

4.2.1. Mental factor

The complexity that arises from the high number of mechanical, electrical and thermal interfaces in spacecraft and the vast amount of information and documents describing their individual features is believed to be one of the major contributors to task complexity in spacecraft AIV.

Two dimensions are considered for this factor. The number of different interface groups that have to be considered during the process and the information sources and documents that describe the interfaces. Furthermore, any information regarding specialized tools or additional means of information transport, like a HMD are considered. An interface group can be, for example, a connector, a set of screws or a hole pattern but also thermal interfaces between components.

The sources of information considered are applicable documents, the figures, drawings, etc. given on the right side of the operational description in the OVP as well as any additional information or document present in the overhead of the procedure. This can be connector sequence diagrams, connector pin allocations, technical drawings, etc.

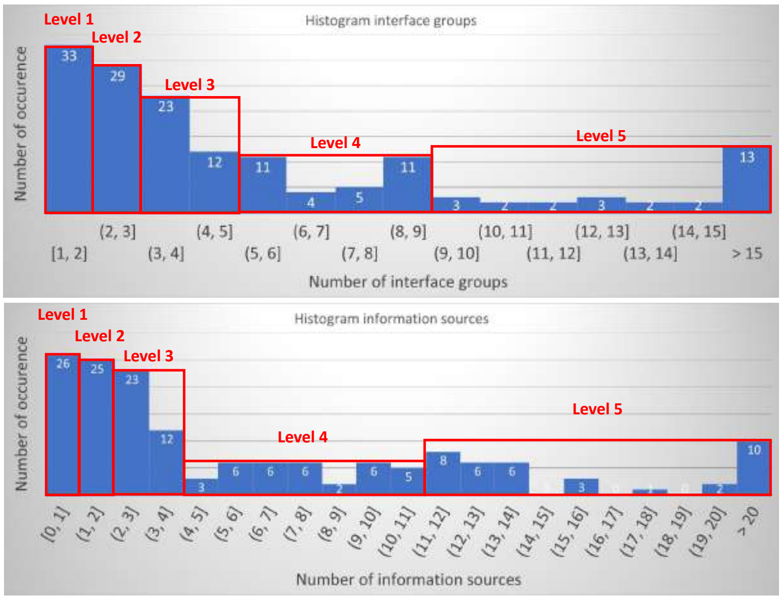


Figure 4.12.: Histograms for the mental factor

4.2.2. Effort factor

The effort factor shall capture the increasing complexity of having to deal with large numbers of parts and also difficult tooling required for the tasks. The first dimension is the product dimension. It covers the influence of number of products but also number of product types used during the process. A product is any part, component, software, fastener or consumable that is needed. Two different sets of screws are considered two types of products. The overall number of products over all types is then the number of products. For this there were also histograms made to determine the correct spacing of the five levels.

It is however believed that a larger amount of different product types is having a larger influence towards complexity than the number of products overall. The level for the types of products is therefore weighted with a factor of 10 towards the product factor. The two sub dimensions are added together and then divided by 11. This results in a range from 1 to 5 which is then the input for the first dimension of the effort factor
The second dimension of the effort factor is the tooling complexity. Each tool used during the execution of the task is categorized into one of five levels of difficulty. The categories are set to have specific requirements to allow for the simple determination of a tools difficulty. Table 4.2 gives an overview over the difficulty levels, their description and some examples.

The number of tools is evaluated per difficulty level and multiplied with the square of the level. This is done to recognize the non-linear increase in complexity increase by having one more difficult tool than a high number of low difficulty ones. The result for each level is then summed up. This is used as determining factor for the level of tooling complexity. The levels were split up using a histogram of the above mentioned dataset. Figure 4.13 shows the components that make up the effort factor.

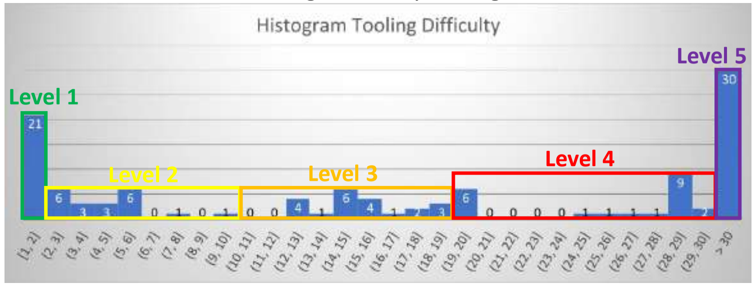
Table 4.2.: The five difficulty levels for tools used in a procedure.

Difficulty	Description	Example
1	**no training required, household tool**	**screwdrivers, pliers, cloth**
2	**instruction needed, settings to correctly set**	**cordless screwdriver, multimeter, gluing protocols**
3	**detailed instruction/training needed, calibration needed**	**oscilloscope, torque wrench, glue applicator**
4	**special training needed, hazardous if used wrong**	**field power supply, robot MGSE**
5	**project specific tool/GSE**	**MMX HDRM tensioner, custom alignment tools**

Effort complexity matrix

Products	Levels	Factor Tooling Complexity 1	2	3	4	5
	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

Tooling Difficulty Histogram



Product complexity matrix

No. of Types		No. of Products	1-2	3-5	6-10	11-28	>28
		Levels	1	2	3	4	5
	1-2	1	1,0	1,1	1,2	1,3	1,4
	3-4	2	1,9	2,0	2,1	2,2	2,3
	5-7	3	2,8	2,9	3,0	3,1	3,2
	8-13	4	3,7	3,8	3,9	4,0	4,1
	>13	5	4,6	4,7	4,8	4,9	5,0

Figure 4.13.: Components of the effort factor complexity matrix. Tooling complexity(right), product factor matrix(bottom)

4.2.3. Physical factor

The physical factor shall represent the added complexity to a task by having larger and/or heavier objects to manipulate. The two dimensions are therefore Size and Weight. The properties of the component or product with the largest physical dimension, that has to be manipulated, is considered. Larger or heavier components require larger and heavier GSEs which in turn result in an increase in complexity.

Table 4.3.: The levels for the Size and Weight of the component used as input for the physical factor.

Level	Size	Level	Weight
1	**<50mm**	1	**<1kg**
2	**<100mm**	2	**1 - 20kg**
3	**<500mm**	3	**20 - 100kg**
4	**<1000mm**	4	**100 - 500kg**
5	**>1000mm**	5	**>1000kg**

4.3. Development of tools and test setup

The following sections describe the development of the experimental test to be used for the evaluation of HoloLens 2 and the JARVIS. The goal is to evaluate the possible reduction in workload and ergonomic improvements when using the proposed assistance systems in comparison with a reference case that uses traditional paper instructions and a table as MGSE.

4.3.1. Experiment Methodology

To analyze and assess the usage of augmented reality and robot-assistance during mechanical integration activities three major evaluation criteria are looked at. The time needed for the completion of the task, the subjective workload and the ergonomics/posture fo the subject during the task. Additionally, the number of mistakes made for each task and assistance system configuration is tracked. Figure 4.14 shows the overall procedure during the test.

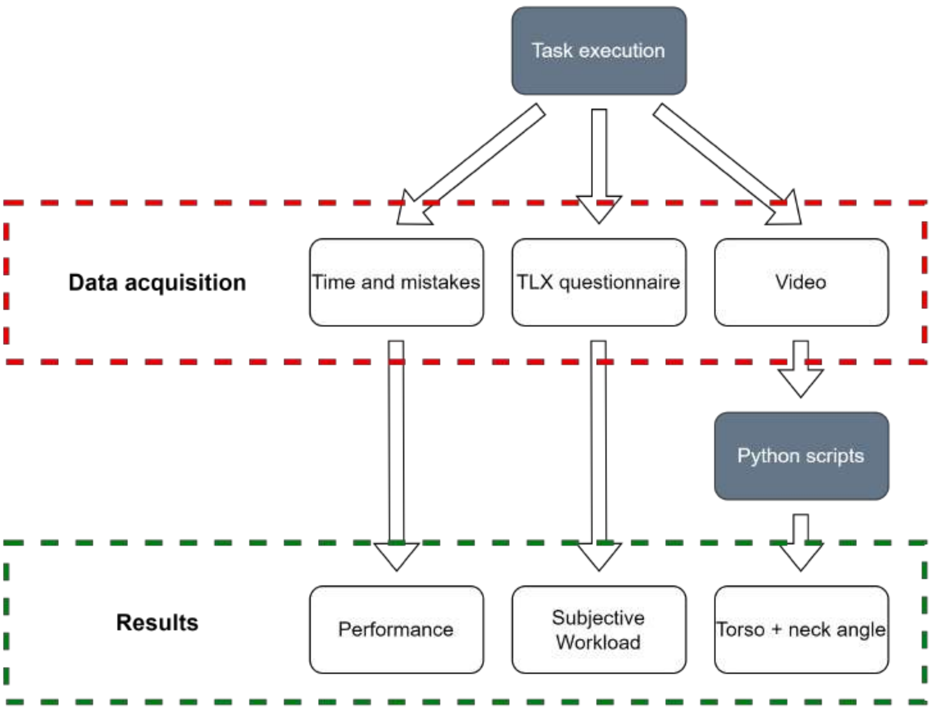


Figure 4.14.: The methods of evaluation used during the experiments and their outcomes

The time is a simple to track and widely used criteria when evaluating performance in a task. The subjective workload will be evaluated with the NASA Task Load Index(TLX) questionnaire. Both assistance systems have the potential to reduce the subjective workload. To assess the ergonomics a software is developed to analyze the posture of test subjects via Artificial intelligence (AI) based motion tracking. An ergonomic improvement is mainly believed to be the result of the robot usage.
Three types of tasks are done in four different combinations of assistance systems. A paper-based OVP with the setup on a table (T+P) will serve as the reference representing the traditional way. Using the HoloLens 2 with the setup on a table (T+AR) will be the first configuration to introduce an assistance system to the operator. Both are then also done while having mounted the setup to the KUKA KR500 robot MGSE (R+P and R+AR). This way the individual influence of the assistance system on the evaluation criteria can be determined. In the following sections the configurations will be referred to using their acronyms.
The tasks are done pairwise with each pair representing one type of task done with each paper and AR-based documentation. In doing so the direct comparison between paper and AR-based documentation is possible. Each subject does the task pair in different, random order. Also some subjects started using the AR-based documentation while others began with the paper-based reference. This is done to increase the validity of the results and reduce biasing due to to the same order of tasks done. To limit the number of times the setup needs to be mounted and demounted to the robot all subjects started with the setup being on a table. Each performed 6 tasks, 1 pair per task type. On a second day they would do the remaining 6 tasks with the test setup mounted to the robot. This was also done to ensure a resting period of at least 24 hours and to prevent familiarization with the tasks. Splitting up the experiments also allowed for easier scheduling with the subjects.

4.3.2. Experiment design

The following sections describe the experiments that are developed to assess the impact of AR and robot on the workload and ergonomics. Three types of tasks in four configurations are carried out by 6 test subjects. The time for each task is tracked via stopwatch and the performance of each subject assessed by the correct fulfillment of each task. Furthermore each subject is continuously filmed during the experiment. Afterwards a posture recognition program is used to evaluate ergonomic factors. Finally each subject fills out a National Aeronautics and Space Agency (NASA) TLX questionnaire after each task to assess the subjective workload of the task. The following sections give detailed descriptions of the complete experiment.

4.3.2.1. Test subjects

The possible group of subjects is limited to the employees of the institute due to access restrictions to the laboratories. Additionally, the time required for the completion of the experiment is around 6h per subject. This, in combination with the schedule of each subject and the availability of the laboratory space further narrowed down the possible number of experiments that could be done within the scope of this work.
Two groups of test subjects were chosen to carry out the experiments. In order to assess whether the use of assistance systems is more or less beneficial for experienced or inexperienced users a non-proficient and a proficient group of subjects is selected. This proficiency regards the experience in spacecraft or mechanical integration.
A subject is considered proficient if:

- he or she has more than 100h of integration work experience on spacecraft hardware

- he or she has worked for more than 1 year within the aerospace industry in a technical position with practical work on hardware

- he or she has worked for more than 3 years in a technical position with practical work on hardware outside of the aerospace industry

This categorization has been done on the basis of the review from Quinones et.al.[39]. There, work experience is found to be measured mostly by time. Secondly the amount and type of work done previously is used. Lastly, some studies reviewed examined work experience at the task and organizational level. Since no information on the task and organizational level of experience of the possible subjects was available the categorization had to be done using time and type as a criterion. With this definition 3 subjects were picked from a list of volunteers out of the staff of the DLR Institute of Space Systems in Bremen to comprise the proficient group.
The non-proficient group was chosen from the same list of volunteers. 3 subjects were chosen who had no experience in spacecraft or mechanical integration work.
Each subject was assigned an arbitrary identifier to assure anonymity in the data. An "A" prefix denotes the non-proficient group, while a "B" is used for the proficient subjects. 4 male and 2 female subjects have been selected. However no female volunteer fit into the definition of proficient. Also no female employee outside the list of volunteers could be found that fit into the proficient group. This can be explained with an enduring systemic imbalance of male and female workers in the field of STEM professions.[40]. 20% of the workforce in the international space industry are women [41]. This means that 33% for the overall subject group is an over representation however, within the proficient group women are underrepresented since

41% of the scientists and engineers in the EU are women.
During the execution subject B3 could not perform the second part on the robot and therefore a fourth subject was selected. For the fourth subject an additional identifier, B4, is used since half a data set already existed for B3 and confusion in the data analysis needed to be prevented.

4.3.2.2. Hardware

Modular Experiment Rig - MExR
The goal for the Modular Experiment Rig is to enable multiple different tasks and also developing a modular setup for future experiments. It needs to function as a modular platform for the experiments during this thesis but is also meant to be used during future experiments to test and validate applications and procedures. A major feature that the rig needs to have is the ability to mount or install components on each side. Due to the high integration density of spacecraft in general and ReFEx in particular it is frequently necessary to place components on every side of a structure. This also places higher demands on the handling of the structure during the AIV campaign and makes complex MGSE a necessity. The design requirements for the Modular Experiment Rig are shown in table B.4 an appendix B.

Figure 4.15 shows the final CAD model of the Modular Experiment Rig. It is built from item line 8 components. They are chosen because they are readily available with short delivery times and have been used previously by the DLR. Therefore parts were partly already in storage in the workshop of the clean room. For the floor plates two profile 8 bed plates were combined with a matching bed plate connection. These were the only parts that needed to be ordered in custom length. All profiles were then cut to length and assembled in the workshop of the clean room. After a thorough cleaning and subsequent wipe down with IPA 99,9% to ensure minimal particle pollution the MExR was transferred into the clean room.

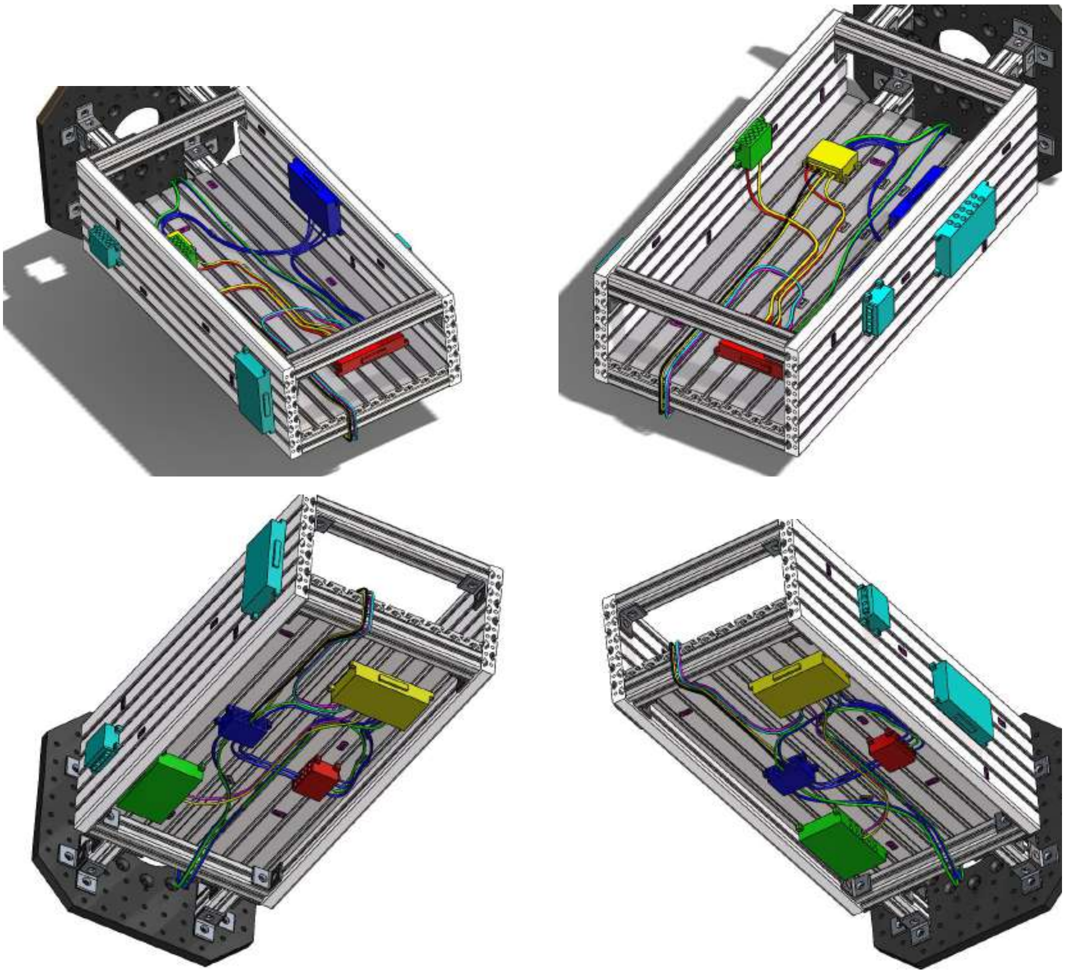


Figure 4.15.: The Modular Experiment Rig shown from 4 angles in Solidworks.

QR-code holder

Since the current version of the DLR Holo-Space-Tool requires a QR-code as reference for the position of 3D models a modular way of mounting this code to the experiment rig but also the JARVIS flange plate was developed. Due to the wide variety of GSEs mounted to the flange plate of the robot the QR-code needed to be modular in it´s position as it is only of secondary priority with regards to space allocation on the plate. It is therefore designed to only require two vertically adjacent holes in the robot flange plate. The flange plate features a 40x40mm hole pattern. This allows for it to be magnetically mounted to 16 positions around the four sides of the plate via two M8 cylinder-head screws. Since the upper left corner of the QR-code needed to be positioned over the center of the robot each time the plate holding it is placed in two dovetail slots. This way it can be moved when mounted closer or further from the center. This also allowed for the adapter on the experiment rig to be designed in a way that it positions the QR-code at the exact same position relative to the MExR as it would be on the robot. Therefore the same coordinate transformations for the models intended for use during robot experiments could be used for the table setup.

To ensure detection of the QR-code by the HoloLens during the experiments and in future practical applications the size that could be mounted to the QR-code holder was set to 15x15cm. Fischer [11] reported near a nearly linear relation between usable distance and size but ony tested up to 6x6cm.
Furthermore the QR-code holder will be positioned close to the axis five hinge and could potentially come in contact with the robot arm. To avoid damage to the robot or the holder it is designed to be magnetically attached. This ensures that the holder yields under the force of collision rather than breaking. It also allows for fast and easy mounting and removal during operations or when not needed.
Most of the components are 3D-printed to allow for fast iteration during design stages and a cost-efficient design fully built on site.

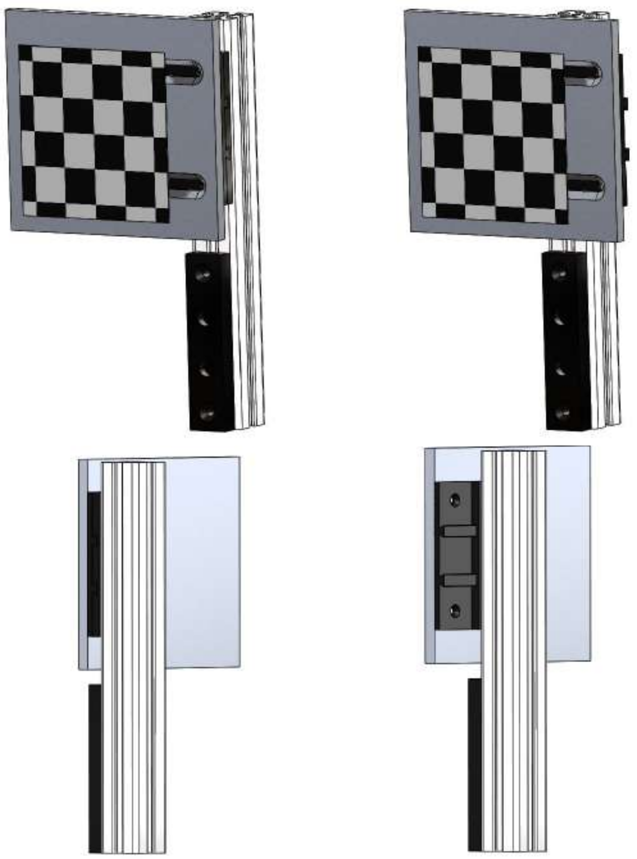


Figure 4.16.: QR-code holder CAD

ready2_pilot

The wireless control package KUKA ready2_pilot offers a simple and intuitive way of guiding an industrial robot.[42] It features a 6D mouse that can be mounted via adapter plates in every orientation and allows the user to move the robot with one hand in every translational or rotational direction within the movement envelope of the robot. The 6D mouse can be seen in figure 4.17.

Figure 4.17.: The MExR mounted to the JARVIS robot with the ready2_pilot 6D mouse in the front and the QR-code on top of the robot mounting plate.

4.3.2.3. Task Description

Three types of tasks are developed to serve as reference to actual activities during spacecraft integration. They focus on mechanical integration. Since the order of task type is different for each test subject the tasks need to be do able independently of each other. Overall 4 different versions of each type of task are designed.

For type 1 the task is to integrate two breakout box(BOB) dummies into various positions of the MExR. Both are integrated into the rig by 4 ISO 4762 - M5x25 screws with ISO 7090 - M5 washers. Two different sizes of breakout box are used and during each task one of either size is to be integrated. The BOB dummies are 3D printed versions of boxes designed for the ReFEx project. They are therefore comparable in dimensions and interfaces but not in terms of weight. Figure 4.18 shows the two different box types.

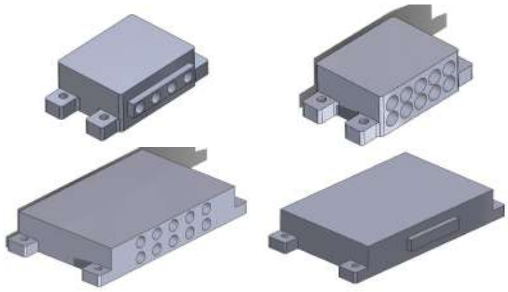


Figure 4.18.: Boxes for task type 1

During task type 2 the subject has to glue 6 TC105 cable tie holders into 6 different positions during each task. Instead of using ScotchWeld 6062 adhesives double sided tape is applied. They are prepared prior to the experiment. This was done due to the high demands in time and effort to remove 24 TC105 that would have been glued in with ScotchWeld from the MExR to reset the setup for the next subject.
Task 3 resembles a harness routing task. Two dummy harnesses are to be integrated into the MExR. These are made from PVC tubing which was already available in DLR storage. This tubing gives a suitable representation of the stiffness of a copper cable harness while being less expensive. The dummy harnesses are of two different lengths and are each comprised of two tubes. A total of 8 different harnesses were set up. They are integrated onto TC105 which are glued in place with Scotchweld. This was done to ensure equal rigidity than in actual spacecraft and to guarantee equal conditions for each subject independently of the performance during task type 2. Also in some task combination the task type 3 occurred before type 2.

4.3.2.4. Experiment procedure

Each subject performs each task type 4 times in 4 different configurations giving 12 tasks overall per subject. The order of the tasks is randomized between each subject to prevent familiarization effects in the data. To reduce the amount of time needed for the experiments they were split up. Depending on the subject the overall time for the execution could be up to 5h 30min. Splitting it up into two session allowed for easier scheduling, resting periods and at least 24h of time between the sessions to reduce familiarization with the tasks. First all subjects performed 6 tasks in configurations 1 and 2. Afterwards the MExR was mounted onto the JARVIS adapter plate and all subjects performed the second 6 tasks in configurations 3 and 4.

Briefing

Prior to the experiment all subjects were briefed using a PowerPoint presentation to ensure the same information was given to every subject even though not all were briefed at once due to scheduling conflicts. This presentation introduced the subjects to the experiment idea and goals, described the overall setup and depicted the three different methods of data acquisition. The time via stopwatch, the subjective workload via NASA TLX questionnaire and the posture via video analysis. Introducing the subjects to the TLX questionnaire poses the chance of introducing a social bias to answer according to the desired output. During future experiments the briefing could be minimized or omitted if the setup allows for it.

Furthermore, the two assistance systems were discussed. The JARVIS robot was introduced with its specifications and the intended use during the presentation but also with the foreseeable future applications. This was done to motivate the subjects to also think about the possibilities and therefore actively include them in the process of developing new innovative applications. The actual introduction to the usage and safety considerations was done directly prior to the experiments in the clean room.

At the end of the briefing each subject had the opportunity to familiarize with the MS HoloLens 2. For this, three example videos, showing the most important features and interaction possibilities, were shown. They were recorded prior to the briefing and displayed the eye calibration, the manipulation of windows and holograms as well as the use of the DLR Holo-Space-Tool application.
The eye-calibration is a built in feature of the HoloLens 2 which is used to "improve display quality, and to ensure that all holograms are positioned accurately and comfortable to view in 3D."[43]. Holograms and windows can be manipulated via hand gesture or speech input. Spoken commands are however not used during the experiments. Familiarizing the test subjects with the manipulation of holograms via hand gestures is however important. For this a built-in function was used. The "Tipps" application. It guides the user through moving holograms around and scaling them. This can be done either by directly grabbing the hologram or via the "hand ray".

This acts as an extension of the users arm and allows manipulation and interaction with the holograms over arbitrary distances. This feature is especially useful once the entire three-dimensional space around the user is to be used to place windows and hologram as it allows for the placement of those virtual objects without actually moving.
Lastly the users were introduced to the DLR Holo-Space-Tool. Introducing the different windows, showing the access to the 3D model library and how to display holograms in reference to a QR-code. Most importantly they were familiarized with the PDF-Viewer used to display procedures during the experiments and how to manipulate it.

Experiment execution

The subject was introduced to the clean room, the correct clothing and procedure of passing through the lock at the entry prior to entering it. In the experiment area the tools at their disposal and the general implications of working in a clean room were introduced. This included sensibility towards particle contamination and also the need for regular drinking pauses due to the lower humidity in the integration facility.
Initially the holographic work environment was setup by each subject to the point at which they could open the respective procedure or select the 3D model necessary. Afterwards the tasks were executed.
The first set of 6 tasks was done with the MExR on a table. Due to the weight of the MExR every time it needed to be turned around or moved, the experiment conductor assisted the subject according to their commands. Apart from that no help was issued and all necessary information needed to be extracted from the procedure on paper or the holographic procedure and virtual model. In case of technical issues with the HoloLens 2 time was stopped and the problem debugged before restarting the time.
The setup and work area were reset after each task. During the task they were filmed with a Sony DSC-RX100 on a tripod at a constant angle of about 45° to the experiment setup. The time was taken with a stopwatch. The subjects were given a "go" command in the beginning and time was stopped once they announced being finished. In between two tasks the subjects filled out the NASA TLX questionnaire. After finishing the 6 task they then had the opportunity to give remarks about the tasks, their experience with the respective assistance system and ideas of additional features or future applications. This solely served as an informal way of including the subjects in the development of assistance systems and no special attention was put on interview techniques.

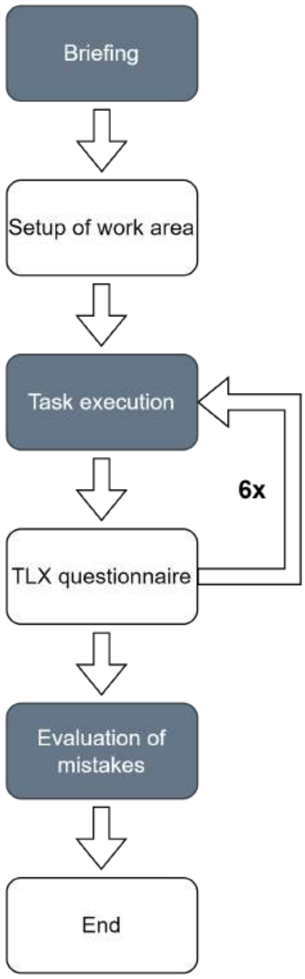


Figure 4.19.

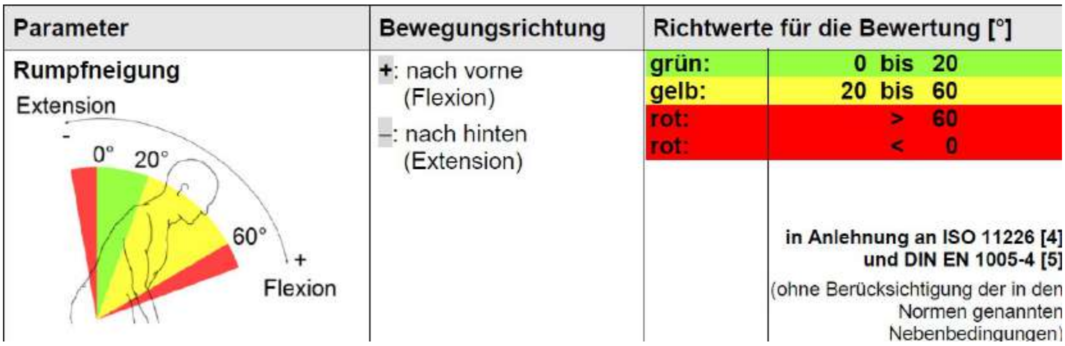
The second set of 6 tasks was done with the MExR mounted to the JARVIS robot. After successfully passing the lock the subjects were introduced to the robot. They were given a short briefing on safety and how to use the ready2pilot 6D mouse to move the setup. They then had the opportunity to familiarize themselves with the controls for a short time before the experiments were conducted. During the experiments, safety checks prior to the movement of the robot were implemented into the procedure and had to be acknowledged by the subject. Only then the dead man´s switch on the remote control was depressed by the experiment conductor and the robot could be commanded with the ready2pilot. This ensured no loose parts or tools were left in the rig. Furthermore any possible collision or unsafe movement of the robot could be prevented by the release of the dead man´s switch in the hands of the experiment conductor at which point the robot would stop immediately. Otherwise the experiment procedure remained the same as with the setup on the table. Pictures of the setup in the clean room can be found in appendix B.

4.3.3. Posture Analysis

One of the main motivations for the implementation of the JARVIS industrial robot as a MGSE was the improved ergonomics for the operator. One quarter of employees in Germany are regularly suffering from back pain.[44]

Figure 4.20.: An example showing unergonomic posture in space systems integration.[45]

Raising the spacecraft or system to a comfortable working height custom to the individual worker is only the first step in many that the robot can aid in ergonomics. The quantitative analysis of ergonomics improvement is however difficult. It is often done via observation, which is not exact and also time consuming.
For the purpose of the experiments conducted in the framework of this thesis and as a first test for the standardized experiment setup, video-based analysis of the posture is used. This is done using open-source python packages. In the first version the torso angle between upper and lower body as well as the neck angle are evaluated. The output is then compared to standards in the field of workers protection like the DGUV 208-033.[46]



Parameter	Bewegungsrichtung	Richtwerte für die Bewertung [°]	
Rumpfneigung	+: nach vorne (Flexion)	grün:	0 bis 20
	–: nach hinten (Extension)	gelb:	20 bis 60
		rot:	> 60
		rot:	< 0
			in Anlehnung an ISO 11226 [4] und DIN EN 1005-4 [5] (ohne Berücksichtigung der in den Normen genannten Nebenbedingungen)

Figure 4.21.: The angular ranges for the torso angle and their health assessment according to DGUV 208-033 [46]

Parameter	Bewegungsrichtung	Richtwerte für die Bewertung [°]	
Kopfneigung	+: nach vorne (Flexion)	grün:	0 bis 25
	–: nach hinten (Extension)	gelb:	25 bis 85
		rot:	> 85
		rot:	< 0
			in Anlehnung an ISO 11226 [4] (ohne Berücksichtigung der in der Norm genannten Nebenbedingungen)

Figure 4.22.: The angular ranges for the neck angle and their health assessment according to DGUV 208-033 [46]

4.3.3.1. PoseEstimation

For the posture analysis a python program is developed. The two main packages used are the OpenCV library for computer vision applications and the MediaPipe Pose package. Both are open-source python packages. MediaPipe Pose is a machine-learning solution for high-fidelity body pose tracking. It infers 33 3D landmarks on the whole body in every RGB video frame. The input is a video file in MPEG4 format with an aspect ratio of 16:9. Other aspect ratios have been resulting in clinched video capture by the python code which resulted in incorrect calculation of the angles. The output is a text file containing 33 lines per frame each containing the coordinates and the visibility of the landmark.

Figure 4.23.: An example frame showing the landmarks detected by the PoseEstimation software

The landmarks can be seen in figure 4.24. For each landmark the code puts out the x, y and z coordinates plus a visibility value. The origin is in the center of the hip. The visibility is a value between 0 and 1 that indicates the likelihood of the landmark being visible in the image.[47]

A second script is created which reads in the text file of the first script. It splits the data and stores the values for each landmark in lists. Afterwards the calculations for the angles are executed.
With the coordinates the vectors between the landmarks and subsequently the angles between the vectors can be calculated. This is then used in combination with the visibility values for the respective landmarks to determine the angle of the torso to the legs and the head to the torso.

For the torso angle landmarks 11, 12, 23, 24, 25 and 26 are used. If all of the visibilities are above a threshold of 0.9 the average of the two angles for the two body sides is calculated. In the case that one of the landmarks is below the threshold the respective side is dropped from the analysis. Should both sides have landmarks with visibilities below 0.9 the average is still calculated but the data marked as flawed for later use. A numeric marker is also added for the other cases to distinguish which calculation scheme was used by the code.

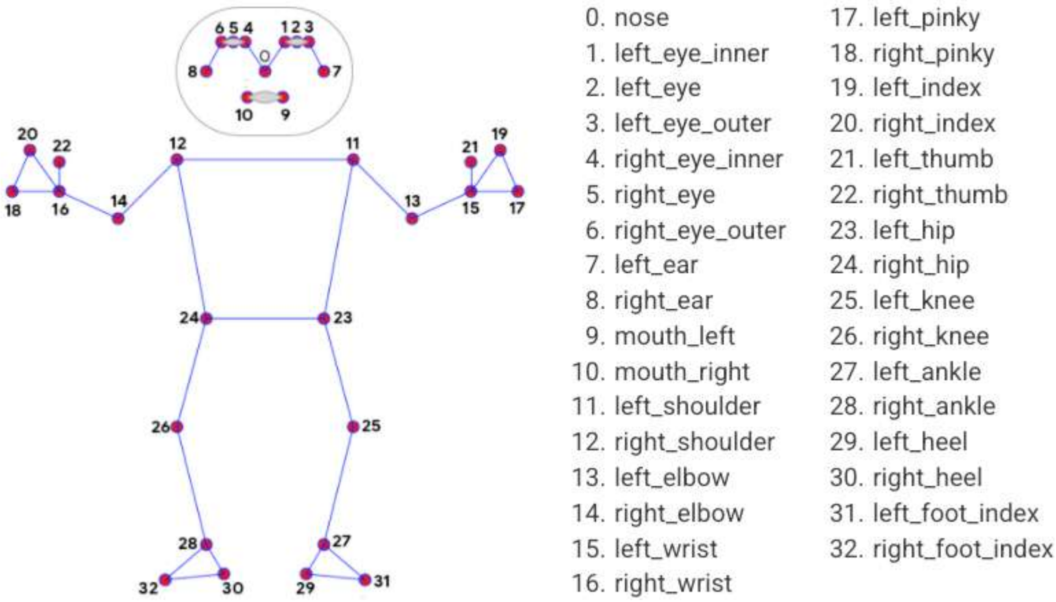


Figure 4.24.: An overview over the tracked landmarks on the body.[47]

For the neck angle two planes are calculated. One is composed of the shoulder points (11 and 12) and one hip point (24), the other using the right and left eye and ear (5, 8 and 7, 2). With these the normal vectors of the planes are calculated and subsequently the angle between these two normal vectors. Therefore the result has to be subtracted by 90°.

4.3.3.2. Visibility

Figure 4.25.: Overall

For the correct calculation and analysis of the body posture the visibility of the respective landmarks is of high importance. The camera angle during the experiment therefore had to be chosen in a way that the test subject would be in view for as much time as possible. Furthermore an angle offset to the right or left of a person rather than directly from the front or back is thought to give better results. Due to the nature of the experiment setup the test subject could however be directly on the opposite side of the setup with the MExR in between person and camera. This could not be avoided with a setup using only one camera.
Another challenge is the mainly white environment in the clean room paired with the white clothing that has to be worn. The limited contrast between background and person could impair the machine-learning algorithms ability to successfully track the landmarks.
Furthermore the the standard clean room coat and the limitations it infers have to be considered. It has to reach below the knees due to particle pollution requirements. This however results in the knees not been distinctly visible which in early trials has been found to be a limiting factor. It was therefore decided to use clean room overalls. They have individual legs so that the knees can be distinguished and were fitted with green tape stripes to aid in contrast. The overall can be seen in figure 4.25. They are however only available in a limited number of sizes since ideal fit to a person is not of high priority during clean room activities. This lead to loose fit on smaller persons which resulted in wrinkles and bulges on the overalls. Distinguishing between actual body contour and overall misfit could be an additional limiting factor on the codes performance. Additionally, masks or beard nets as well as hair nets or caps have to be worn in the clean room. These might also infringe the codes ability to track the head features but are not optional and no alternative could be found.

4.3.4. NASA Task Load Index

The NASA Task Load Index (TLX) is a tool to subjectively assess the workload. It was developed in the 1980s by Sandra Hart of the NASA Ames Research Center. [48] "By incorporating a multi-dimensional rating procedure, NASA TLX derives an overall workload score based on a weighted average of ratings on six sub-scales."[49]

The six rating scales are:

- Mental Demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exact or forgiving? [48]

- Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?.[48]

- Temporal Demand: How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic? [48]

- Performance: How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with performance in accomplishing these goals? [48]

- Effort:How hard did you have to work (mentally and physically) to accomplish your level of performance? [48]

- Frustration Level: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task? [48]

It has been developed especially for the assessment of the workload felt by operators of human-machine interfaces. It has been cited by over 14000 papers, articles and books according to Google Scholar. It is considered a well-established research tool and consequently also used during this work to assess the effect of additional assistance systems on the perceived workload of the operator.

The TLX questionnaire consist of two parts. The first part is a pairwise comparison of the sub-scales. 15 possible pair-wise comparisons of the six scales are presented to the subject. By choosing the factor that contributed more to the workload of the task a weighting is obtained. Each task can have a weight ranging from 0 to 5 depending on how often it is picked. Zero represents "not relevant" to the task and five "more important than any other factor"[50]
The second one gives a rating scale for each of the six sub-scales. Each scale ranges from 0 to 100 points with 5-point steps anchored by bi-polar descriptors (e.g. High/Low). Figure B.5 shows the rating page of the questionnaire.
The rating of each sub-scale is then multiplied with its respective weight and divided by 15 (the sum of the weights) to get the Weighted Task Load Index. Researchers

have also proposed to omit the weighting step and use the stand-alone ratings as "Raw TLX". [51]
The NASA TLX questionnaire is available as a paper version or as an App for the iOS platform. This made it convenient to use on the DLR-owned, already existing, iPads in the clean room. It is not officially available for other operating systems. Unofficial JAVA versions, however, do exist. The subjects are presented with the questionnaire immediately after completing the task. A picture of the questionnaire can be seen in the Appendix B

4.3.5. Limitations

For the frame of these initial tests some limitations have to be considered and discussed. The position of the robot in the clean room means the tests have to be carried out there. This limits the possible subjects to employees of the DLR. This may result in a non-representative group of test subjects and a limited data set. Executing the tests in the clean room also puts additional requirements onto the test setup. The subjects need to wear respective clothing and the experiments have to be scheduled around on-going projects that require the robot or clean room space. The available time and the proposed 12 tasks per subject resulted in an initial number of six subjects.
Only one camera that would record in the required 16:9 aspect ratio and in a file format that could be read by the python scripts for the posture estimation was readily available. This limits the visible area and could result in subjects being covered by objects or the test setup.
Using one QR-code to position the holographic overlay requires this QR-code to be mounted in a fixed position to the test setup. For the full flexibility of the robot usage this could result in the code being in positions were it is hard to see and read. For example, when the setup is turned upside down.

4.3.6. Expectations

Due to the limited data set of only six subjects the results are expected to be heavily influenced by individual factors. Trends on the applicability of the used assistance systems and indications on future improvements of the setup used should however be outcomes of the tests.
The use of the current version of AR application may be not intuitive enough. This could result in a too large relative overhead for the short experimental tasks. The accuracy of hologram positioning using one QR-code and the manual update of the overlay after each repositioning of the setup might result in increases of the time needed. The orientation and correct execution of the tasks is expected to

improve for the subjects when using the HoloLens. The three different task types are expected to benefit to various degrees from the AR. The time and workload improvements for task type 1 are expected to be less than for the other two tasks. The multiple different positions that a cable tie needs to be correctly glued to lead to the expectation that task type 2 will benefit the most.
The workload analysis using the NASA TLX questionnaire is believed to be highly influenced by individual factors due to its subjective nature. The limited data set of only six subjects does not allow for statistically valid analysis of the data. Therefore no expectations regarding the outcome of the workload analysis can be put forth. The experiences with the data acquisition and the time needed to answer the questionnaire are however valuable information regarding possible future use.
The ergonomic improvements while using the robot compared to the table to position the test setup is expected to be visible for all subjects and should therefore be discernible from the limited data set. The adjustment of the height of the setup should lead to less flexion of the upper body. The free rotational and translational positioning of the setup should improve the neck and torso angle of all subjects given that these features are used to their full potential. The added flexibility of positioning the procedure into convenient positions in the three-dimensional space is expected to have a positive effect on the neck angle. This should also apply to all task types.
The limited visibility of the subject due to only one camera may however result in a small fraction of flawed data.

5. Evaluation of AR and Robot

The following sections show the obtained results from the experiments run. First, the absolute time needed is depicted in section 5.1. Furthermore, the change in time per task needed compared to the reference case is highlighted. Afterwards, section 5.3 shows the TLX questionnaire results and depicts the change in workload for the different configurations of assistance system. Lastly, the results from the posture analysis using python are shown in section 5.4. Here the difference in posture comparing table and robot tasks are shown in detail as well. Additionally section 5.2 briefly depicts the mistakes made by the subjects during the experiments.

5.1. Time

5.1.1. Absolute times

Figure 5.1 shows the times needed by the subjects per task type. Each graph represents one configuration. The reference configuration 1 (paper procedure and setup on table) can be seen in the top left corner. The configurations 2 (T+AR) in the top right, 3 (R+P) and 4 (R+AR) in the bottom left and right respectively. Table 5.1 lists the average time needed per task type and configuration. A full table of all times can be seen in the Appendix B.5.

It can be seen that the configuration with the MExR mounted to the robot and using the paper-based procedure took, in average, the least time. This is followed by table + paper and robot + AR. Table + AR was the slowest configuration. This is consistent over all three task types.

Task type 2 took the longest in each configuration with over twice the average time needed in some cases. Apart from subject A3 in the two AR configurations this

Table 5.1.: Average time per task type and configuration

Average times in mm:ss				
	Table + Paper	Table + AR	Robot + Paper	Robot + AR
Type 1	12:11	17:14	08:59	12:49
Type 2	25:37	32:59	17:52	28:22
Type 3	18:16	23:46	12:05	21:02

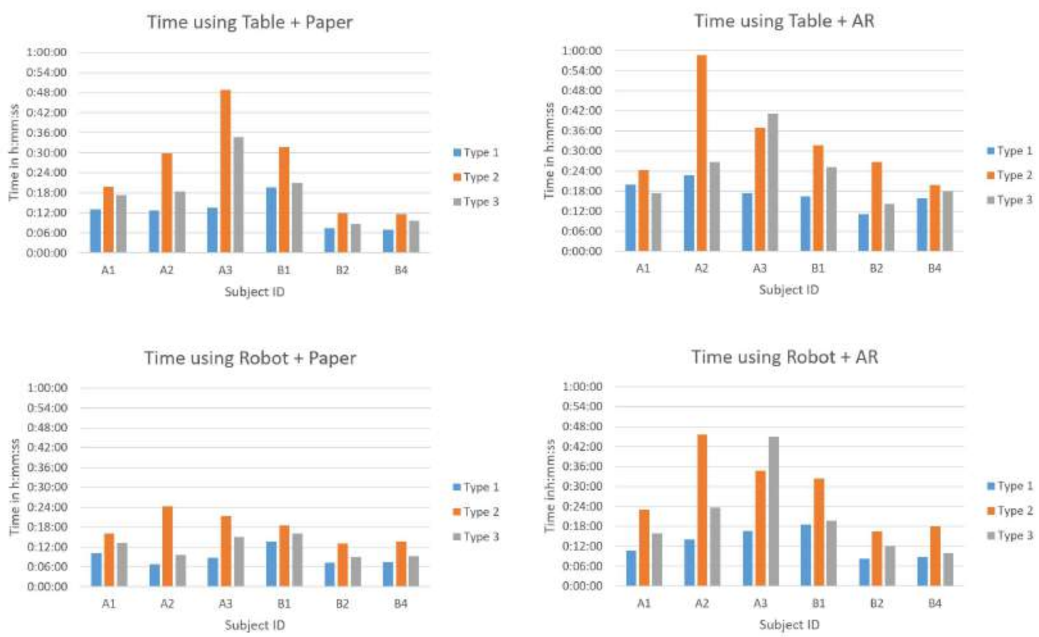


Figure 5.1.: The absolute times needed for the task types over the Subject ID.

is also true for each subject. Here task type 3 (grey, for subject A3) took longer with 41 min 14 s compared to 36 min 55 s of task type 2 (orange) for the table + AR configuration.(5.1, top right) This is a difference of 10.5%. Using the robot + AR configuration (5.1, bottom right) type 3 (grey) took 44 min 57 s compared to 34 min 46 s for type 2 (orange) which is a difference of 22.6%.
Task type 1 was the fastest for each subject and configuration apart from subject A1 in configuration table + AR. Here type 1 took 19 min 54 s whereas type 3 took 17 min 21 s, a difference of 14.7%.

5.1.2. Relative times

Figure 5.2 shows the relative change in time in percent for the task execution compared to the reference configuration using paper+ table. A negative value denotes a decrease in time while a positive value is an increase in time needed. When looking at the change in time for the different configurations it can be seen that the configurations using AR resulted in an increase in time for most tasks and subjects. The configuration using the HoloLens in combination with the setup on the table resulted in more than twice the time need for some tasks. Subject B2 had an increase in

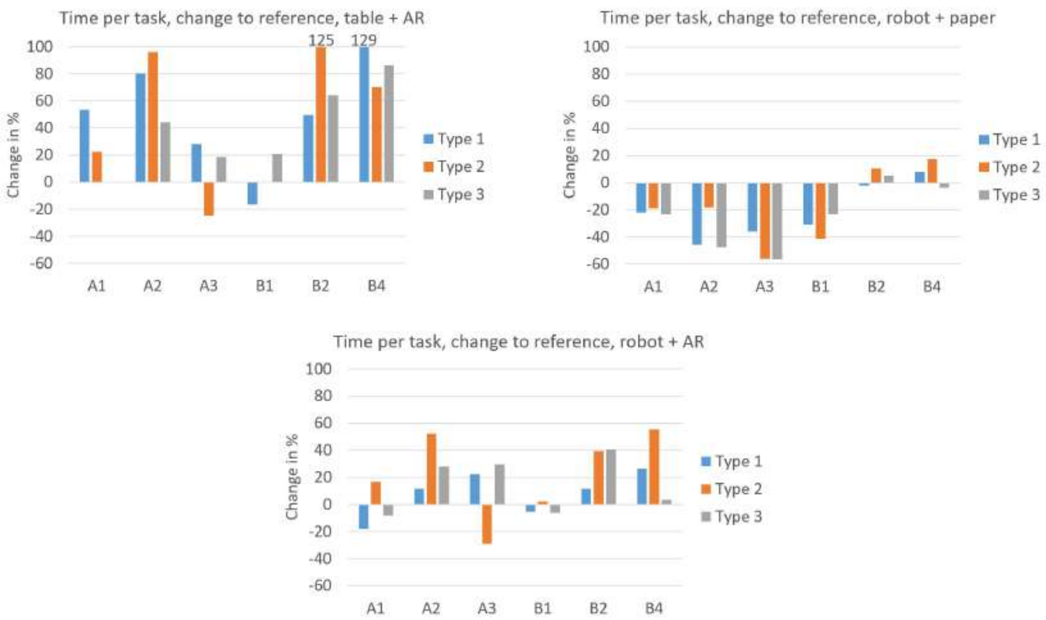


Figure 5.2.: The relative change in time needed compared to the reference configuration.

time of 125% executing task 2 with respect to the reference configuration. Subject B4 an increase of 129% for task type 1. Only for Subject A3 task type 2 and subject B1 task type 1 a decrease in time needed can be seen.
Notably subjects A1 through B1 were faster for all tasks using the robot + paper configuration while subjects B2 and B4 were slower or only slightly faster.

Figure 5.3 shows the change of time needed per task split up for each subject. Subject A1 had an increase in time using the augmented reality application for 3 of six tasks executed with it. Only for two tasks a decrease in time could be seen when using the AR. Both in combination with the robot. 5 of 6 tasks executed using the robot showed a decrease in time.
For subject A2 only the configuration using the robot and paper procedure resulted in faster times. When wearing the HoloLens more than 90% increase in time can be seen for some cases. The change is highest for task type 2 while also the decrease in time for configuration 2 (T + AR) is the smallest for this task.
5 of 9 tasks showed a decrease in time needed for subject A3. Notably task type 2 is executed faster with all combinations using assistance systems. Types 1 and 3 however have taken longer for the combinations with the augmented reality system. Only combination 3 using the robot and paper version of the procedure decreased the time needed for all three task types.

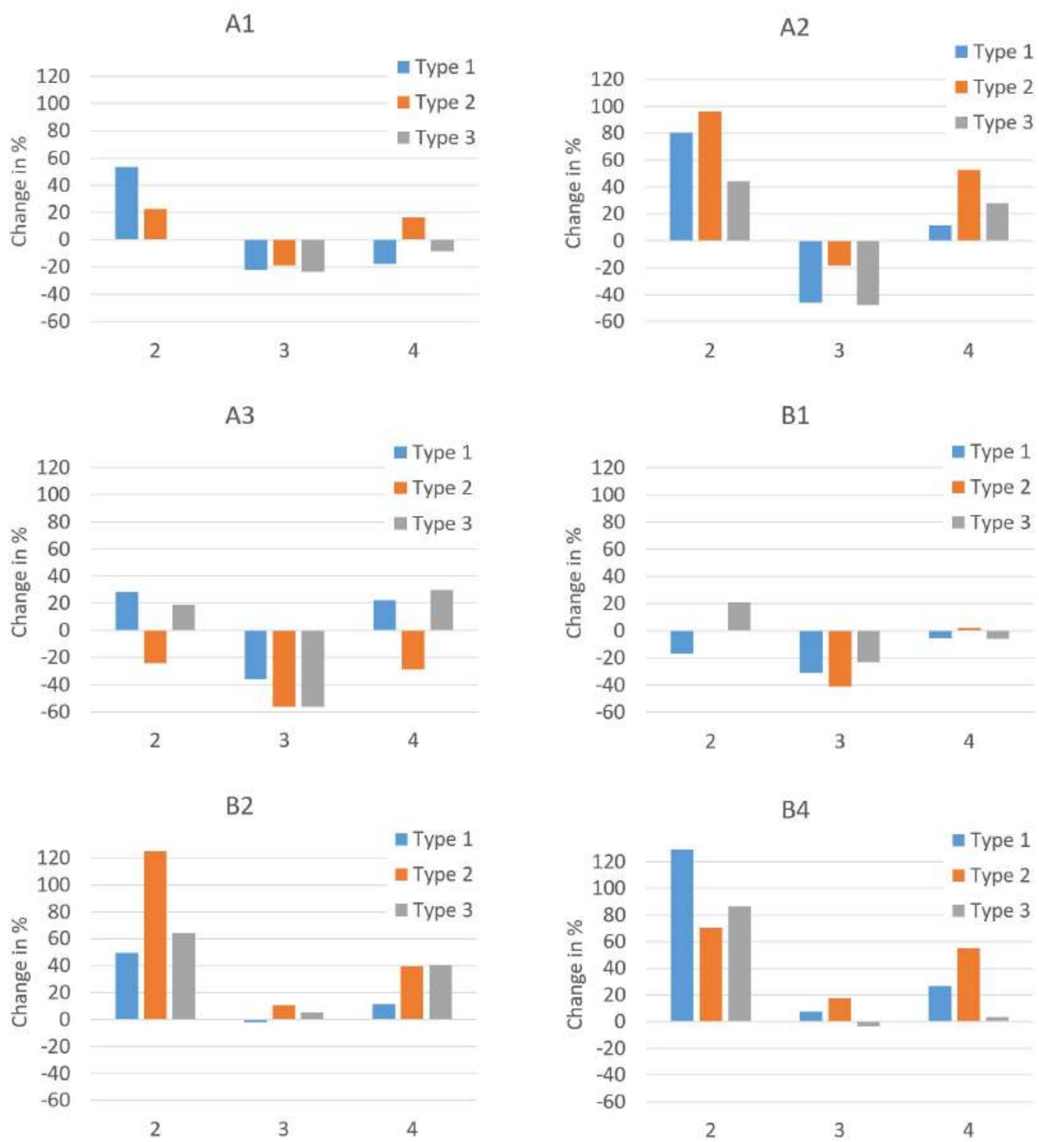


Figure 5.3.: The relative change in time needed for the task types over the configuration for each subject.

Subject B2 executed 6 out of 9 tasks faster when using an assistance system. Again it can be seen that all three tasks done with robot and paper show a decrease in time. Only task type 3 with the HoloLens and MExR on the table shows a notable increase in time. The combination of robot and augmented reality showed less than

10% decrease in time for task types 1 and 3 and an increase for type 2 of only 2%. 8 out of 9 tasks executed with one of the combinations show an increase in execution time for subject B2. The changes are smallest for the combination of robot and paper procedure. Only task type 1 with this combination shows a decrease in time. This is however very small with only 2%. Using the augmented reality system with the setup on the table caused the biggest increase in time needed of up to 125%. Similarly, subject B4 showed also an increase in time for 8 out 9 tasks. Again the changes are smallest for the combination using the robot and paper version of the procedure. Only task type 3 executed with this combination showed a decrease in time of 3.6%. Subject B4 also shows the largest increase of 129% in time for any of the subjects and assistance system combinations.

5.2. Mistakes made

In 12 of the 72 tasks executed mistakes were made that were not recognized or that would have potentially led to damage in the case of an actual spacecraft. This equates to 16.6%. Tracked were the correct placement and orientation of all components and fasteners to be inserted, the correct safety check before moving the setup either by hand or via the robot and the correct choice of component or part. Due to the overall small amount fo mistakes and high number of tasks without any mistakes the Mean time between failure (MTBF) was not evaluated. 714 items were tracked out of which 21 mistakes were made. This equates to (2.9%). Of these, 12 happened using configuration 1 (T+P) (57.1%), three in configuration T+AR(14.3%), four in configuration R+P (19%) and two with the configuration R+AR (9.5%). [figure 5.4] 14 of 21 mistakes were made while performing task type 2 (66.6%), six during type 3 (28.6%) and one during task type 1(4.8%). The most common mistake were misplaced TC105 that needed to be glued in during task type 2. All of the 14 mistakes made during type 2 were of this nature. In two occasions the subject forgot a cable tie, four times the harness to be inserted was not placed correctly and one time a safety check was not done properly and a loose tool was left in the MExR prior to moving it. Table 5.2 shows the number of mistakes made per subject and configuration. It can be seen that the use of an assistance system reduced the number of mistakes for all subjects.

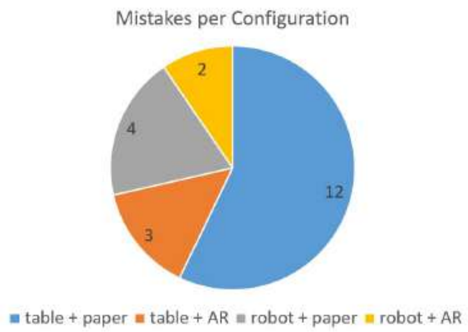


Figure 5.4.: Mistakes per configuration

Table 5.2.: Mistakes made per subject and configuration.

Configuration	A1	A2	A3	B1	B2	B4
Table + Paper	5	0	2	4	1	0
Table + AR	0	0	1	1	0	0
Robot + Paper	1	1	1	1	0	0
Robot + AR	2	0	0	0	0	0

5.3. TLX

The following section shows the results of the NASA TLX workload questionnaires. First the overall weighted load index is presented, afterwards the mental as well as the physical workload are looked at closer.

5.3.1. Weighted Load Index

Figure 5.5 shows the mean of the weighted load index of all 4 configurations of assistance systems. This was done to get an overview over the individual subjective workload during the entire experiment. This can aid in to put later results into perspective. It shows a similar behavior of the workload with respect to the task types as the absolute time did.
It can be seen that overall the execution of task type 1 resulted in the lowest subjective workload, except for subject B1. Here the workload is however nearly identical for all three task types. Three of six subjects, A1, A2 and B2, felt the highest workload when performing task type 2. Two subject, A3 and B4, noted the highest workload for task type 3. Notably two of the proficient group have lower perceived workloads than all of the non-proficient subjects. Subjects A2 and A3 also have higher subjective workloads than all of the proficient group.

Figure 5.6 shows the relative change of the weighted workload for the individual subjects with respect to the reference configuration table + paper. It can be seen that for most of the combinations and tasks the workload decreased with the introduction of an assistance system. For the configuration table + AR 8 out of 18 tasks (44%) were perceived to require a lower workload. 14 of 18 (77.7%) workload factors for the configuration robot + paper show a decrease. 11 factors (61%) have decreased with the configuration robot + AR.

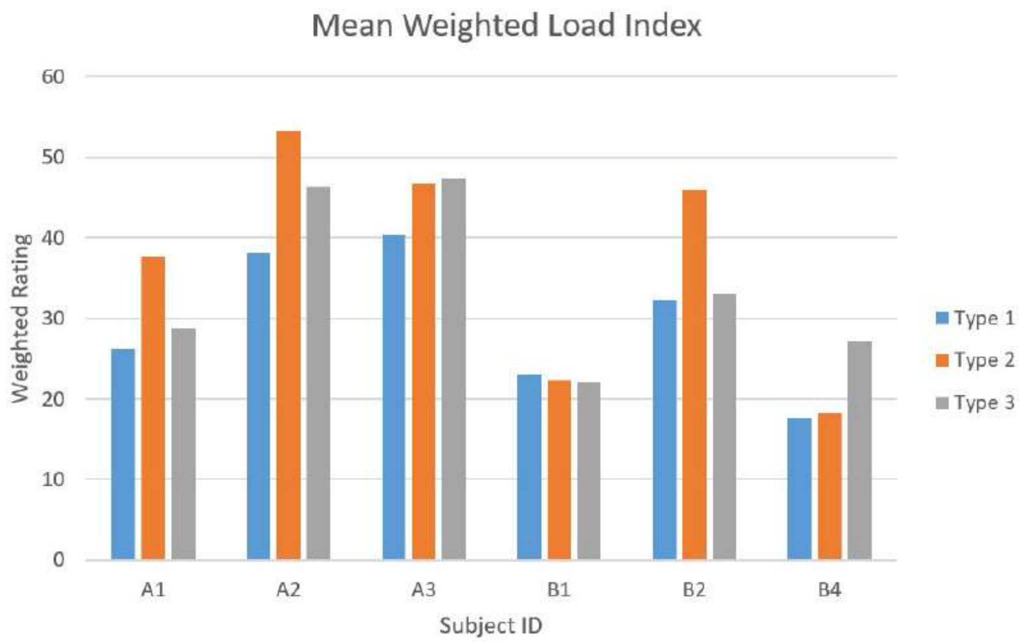


Figure 5.5.: The mean weighted load index over the subject ID for the three different task types.

When looking at the individual subjects, for A1, it can be seen that for the configuration table + AR and task type 1 a 135% increase is perceived. This has to be discussed in more detail in section 6.4. For the types 2 and 3 there is a decrease in workload reported. The combination robot + AR shows an increase in workload for all three task types.

Subject A2 shows a decrease in workload for all task types with the configurations R+P and R+AR. For configuration T+AR, types 1 and 3 are perceived to have an increased workload while for type 2 it decreased.

7 out of 9 (77.7%) tasks are felt to have a decreased workload for subject A3. Only task three in configuration robot + AR is reported with a higher workload than the reference. The change is however small for configuration table + AR.

Subject B1 shows a decreased workload for 8 out of 9 (89%) tasks done with assistance systems. Task type 2 executed with configuration T+AR shows a minimal increase of 1.3%.

For subject B2 only two tasks (22%) are perceived to have had a decreased workload when performed with an assistance system, type 2 for configuration R+P and type 3 for configuration R+AR. Using the paper procedure plus AR led to an increase in all three task types with an increase of 148% for type 1.

For subject B4 task type 2 was perceived to have a higher workload with any of the

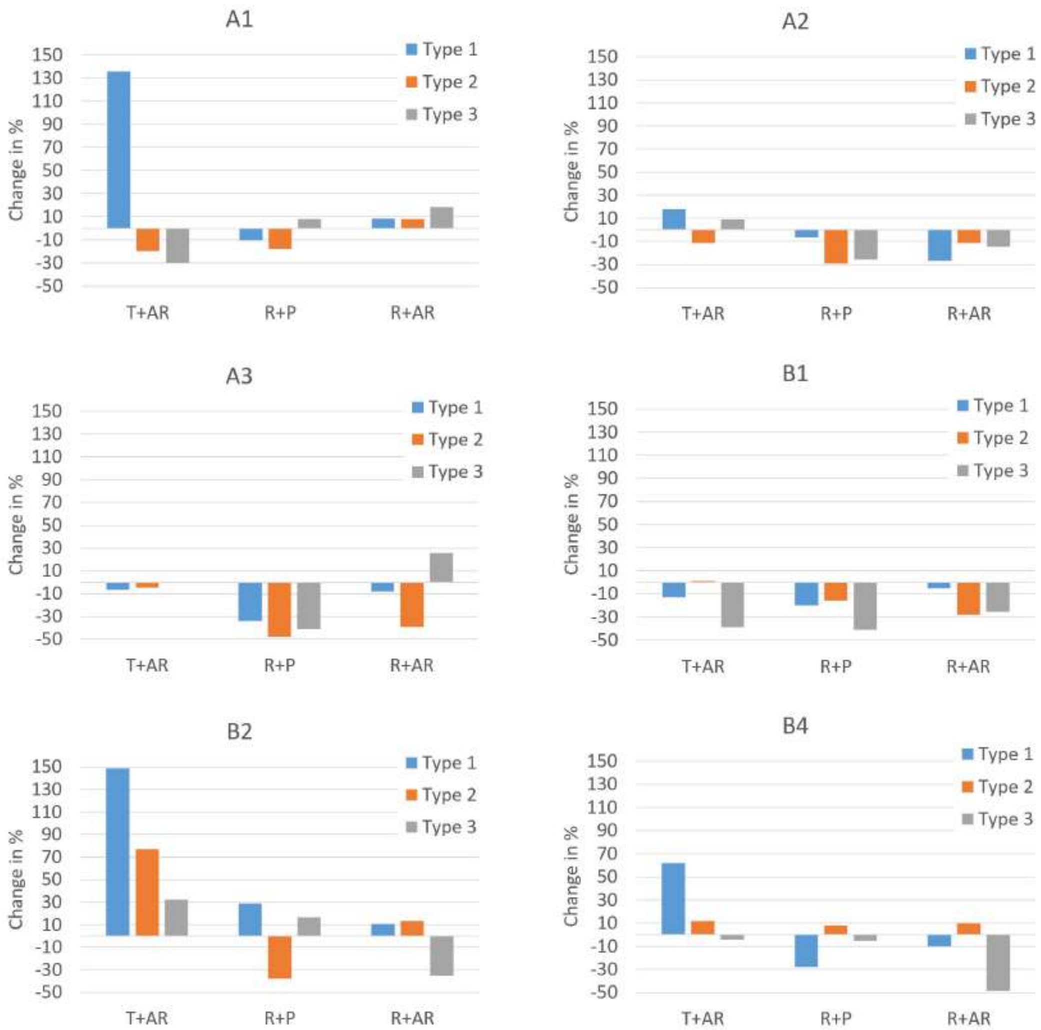


Figure 5.6.: The relative change in TLX weighted workload perceived for the task types over the configuration for each subject.

combinations of assistance systems. 5 of 9 (55%) tasks show a decrease in workload. The combinations including the robot lowered the workload for types 1 and 3. The HoloLens in combination with the table only for task type 3. The highest increase in felt workload for subject B4 is seen with task type 1 and configuration T+AR. Figure 5.6 shows the change of workload over the three configurations of assistance systems. It can be seen that the configurations including the robot show a decrease in perceived workload for all task types. For configuration T+AR only the workload for type 3 decreased. Also task type 1 shows a high increase on average compared to the change in the other tasks.

5.3.2. Mental Load

To look at the effect of the assistance systems on the mental workload figure 5.7 shows the change in the respective TLX adjusted factor with respect to the configuration table + paper. It can be seen that for 30 of 54 tasks (55.5%) the mental workload decreases. It increases for 19 of 54 tasks (35.2%). For 10 of 18 tasks of type 2 it increases (55.5%), while it decreases for 14 of 18 for type 1 (77.7%). The mental workload decreases for 9 of type 3 (50%). For 5 tasks it stays the same. Subjects A2 and B2 show substantial increases for task type 2 of more than 100% in 5 of 6 cases. While all 6 tasks of type 1 are felt to have a smaller mental workload. Subject A3 also reports all three tasks of type 1 to have a lower mental workload than with the paper procedure and the MExR on the table.

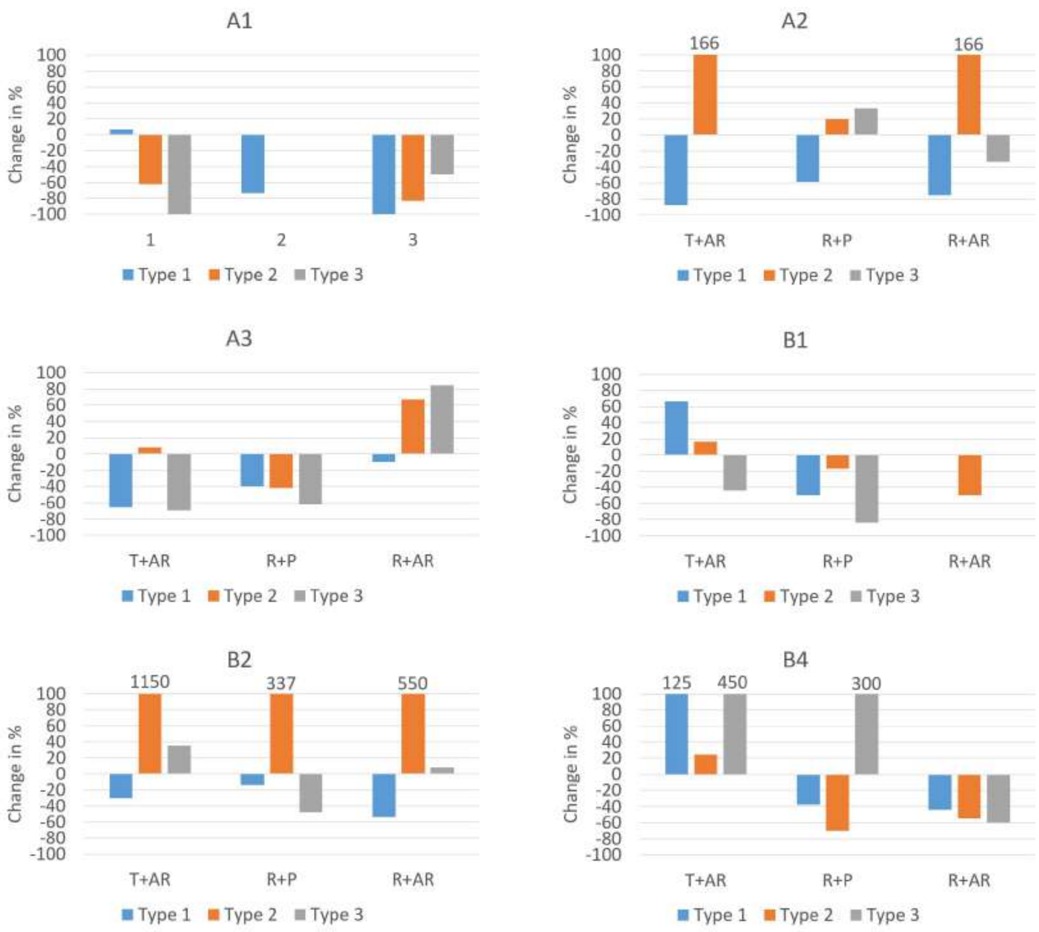


Figure 5.7.: The relative change in TLX mental workload perceived for the task types over the configuration for each subject.

5.4. Body posture

For the 6 subjects and one camera large amounts of video data was captured during the experiments.(338GB) This is mostly due to the high resolution of 17MP of the camera that was used. This was however the lowest setting that the camera could be set to. Furthermore, the python code could not analyze the video files in real time but, depending on the computational power, only at half the initial frame rate. Therefore the raw video material was cut to omit all parts in which the subject was not actually working on the task. This decreased the length of the files in average by 137% to the original length. This also shows the large overhead of setup, orientation and documentation work that has to be done during the tasks.

The output file of the code consisted of 33 entries, each containing 5 values, per frame, for a video file with a rate of 50 frames per second. This is a too detailed set of data for the application at hand and would also increase the computational effort for the analysis considering 72 individual output files are created and need to be analyzed. Therefore the values for the coordinates where averaged over 50 frames resulting in data rate of 1 Hz. This is still a sufficient resolution for time frames of several minutes and decreased the time needed to analyze a file from 1-2 minutes to 5-10 seconds. Afterwards the two relevant angles were analyzed using another python script. The results for the torso and neck angle are shown in the following sections.

5.4.1. Torso angle

The torso angle is analyzed in three angular ranges of flexion.[46] Neutral ranging from 0° to 20° flexion, moderate from 20° to 60° and terminal for over 60°. Extension was not observed during any of the experiments and can therefore be omitted. Times in which both body sides included landmarks with visibilities below the threshold of 0.9 are marked as "flawed data". Detailed results for two subjects, A1 and B2, are shown exemplary and the data for all subjects can be found in the Appendix. In total 29 out of 36 (80.5%) of tasks done with the robot show an increase in time spent in the neutral range of flexion. 23 of 36 (63.8%) show a decrease for the terminal range. Figure 5.8 shows the average change in time for the torso angle ranges for

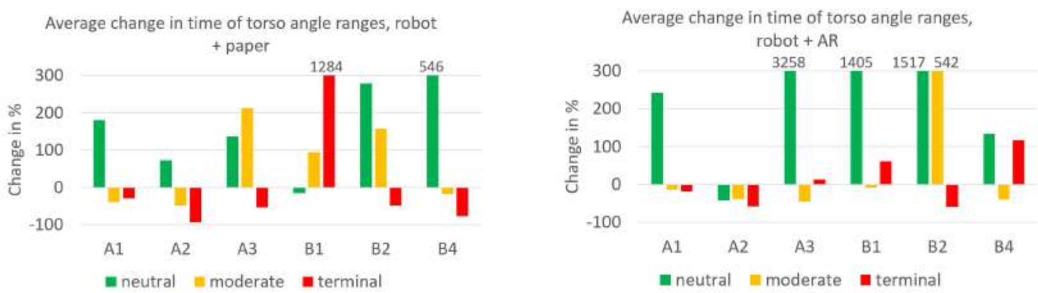


Figure 5.8.: The average change in time for each torso angle range for all subjects. The change from table + paper to robot + paper on the left and the change from table + AR to robot + AR on the right.

configuration R+P and R+AR compared to the respective paper version. It can be seen that the relative time in which a subjects torso angle is within the neutral range increases for all but two cases. The time for the terminal range decreases in 8 out of 12 cases. The large percentages for some cases can be explained by an extremely small time for these ranges in the reference case. This data is also subject to large deviations due to the sometimes large time frames of flawed data.

5.4.1.1. A1

Figure 5.9 shows the relative time of the task types for the angular ranges. The configuration including the robot (3 and 4) are depicted adjacent to the table version to allow for a direct comparison.
It can be seen that in all cases the robot configuration increased the time of posture in the neutral range. The times with moderate or terminal flexion are decreased. For the majority of tasks executed in configurations including the setup on the table (1 and 2) most time was spent in the moderate range. The example of task type 3 executed in configuration 2 shows the longest period of time spent in the terminal range of flexion. This is decreased to zero in configuration 4. For subject A1 there were also very little times where the data is flawed due to insufficient visibility.

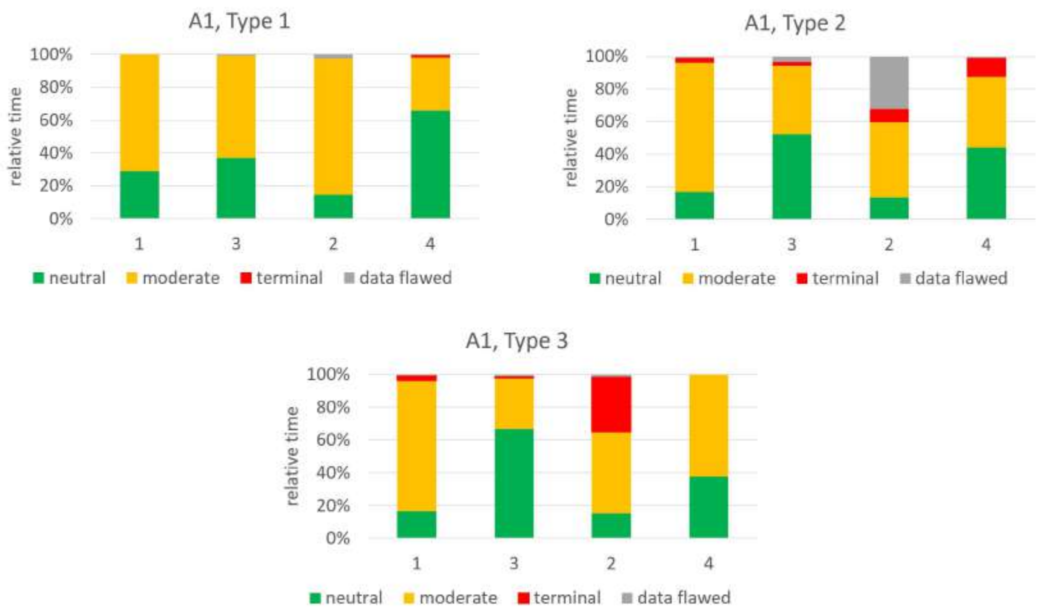


Figure 5.9.: The relative time for each torso angle range for subject A1. Note the change in order of the configurations.

5.4.1.2. B2

For subject B2 it can be seen that for substantial periods of time the data is marked as flawed due to insufficient visibility of landmarks on both sides of the body. Especially for task type 1. Notably the time with flawed data was less with the configurations using the robot. For the usable periods it can be seen that the time spent in the neutral range increased for the configurations including the robot. Also the time in the terminal region decreased or stayed the same. The moderate range was the biggest contributor in 7 and the neutral range in 4 tasks.

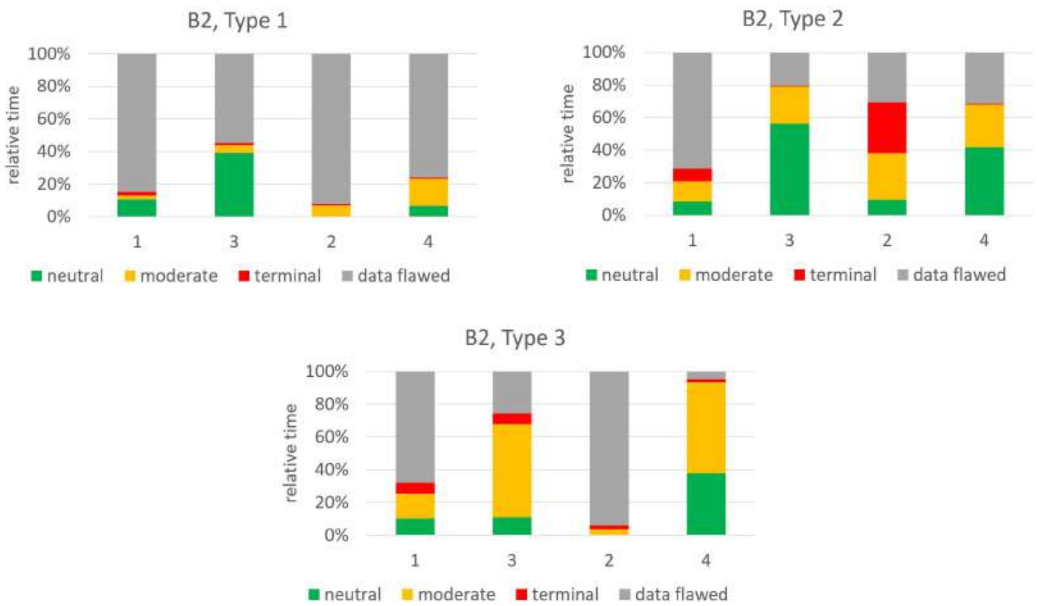


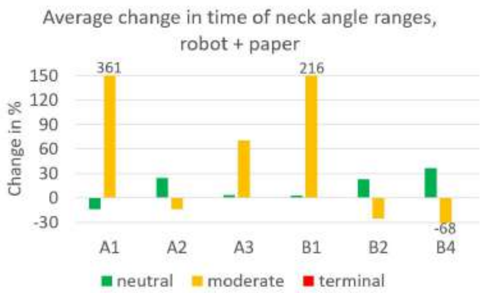
Figure 5.10.: The relative time for each torso angle range for subject B2. Note the change in order of the configurations.

5.4.2. Neck angle

The neck angle is analyzed for three angular ranges of flexion.[46] The neutral range from 0° to 25° flexion, moderate from 25° to 85° and the terminal range above 85°. Extension was not observed and was therefore omitted. The same decision making scheme on how to mark flawed data was used as with the torso angles. For the neck angle analysis substantially less data is flawed. This can be explained with the better visibility of the respective body landmarks on the head and shoulders. These are less likely to be covered by objects due to their higher position on the body than, for example, the knees.

The terminal range of motion is considerably smaller compared to the torso angle. A neck angle of 85° is rarely reached and also the neck cannot be bent considerably

more than that. This explains the little times in which the data shows posture in the terminal range.
Figure 5.11 shows the average change in time for the neck angle ranges for configuration 3 and 4 with respect to the reference configuration 1. It can be seen that for 10 out of 12 tasks (83.3%) the neutral range increased compared to the respective table configuration. The improvements are however small. The moderate range increases in 6 out of 12 cases (50%). The increases are generally larger than the decreases and the data not as convincing as it was the case for the torso angle.



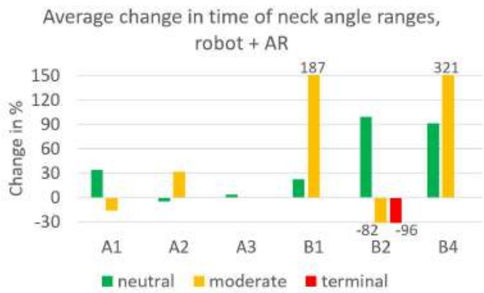


Figure 5.11.: The average change in time for each neck angle range for all subjects. The change from table + paper to robot + paper on the left and the change from table + AR to robot + AR on the right.

5.4.2.1. A1

When looking at the changes for the different task types and configurations for subject A1 in figure 5.12 a high amount of relative time spent in the neutral range is visible. This is not in agreement with the expectations and will be discussed further in section 6.5.1. Furthermore in the case of types 1 and 3 a decrease in relative time in the neutral range can be seen when going from configuration T+P to R+P. The same is true for task type 2 going from table + AR to robot + AR.
Only very little data is marked as flawed and even less is in the terminal regime.

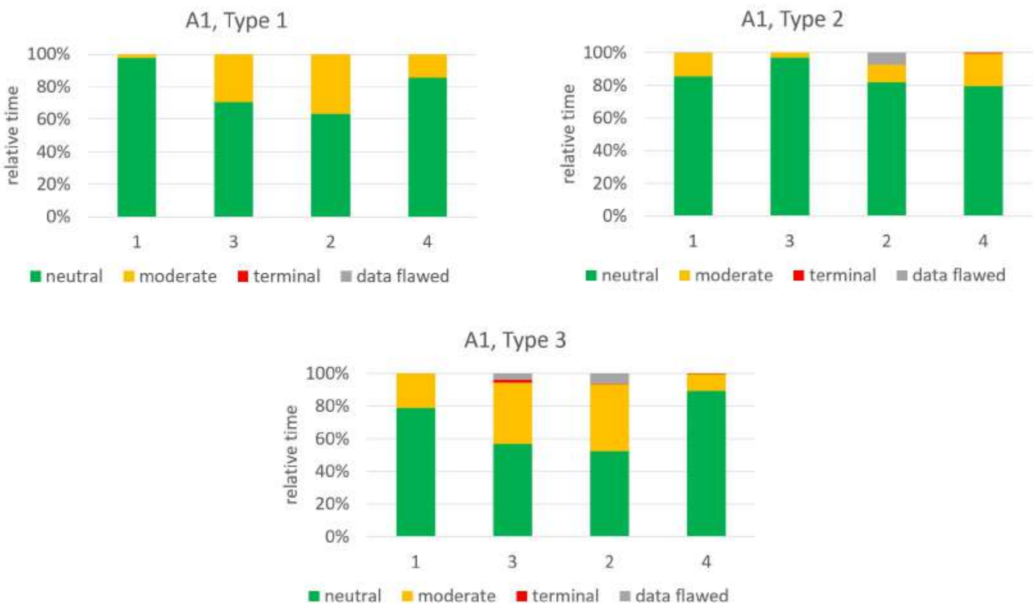


Figure 5.12.: The relative time for each neck angle range for subject A1. Note the change in order of the configurations.

5.4.2.2. B2

Figure 5.13 shows the percentages of time spent in the three angular ranges for the three task types for subject B2. Again it can be seen that most of the time during the tasks the neck angle is within the neutral range. Only very little time is marked as flawed data. Terminal neck angles can be seen mostly in configurations T+P and T+AR and they are reduced considerably when moving to the robot configurations. Also the time spent in the moderate range is decreased in all cases looking at the comparison between table and robot configurations.

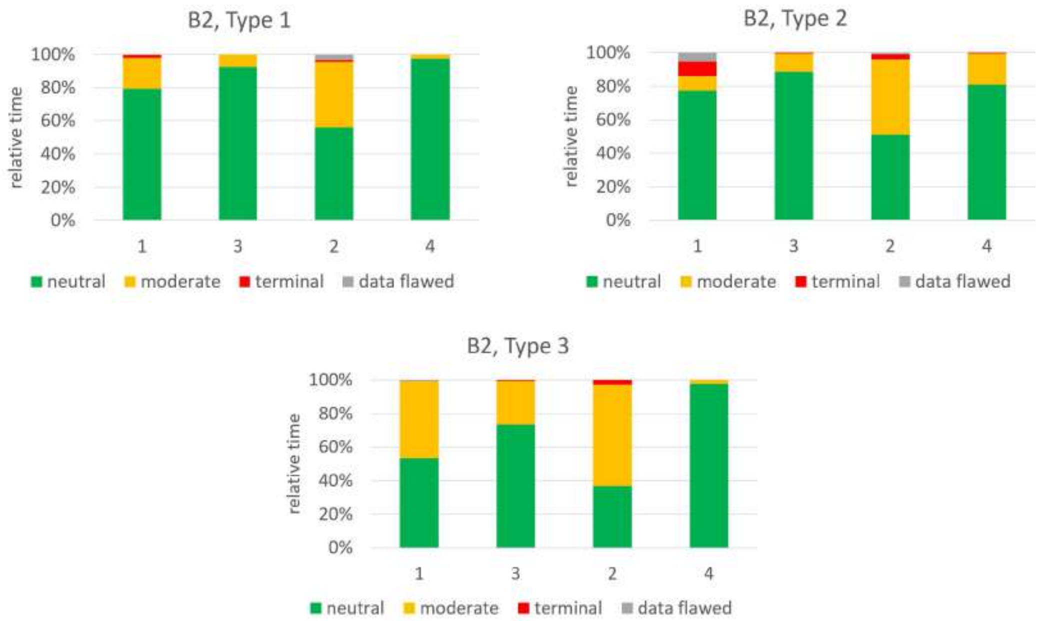


Figure 5.13.: The relative time for each neck angle range for subject B2. Note the change in order of the configurations.

6. Discussion

In the following sections the results are discussed. In general the conducted experiments have to be understood as an initial test of evaluation tools and the overall concept. Multiple improvements to the experiment procedure, task design and data acquisition are discussed.
Additionally, section 6.10 lists the multiple inputs from the subjects towards uses of the assistance systems and the experiment design. The Modular Experiment Rig (MExR) performed as expected and is proposed to be used for future experiments as a flexible and modular platform.

6.1. Complexity factor

Through the use of inputs to the complexity model that are discernible from procedures but also during the creation of a procedure the complexity factor can give a valuable insight into how complex a task needs to be to benefit most from the use of an assistance system. It needs to be validated with the help of experiments that use tasks with relevant spacing in the complexity factor. The tasks used during the experiments for this work did not provide this spacing as can be seen from figure 6.1.

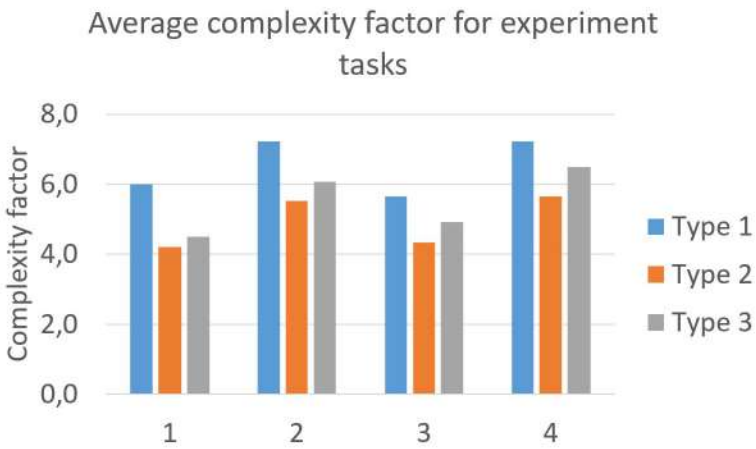


Figure 6.1.: Average complexity factors of the task types over the configuration.

They also show opposite behavior as the typical time and workload results suggest. With the current data set this is not explainable and further tests need to be done. In a subjective review by an involved engineer of the calculated complexity factors for the as-run procedure of the MMX project the model was estimated to give good results. These are shown in table B.1 in the appendix B.

6.2. Time needed

Although the time needed for a task is not the most important factor for activities in spacecraft AIV it can give a good insight into the applicability and user friendliness of a system.
The time needed for the tasks is heavily influenced by the familiarity of the subject with the tasks. This can be seen from the data when looking at the times for the robot procedures. These were done on the second day for each subject and it is believed that the familiarization has a larger influence on the time than the use of the robot. Moving the setup with a second person by hand was subjectively felt to be faster by the experiment conductor although this time was not tracked. It could however be extracted from the raw video footage if relevant for future iterations of the tests.
On the first day and wearing the HoloLens for the first time in an actual task environment took the subjects the longest. This is also due to the lack of experience with the augmented reality system. Furthermore, the technical issues with the PDF-reader becoming unresponsive added to the longer times for the configurations using the HoloLens. This shows that an intuitive and fast application is necessary to not elongate every task. For future experiments it would also be necessary to have subject which are more familiar with the use of the HoloLens and application prior to the experiments. Also randomizing the order of using the robot and table configurations would be required to enable a assertion about the influence of the robot on the time needed.
The influence of the proficiency of the subjects can also be seen from the times. Subjects B2 and B4 were faster in all tasks and configurations than the non-proficient subjects. They also showed some of the highest increases in time when using another than the reference configuration that they are used to. Only subject B1 was slower than subject A1. Subject A1 was the youngest participant and can therefore be expected to have a faster and more effortless familiarization with the HoloLens which could have led to the fastest time within the non-proficient group and also the faster time than subject B1.
Although some of the results show a general trend these can have resulted from the non ideal procedure. The limited data situation and therefore lack of statistically meaningful analysis of the data also means these statements have to be considered

highly influenced by the individual subjects capabilities and day to day changes in the performances. To fully validate the benefits of the used systems a larger set of experiments has to be done and the procedure and task order fully randomized.

6.3. Mistakes

Notably the percentage of faulty tasks decreased significantly from using the paper procedure to the augmented reality configurations. However, the limited data set makes the results of the tracked mistakes not representative. The small amount of mistakes made with respect to the overall number of tracked items can have multiple reasons and the influence of the individual operator has to be ruled out using a statistically more valid data set during future experiments.

6.4. Task Load Index

Using the NASA TLX questionnaire for further evaluation of the applicability of assistance systems seems to be a reasonable choice. Filling out the questionnaire on an iPad right after the task did not interfere with the experiment procedure, took little time and is straightforward in the analysis afterwards. It can give valuable insight into the dimensions of the workload and which factor benefits the most from any assistance system to be evaluated. The before mentioned familiarization effect is not visible with the TLX data but an influence cannot be ruled out and has to be studied further.
When looking at the results the use of assistance systems seems to have a positive influence on the subjective workload. 30 of 54 tasks (55.5%) show a reduced mental workload, 31 out of 54 (57%) show a decrease in overall weighted workload. Due to the limited data points it is however not distinguishable if the visible effects are actually caused by the assistance system or other factors. The individual subjects influence in the data is too high and therefore effects like the individual capabilities or faults while rating the task on the questionnaire may cause the increase or decrease in the data. One data point per subject and tasks is not representative.
For example when looking at the 135% increase in perceived workload for task type 1 and the configuration table + AR for subject A1 this increase can be explained by the subjects difficulties using the DLR Holo-Space-Tool and the HoloLens in general. This was the first task with this system done by subject A1 and the application and handling were not yet fully internalized. All other tasks showed a decrease or only small increase in workload.
No discernible influence of the proficiency of the subjects on the change in workload is seen. This is presumably also due to the limited data set.

6.5. Video analysis

Looking at the results of the posture analysis it can be seen that especially for the torso angle an improvement of the posture is visible for almost all cases. The relative time spent in the terminal region is decreasing in all cases when moving from the table mounted setup to the robot. It has however to be noted that insufficient visibility resulted in high amounts of flawed data. An analysis of the absolute time an operator works in a specific posture can therefore not be done reliably. The time spent in an unhealthy or unergonomic posture is however an important factor when evaluating operator health. Once the video capture setup is optimized to reduce the amount of flawed data this absolute time analysis can also be done with the python scripts at hand. The relative time analysis as done during this thesis gives however a good idea on the potential for improving operator posture when using a flexible robot MGSE.

6.5.1. Viewing angle/number of cameras

As can be seen from the high ratio of flawed data in especially the torso angle analysis, one camera is not enough. The subjects sometimes needed to move behind the setup and the view of the camera would therefore be obstructed. Additionally the neck angle results showed some strong disagreement with the expectations and the observations during the experiments. To better understand the problems four test videos were filmed. Two for each of the two angles to be analyzed. The subject is at viewing angles of 0°, ±90° and 180° to the camera for the first video. The second video is starting at an angle of -45° and goes to +45°, 135° and -135°. For the torso angle the subject bowed down well below 60° torso angle, came back up to a straight standing position and then turned roughly 90° 3 times and repeating the bowing movement in each position. The same procedure was done for the neck angle. Here the head was bowed until the chin touched the chest. Figures 6.2 through 6.5 show the results. For each of the distinct movements the time frame is marked in the plot of the angle output over the time by the python script.

Looking at the neck angle while facing the camera starting at an angle of 0° it can be seen that for each position relative to the camera the calculated angle is vastly different. For the position facing away from the camera the angle is even below the starting angles for the other positions. Even in the times between two head movements the angle does not go to zero but remains between 30-50°. The zero value is not reached and the lowest reached point is also different between each position looking at figure 6.2.

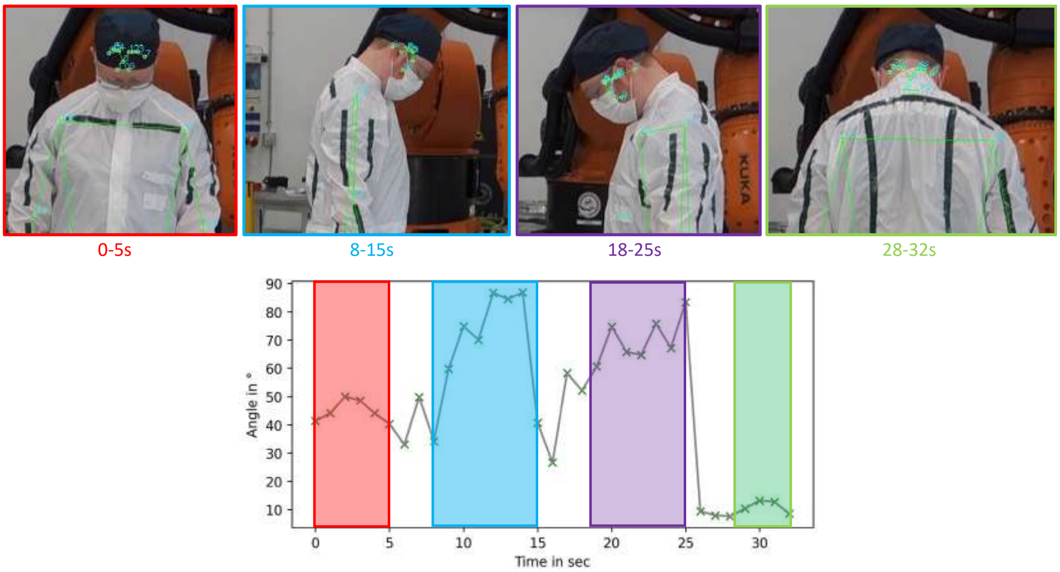


Figure 6.2.: Results of the test video for the neck angle analysis with an approximate viewing angle of 90°.

These findings indicate that the viewing angle of the person has a strong influence on the calculated angle. The neck angle analysis improves when using a more angled view of the person as can be seen from figure 6.3. The positions looking away from the camera give worse results than the first two. It can be taken away from the results that a viewing angle between 45° and 90° gives the best results.

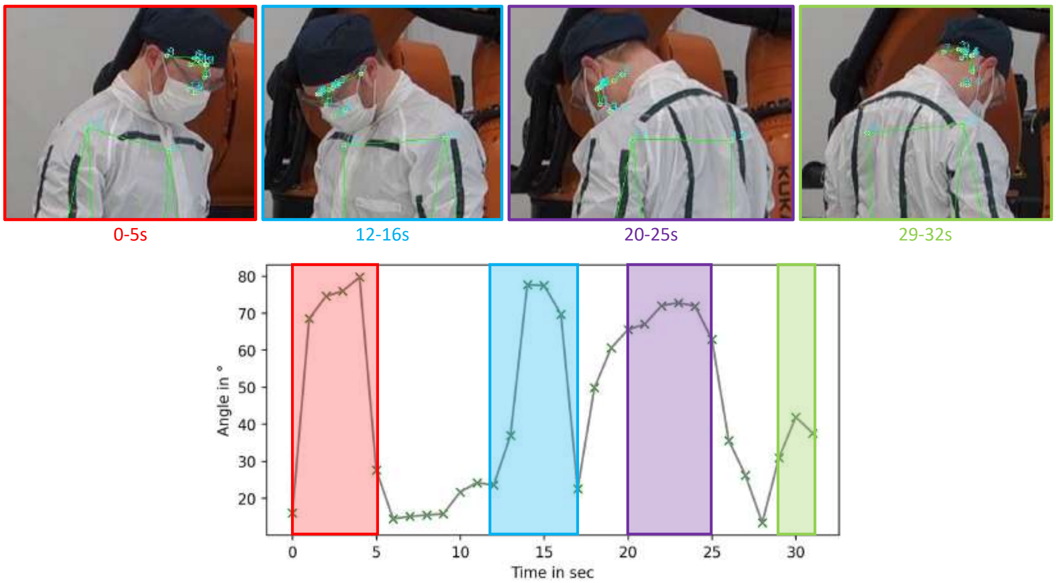


Figure 6.3.: Results of the test video for the neck angle analysis with an approximate viewing angle of 45°.

For the torso angle the positions at 90° to the camera (blue and violet in figure 6.4) and +45° and -45° (red and blue in figure 6.5) give the best results. Although the calculated angles also do not start from zero and do not reach zero in between when standing straight, the behavior is in better agreement with the actual physical movement for the torso angle. The calculated angles are in best agreement with the actual movement when the person is at an angle of 90° to the camera. When looking at the position facing away from the camera (figure6.4, right) it can seen that the algorithm is not able to correctly track the shoulder points which are obstructed from the camera view by the rest of the body. The same could be seen during times when the subject was mostly covered from view by the test setup. In those cases the algorithm either tracked no landmarks but also sometimes tracked arbitrary points in the room and on the robot arm. Sustained visibility of the subject therefore is of key importance for future experiments.

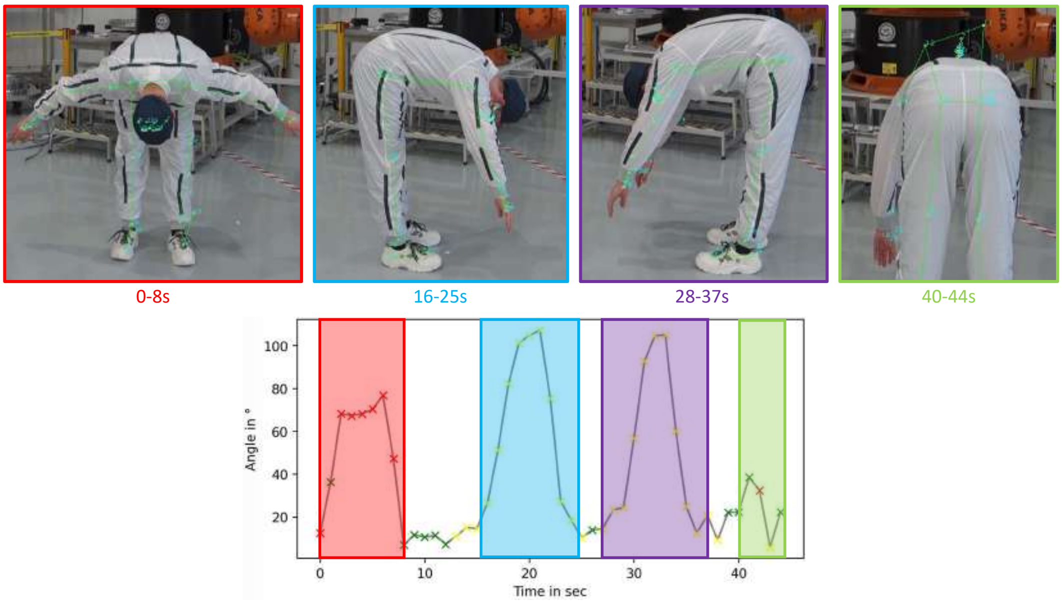


Figure 6.4.: Results of the test video for the torso angle analysis with an approximate viewing angle of 90°.

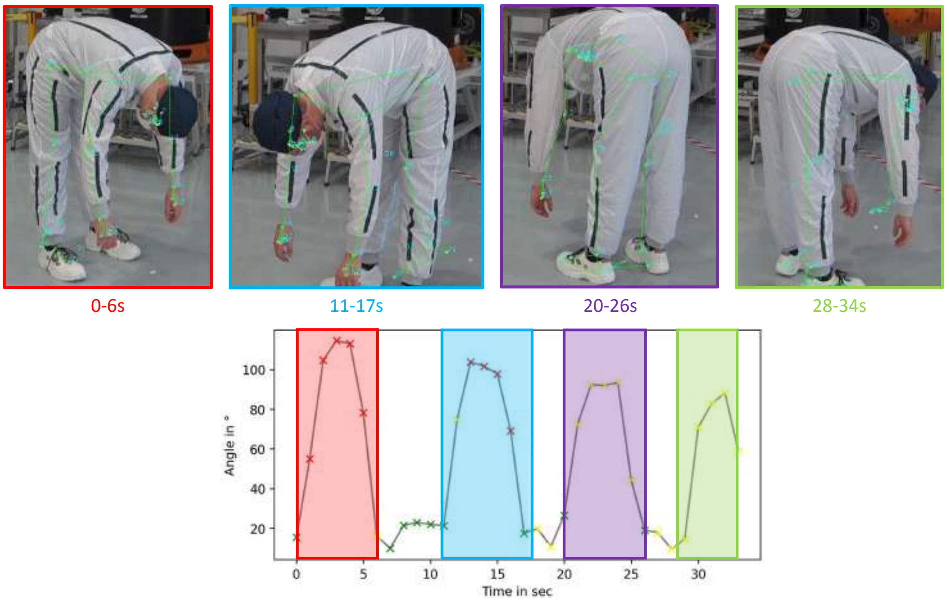


Figure 6.5.: Results of the test video for the torso angle analysis with an approximate viewing angle of 45°.

6.6. Procedure

Due to the long time for each task and the resulting scheduling difficulties the procedure had to be setup as it was. This is however not ideal with regards to the obtained data. Especially when looking at the time results a significant decrease in time needed for the experiments could be seen for configurations Robot + paper and robot + AR. This may not be a result of the use of the robot but comes from the fact that these two were always done on the second day for each subject. Familiarization with the tasks is believed to be a much more substantial influence with regards to the time needed than the robot. To eliminate this familiarization different steps could be taken. Firstly, the tasks should not be executed in pairs so that not two tasks of the same type are executed directly after each other. The tasks could also be more diverse. This would however lead to less comparability between the tasks and the influence of the assistance systems. Another approach could be to introduce biasing tasks that would familiarize the subjects with basic task concepts. Furthermore the time spent for a task might not be the most relevant indicator. The successful and correct completion of a task are the main performance indicator for AIV activities. Since in most cases the subject did not notice if they had made a mistake familiarization is not believed to have made an impact on the number of mistakes made during a task. This also would need to be validated further by increasing the data set.

6.7. DLR Holo Space Tool

In its current version the DLR Holo-Space-Tool offers some of the applications that are foreseen to be aiding significantly in AIV activities. This could however only partly be shown during the experiments. This is believed to be mostly due to the lack in usability and intuitiveness. The overhead of setting up the three dimensional environment and the additional steps when displaying the 3D model compared to the paper version make every time gain through better orientation, etc. obsolete.
Additionally the accuracy of parts and objects overlaid onto the physical model was not high enough. Using one QR-code does not seem to suffice for the need to position holograms precisely. While being hard to actually measure, the offset ranged from 5 mm up to 20 mm. For general orientation within a highly complex system that might be good enough but it is not if the AR application should supersede masks or actually measuring distances.
As mentioned before the time needed to complete a task is not the most relevant factor in spacecraft AIV. The reduced number of mistakes made using the Augmented Reality system shows that an improvement for the MTBF could be expected. This is however also to be validated by a larger data set.

A completely new tool is in development within the framework of the Collaborative Processes and Services for Aeronautics and Space (COOPERANTS) project. This is envisioned to incorporate the entire process control from creating the procedure, reviewing it and executing it with the help of different displaying systems like the HoloLens 2 or tablets. This application needs to be an intuitive and reliable tool for the operator to decrease workload and aid in the successful completion of spacecraft AIV activities.

6.8. JARVIS

Using the industrial robot as a flexible MGSE to position the MExR or any other object in the working area has proven to be a valuable addition. Controlling the movement with the 6D mouse mounted to the MExR was intuitive and posed no problem for any of the subjects. It also meant that no additional operator was needed for the repositioning of the MExR. The preliminary results of the posture analysis hint towards an improvement in ergonomics. At least with regards to the torso angle. Subjective reports from the test subjects but also from operators using the robot for actual spacecraft integration already have been unanimously positive. Implementing a smaller version into the digital space lab of the DLR is therefore highly recommended to also allow for the development of further applications as mentioned before. Also safety considerations with regards to the COBOT functionality have to be analyzed further and innovative solutions need to be found to reveal the full potential.

6.9. Future improvements

This section serves to give recommendations for future iterations of the experiment setup towards a standardized test frame for advanced AIV technologies. While some of the developed tools and processes worked well other parts of the experiment need to be improved to enable a sound statement on the applicability of assistance systems.

In future experiments it should be considered to use more than one camera. Ideally four, in 90° separation radially around the experiment area. This would allow for full visibility regardless of the persons location within the area or equipment being in line of sight. Since there is no common coordinate frame between the video files it would however impose additional work on the analysis of the body angles. Running each video separately and deciding afterwards using the visibilities, which camera angle to use for specific time frames of the experiment might be a solution.
Higher contrast and better fitting clothing is also believed to greatly improve the

tracking ability of the code. Ideally, in the digital space laboratory, the test subjects could wear their regular clothing. There it would also not be necessary to wear masks or hair and beard nets.
Additionally a more thorough calibration of the neck angle has to be done and the influence of the viewing angle determined since the subjects are moving within the work area and the viewing angle changes constantly.

The procedure should be randomized even further to allow for a distinction between actual influence of an assistance system configuration or familiarization and individual effects of the subject. The individual tasks need to be changed to have a larger spacing with regards to the complexity factor to validate it. Also the number of different task might need to be improved to get a higher complexity resolution. This would then allow for the assertion of the complexity boundary after which the usage of a specific assistance system is beneficial.

6.10. User feedback

Table B.6 in the appendix B lists various feedback and remarks given by the subjects with regards to the use of the assistance systems. Also included are observations made by the experiment conductor. This can aid in further development of the augmented reality tools and also give inspiration for future tools and systems. It however also lists problems that came up and to which solutions need to be found. In general the feedback was positive. Mostly the usability of the application and the lack of options regarding the visibility of holograms has been criticized. Implementing the individual employees into the process of developing the assistance systems is also believed to result in additional motivation and can lead to further ideas.

7. Summary

This thesis evaluated the workload reduction when using Augmented Reality (AR) and robot-assistance during spacecraft AIV activities. Improving the ergonomics, reducing the workload and maintaining the existing high standard of quality are the major motivation for the use of these systems. For this the current workflow was analyzed and compared to an ideal, fully digitalized workflow. The current paper-based Operation and Verification Procedure (OVP) have limitations in how well they transport information and their flexible use during the operations. They also provide limited use for the information transport out of the clean room and need to be scanned in or values and measurements transcribed manually. Using the third dimension, which can be accessed via AR through a Head mounted display (HMD) like the HoloLens 2, can improve the information transport and subsequently reduce the workload that results from insufficient information display. Displaying parts and components into the physical world, ideally but not exclusively, into the position they need to be integrated can result in faster and easier perception of the task at hand, reduce the failure potential and also aid in a reduction of workload.
The inflexible jigs and GSEs used during traditional spacecraft integration activities can lead to unergonomic postures and overall unpleasant work for the operators imposing a high workload. Using a six-axis industrial robot for handling and positioning of the spacecraft can dramatically improve the ergonomics and consequently reduce the workload for the workforce. To enable quantitative analysis of the ergonomic improvements while using the robot as an MGSE a video analysis tool has been developed. It features an AI-based open-source posture recognition algorithm and can track 33 landmarks on the human body. This was used to develop python scripts that allow for the evaluation of, in a first version, two body angles.
Due to their additional overhead with regards to workload and time a complexity factor model was developed to enable the determination of the boundary beyond which the use becomes beneficial. Through the usage of the NASA TLX questionnaire the individual workload of a test subject could be determined and the impact of current and future assistance systems evaluated.
Six test subjects split into a proficient and a non-proficient group were chosen to perform experiments using four configurations of paper-based or AR documentation and table or robot GSE. This allowed for the determination of the influence of each assistance system and their combinations. The limited data set of six, respectively three for each proficiency group, resulted in data that has to be viewed carefully.

No statistical evaluation is possible and therefore the influence of the individual subjects capabilities in the results is high. It could be seen that the current version of AR application was not intuitive enough and therefore increased the time needed for 26 of 36 (72.2%) tasks. The introduction of the AR system did only result in a decrease in subjective workload in 8 out of 18 (44%) of the tasks done with just the HoloLens. The number of mistakes made during the paper procedure reference was decreased from 12 faulty tasks to three when using the AR. Most of the mistakes were misplaced parts and the 3D overlay could be seen to improve the performance in this regard.
The posture analysis showed a considerable amount of flawed data due to insufficient visibility of the subject. Future experiments therefore need to increase the number of cameras to allow for full visibility of the subject. It could however be seen that introducing the robot improved the posture with regards to the torso angle. The time spent in the neutral regime of flexion increased for 29 of 36 tasks (80.5%) done with the robot as MGSE while the time in the terminal range decreased for 23 of 36 (63.8%). The neck angle analysis showed results that did not fit the observations and expectations. A closer look at the performance of the python script showed an influence of the viewing angle on the results that was not taken into account. This has to be improved in future experiments.
The developed test setup has shown potential to be used for the future evaluation of AR robot assistance. The on-going efforts and the setup of the "Digital Clean Room" laboratory will be able to make use of the developed tools. Together they will enhance the research capabilities in the field of AIV activities in the Institute of Space Systems of the DLR.

8. Outlook

To further improve the knowledge about the impact of AR and robot, additional experiments need to be conducted to broaden the data set. This is necessary to allow for statistically meaningful results. For this the presented evaluation tools should be used. The task design needs to be improved to also allow for the validation of the complexity factor. With the addition of cameras to the test setup a complete body posture analysis will be possible. All of these steps are planned to be done in the framework of the Digital clean room laboratory. This laboratory will aid in the development and evaluation of new tools and processes. This will feature a smaller but equally usable robot but without the need for special clothing. Also access to the laboratory will be much easier and may enable larger subject groups.
Furthermore, the on-going efforts towards a fully digitized AIV environment will provide for more project opportunities. The ideas and projects of the advanced AIV concept will be refined and their applicability and potentials evaluated. Providing the operator with the best tools to achieve the highest standards with respect to quality, ergonomics and reduced workload will be the goal. Robot-assisted spacecraft alignment, in-line verification of mass, center of gravity and moments of intertia are example of the projects worked on with respect to the JARVIS robot. An external partner develops a fully integrated software tool for the AIV workflow and its applicability towards reducing the operator workload will be evaluated within the digital clean room using the presented tools and methods.

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Vorname/n ______________________

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Erklärung und Hinweise Antrag BA-/MA-Arbeit Seite 2 von 2

B. Appendix B

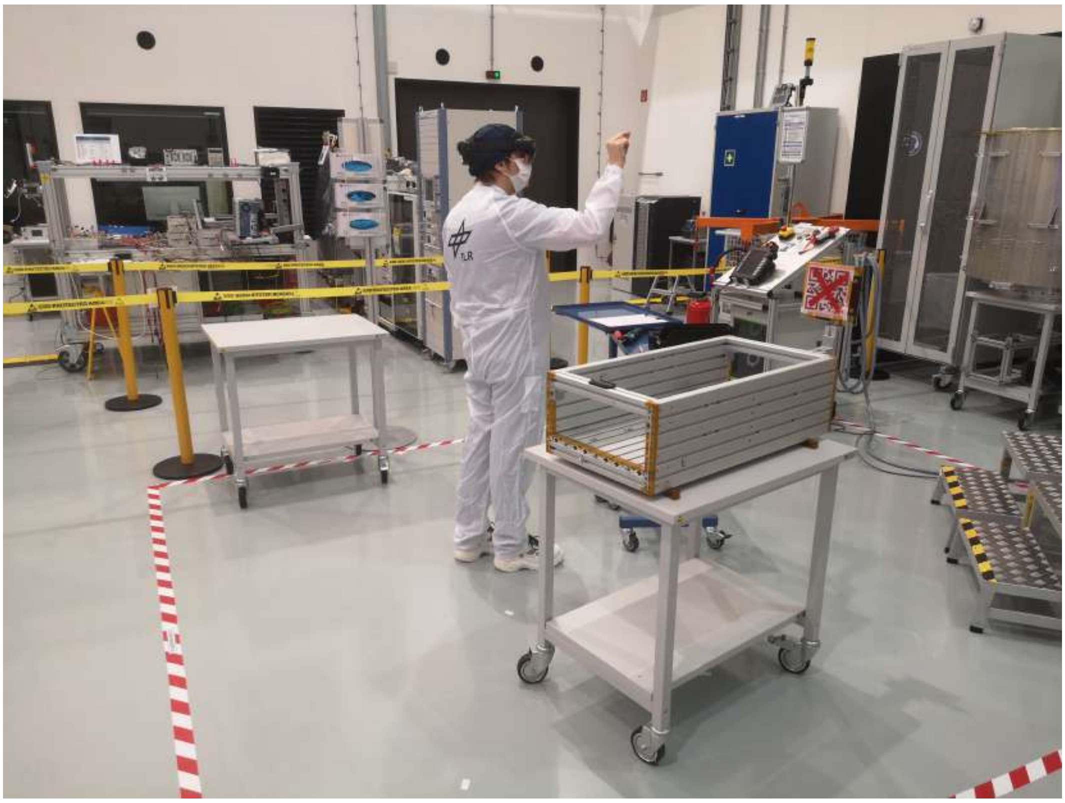


Figure B.1.: Experiment setup in the clean room with test rig on table

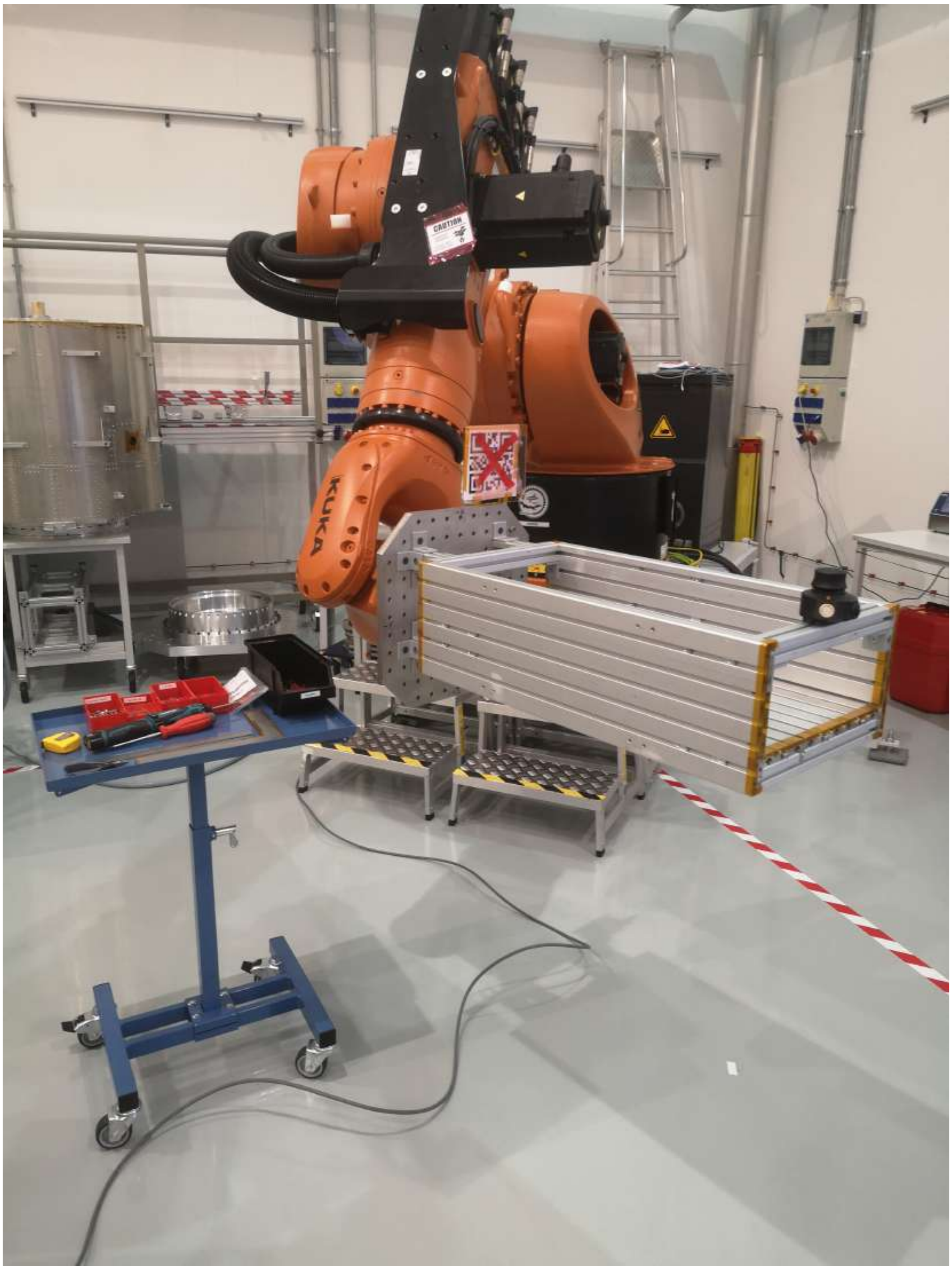


Figure B.2.: Experiment setup in the clean room with test rig on robot

Table B.1.: Complexity factors for the as-run procedures used for the model development.

Procedure	Name	Complexity factor, averaged
EC-AIV-FM-1-1-02	Sun Sensor	13.2
EC-AIV-FM-1-1-01	Bus Structure	7.9
EC-AIV-FM-1-1-14	Hash Shearfield	6.8
EC-AIV-FM-1-1-16	Bus Harness Routing and Screw Lock	10.7
EC-AIV-FM-1-1-06	HFP, TCS, S3H, S3DCDC	13.0
EC-AIV-FM-1-1-10	PL4	12.4
RFX-AIV-SM-1-2-02	EBX1 / EBX1 MU	11.3
RFX-AIV-EM-2-2-02	IET DHS 2	16.8
MMX-AIV-PFM-2-1-01	MECSS MCI	9.0
MMX-AIV-PFM-1-2-07	MECSS Umbilical Integration	10.0
MMX-AIV-PFM-1-1-18	Front Baffle Exchange	12.2
MMX-AIV-PFM-1-1-04	LOCO Integration	19.6
MMX-AIV-PFM-1-1-21	Front Shutter Integration	8.4
MMX-AIV-PFM-1-1-16	LRR Integration	4.2
MMX-AIV-PFM-1-1-03	Baffle Integration	19.4
MMX-AIV-PFM-1-1-08	MLI Integration	15.5

Table B.2.: Possible applications for AR during AIV campaigns. [30]

Task	Description	Area of Operation	Pros	Cons	Status
Display 3D Model - Digital Twin	Positioning a 3D model arbitrarily in the room - testing of integration envelope - Overview	Integration, Ergonomic, AIV planning	- early planning of integration space - three-dimensional overview over the entire model	CAD models need to be prepared for AR	on-going
Display documents	applicable documents can be positioned freely in the room - procedure - ICD - protocols - data sheets	Integration, Verification, Test, Ergonomic	- both hands free - paperless documentation - less focus shifts	may be perceived as stressful for the eyes over longer times	on-going
Digital Clean room	new infrastructure, landmarks, etc. can be displayed, saved for later usage and positioned relative to laboratory coordinate frame	AIV planning, Test	- planning of GSE positioning - standardized alignment of landmarks for measurements - position of instruments	preparation time	TBD
overlaying 3D models	Overlaying a 3D/CAD model over physical hardware	Integration, AIV planning	- faster, simpler, less error prone positioning of components - early detection of deviations regarding integration space	preparation time	on-going
COBOT safety	displaying safety checks and upcoming movements of the robot can increase (perceived) safety when working in close proximity to robot	Integration, Ergonomic, Safety	- safe usage of KUKA robot as COBOT - greater acceptance through visualization of movements	database connection of KUKA robot not possible at this time	TBD

Table B.3.: Possible applications for the JARVIS during AIV campaigns. [30]

Task	Description	Area of Operation	Pros	Cons	Status
Handling	arbitrary positioning of Spacecraft (S/C) relative to operator: - Height Adjustment - Rotation - Translation	Integration, Ergonomy	free positioning in 6 DoF, no complex rigging, no re chucking	Limited to 500 kg	on-going
Alignment	exact positioning to measure IMUs	Verification, Test	repeatable start position, in-line verification	Limited to 500 kg	on-going
Coning	Rotation around axis 5 to measure differences in outside geometry around body axis for rotationally symmetric parts	Verification, Test	in-line verification, no re chucking	Limited to 500 kg	on-going
Life-Tests	testing of operational life of mechanisms and deployables	Verification, Test	in-line verification, no re-chucking	Limited to 500 kg	TBD
Mass determination	using motor currents to determine S/C mass	Verification, Test	in-line verification, no re-chucking	Limited to 500 kg	on-going
CoG determination	using motor currents to determine S/C CoG	Verification, Test	in-line verification, no re-chucking	Limited to 500 kg	on-going
Mating	precise mating of components	Integration, Handling	no re chucking	Limited to 500 kg	TBD

Table B.4.: Requirements on the design of the Modular Experiment Rig (MExR)

ID	Name	Description	Method of Validation
MExR-Req-1	Weight	The Modular Experiment Rig shall have a weight of no less than 15 kg and maximum 30kg.	Test
MExR-Req-2	COTS	The Modular Experiment Rig shall be constructed from COTS components.	Inspection
MExR-Rep-3	Modularity	The Modular Experiment Rig shall have ITEM Profile 8 grooves on each side.	Inspection
MExR-Req-4	JARVIS interface	The Modular Experiment Rig shall be mountable to the JARVIS adapter plate by atleast 6 M8 screws.	Demonstration
MExR-Req-5	Table interface	The Modular Experiment Rig shall be usable on the standard desk with rollers in the DLR Cleanroom.	Demonstration

Table B.5.: Absolute times for all subjects, tasks and configurations

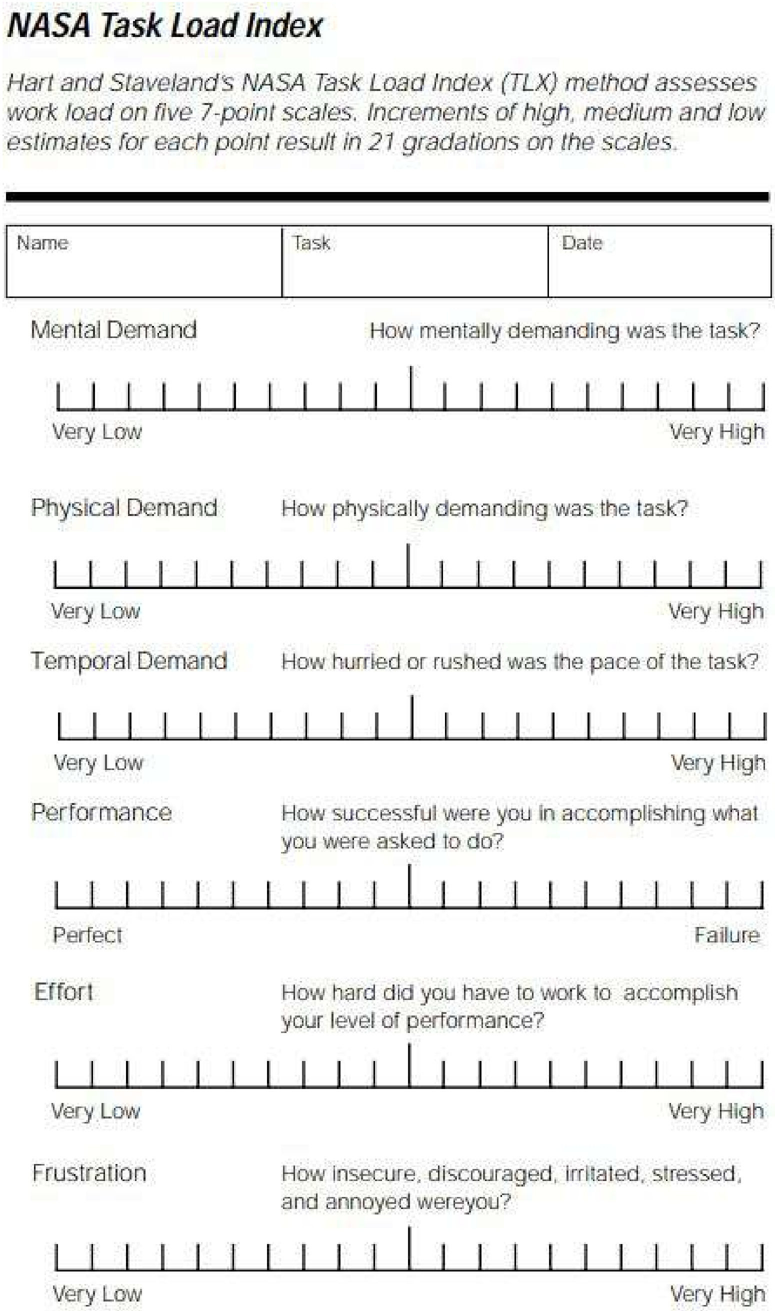
Subject ID	Task Number	Configuration		Time	Subject ID	Task Number	Configuration		Time
A1	11	Tisch	Papier	0:12:59	A2	11	Tisch	Papier	0:12:37
A1	12	Tisch	AR	0:19:54	A2	12	Tisch	AR	0:22:46
A1	21	Tisch	Papier	0:19:46	A2	23	Tisch	Papier	0:29:52
A1	22	Tisch	AR	0:24:13	A2	24	Tisch	AR	0:58:37
A1	31	Tisch	Papier	0:17:18	A2	33	Tisch	Papier	0:18:29
A1	32	Tisch	AR	0:17:21	A2	32	Tisch	AR	0:26:43
A1	13	Roboter	Papier	0:10:07	A2	13	Roboter	Papier	0:06:49
A1	14	Roboter	AR	0:10:40	A2	14	Roboter	AR	0:14:05
A1	23	Roboter	Papier	0:16:01	A2	22	Roboter	Papier	0:24:24
A1	24	Roboter	AR	0:23:01	A2	21	Roboter	AR	0:45:32
A1	33	Roboter	Papier	0:13:16	A2	31	Roboter	Papier	0:09:43
A1	34	Roboter	AR	0:15:52	A2	34	Roboter	AR	0:23:39
A3	11	Tisch	Papier	0:13:34	B1	13	Tisch	Papier	0:19:40
A3	13	Tisch	AR	0:17:23	B1	11	Tisch	AR	0:16:25
A3	23	Tisch	AR	0:36:55	B1	21	Tisch	Papier	0:31:44
A3	24	Tisch	Papier	0:48:52	B1	23	Tisch	AR	0:31:44
A3	31	Tisch	AR	0:41:14	B1	32	Tisch	Papier	0:20:56
A3	33	Tisch	Papier	0:34:41	B1	31	Tisch	AR	0:25:16
A3	12	Roboter	Papier	0:08:41	B1	12	Roboter	Papier	0:13:36
A3	14	Roboter	AR	0:16:34	B1	14	Roboter	AR	0:18:34
A3	21	Roboter	Papier	0:21:22	B1	22	Roboter	Papier	0:18:37
A3	22	Roboter	AR	0:34:46	B1	24	Roboter	AR	0:32:23
A3	32	Roboter	Papier	0:15:07	B1	34	Roboter	Papier	0:16:06
A3	34	Roboter	AR	0:44:57	B1	33	Roboter	AR	0:19:41
B2	11	Tisch	Papier	0:07:25	B4	13	Tisch	Papier	0:06:55
B2	12	Tisch	AR	0:11:06	B4	12	Tisch	AR	0:15:51
B2	23	Tisch	Papier	0:11:52	B4	21	Tisch	Papier	0:11:36
B2	22	Tisch	AR	0:26:43	B4	24	Tisch	AR	0:19:45
B2	32	Tisch	Papier	0:08:35	B4	34	Tisch	Papier	0:09:36
B2	33	Tisch	AR	0:14:07	B4	31	Tisch	AR	0:17:54
B2	14	Roboter	Papier	0:07:16	B4	14	Roboter	Papier	0:07:27
B2	13	Roboter	AR	0:08:16	B4	11	Roboter	AR	0:08:46
B2	21	Roboter	Papier	0:13:08	B4	23	Roboter	Papier	0:13:38
B2	24	Roboter	AR	0:16:31	B4	22	Roboter	AR	0:18:00
B2	31	Roboter	Papier	0:09:02	B4	32	Roboter	Papier	0:09:15
B2	34	Roboter	AR	0:12:04	B4	33	Roboter	AR	0:09:56

Study Group	Subject ID	A1			A2			A3			B1			B2			B4		
		Weight	Rating	Adjusted	Weight	Rating	Adjusted	Weight	Rating	Adjusted	Weight	Rating	Adjusted	Weight	Rating	Adjusted	Weight	Rating	Adjusted
11	Mental Demand	3	25	75	4	30	120	2	50	100	4	25	100	5	60	300	3	15	45
	Physical Demand	1	15	15	0	10	0	1	50	50	4	25	100	4	70	280	2	10	20
	Temporal Demand	4	35	140	5	50	250	4	45	180	0	5	0	0	5	0	0	5	0
	Performance	5	5	25	3	25	75	4	45	180	4	25	100	1	75	75	4	5	20
	Effort	2	20	40	2	50	100	4	45	180	2	15	30	3	60	180	5	25	125
	Frustration	0	5	0	1	50	50	0	35	0	1	0	0	2	5	10	1	15	15
12	Mental Demand	2	40	80	1	15	15	2	30	60	2	15	30	3	70	210	4	45	180
	Physical Demand	0	10	0	0	10	0	0	50	0	1	0	0	5	55	275	2	25	50
	Temporal Demand	1	55	55	5	60	300	3	35	105	4	50	200	0	10	0	0	5	0
	Performance	4	5	20	3	25	75	4	30	120	5	0	0	1	80	80	5	10	50
	Effort	4	60	240	4	45	180	5	30	150	3	25	75	3	60	180	3	35	105
	Frustration	4	75	300	2	65	130	1	20	20	0	0	0	3	25	75	1	20	20
13	Mental Demand	1	20	20	2	25	50	1	35	35	3	20	60	4	35	140	4	20	80
	Physical Demand	0	10	0	1	5	5	4	50	200	4	50	200	2	0	0	4	15	60
	Temporal Demand	4	25	100	5	65	325	4	35	140	1	0	0	0	0	0	0	5	0
	Performance	5	5	25	4	10	40	2	35	70	4	15	60	4	20	80	2	0	0
	Effort	3	30	90	3	45	135	4	50	200	3	20	60	1	5	5	4	25	100
	Frustration	2	15	30	0	35	0	0	50	0	0	0	0	4	35	140	1	10	10
14	Mental Demand	0	10	0	2	15	30	2	45	90	3	20	60	4	65	260	2	25	50
	Physical Demand	3	20	60	0	0	0	1	25	25	1	10	10	2	5	10	2	15	30
	Temporal Demand	1	35	35	5	55	275	4	50	200	4	50	200	0	0	0	0	5	0
	Performance	5	5	25	4	10	40	4	50	200	2	25	50	5	20	100	3	5	15
	Effort	2	20	40	3	25	75	4	30	120	2	20	40	3	15	45	4	20	80
	Frustration	4	40	160	1	15	15	0	35	0	0	5	0	1	10	10	1	5	5
21	Mental Demand	4	60	240	5	80	400	1	35	35	3	50	150	5	35	175	4	25	100
	Physical Demand	0	20	0	4	70	280	0	25	0	2	15	30	0	0	0	2	15	30
	Temporal Demand	3	65	195	1	20	20	4	45	180	1	20	20	1	5	5	0	5	0
	Performance	5	5	25	3	5	15	4	30	120	5	15	75	4	20	80	3	5	15
	Effort	2	60	120	2	50	100	4	25	100	2	25	50	2	0	0	5	20	100
	Frustration	1	30	30	0	55	0	2	20	40	2	25	50	3	40	120	1	10	10
22	Mental Demand	2	45	90	3	60	180	2	50	100	5	25	125	5	100	500	3	15	45
	Physical Demand	0	15	0	0	20	0	1	30	30	1	10	10	3	50	150	2	10	20
	Temporal Demand	2	45	90	4	25	100	4	50	200	2	25	50	0	0	0	0	5	0
	Performance	5	5	25	4	35	140	5	30	150	3	10	30	2	50	100	4	5	20
	Effort	3	40	120	3	60	180	3	25	75	4	25	100	1	50	50	5	35	175
	Frustration	3	55	165	1	50	50	0	25	0	0	0	0	4	70	280	1	20	20

Figure B.3.: NASA TLX raw data part 1

23	Mental Demand	4	60	240	2	75	150	1	65	65	5	35	175	2	20	40	2	15	30
	Physical Demand	0	10	0	0	25	0	0	55	0	3	20	60	5	70	350	1	20	20
	Temporal Demand	3	45	135	3	62	186	4	70	280	1	15	15	4	15	60	0	5	0
	Performance	5	10	50	4	50	200	5	55	275	4	20	80	2	30	60	3	10	30
	Effort	2	30	60	5	65	325	3	45	135	1	30	30	2	50	100	5	15	75
	Frustration	1	15	15	1	60	60	2	55	110	1	20	20	0	20	0	4	30	120
24	Mental Demand	2	20	40	5	80	400	1	60	60	3	25	75	4	65	260	5	25	125
	Physical Demand	0	15	0	4	70	280	2	55	110	2	20	40	1	0	0	2	15	30
	Temporal Demand	3	60	180	1	20	20	5	65	325	1	35	35	0	0	0	0	5	0
	Performance	4	10	40	3	5	15	4	55	220	4	5	20	3	25	75	4	10	40
	Effort	1	25	25	2	50	100	3	65	195	5	20	100	2	15	30	3	25	75
	Frustration	5	75	375	0	55	0	0	55	0	0	55	0	5	65	325	1	15	15
31	Mental Demand	1	20	20	1	40	40	1	40	40	4	35	140	5	25	125	5	55	275
	Physical Demand	2	35	70	0	10	0	4	40	160	2	35	70	1	5	5	3	15	45
	Temporal Demand	4	65	260	5	60	300	4	50	200	0	5	0	0	0	0	0	5	0
	Performance	5	5	25	4	20	80	2	50	100	5	0	0	4	75	300	4	15	60
	Effort	3	20	60	2	25	50	4	60	240	3	20	60	2	20	40	2	15	30
	Frustration	0	10	0	3	30	90	0	50	0	1	5	5	3	30	90	1	45	45
32	Mental Demand	0	10	0	1	30	30	2	25	50	5	50	250	4	60	240	5	40	200
	Physical Demand	4	30	120	1	40	40	1	25	25	2	25	50	4	30	120	1	15	15
	Temporal Demand	3	35	105	4	65	260	4	40	160	0	5	0	0	5	0	0	5	0
	Performance	5	5	25	4	45	180	3	25	75	4	10	40	2	25	50	3	15	45
	Effort	2	10	20	2	55	110	5	25	125	3	25	75	4	15	60	4	35	140
	Frustration	1	35	35	4	50	200	0	15	0	1	35	35	1	10	10	2	25	50
33	Mental Demand	1	20	20	1	30	30	2	65	130	5	50	250	5	65	325	2	10	20
	Physical Demand	0	10	0	0	35	0	1	35	35	4	5	20	3	45	135	3	15	45
	Temporal Demand	4	60	240	5	55	275	3	55	165	2	5	10	1	5	5	0	5	0
	Performance	5	15	75	3	30	90	4	40	160	1	10	10	2	30	60	4	5	20
	Effort	2	15	30	2	40	80	5	50	250	3	15	45	2	20	40	5	30	150
	Frustration	3	35	105	4	70	280	0	50	0	0	25	0	2	35	70	1	10	10
34	Mental Demand	1	10	10	1	20	20	4	60	240	2	20	40	4	65	260	2	25	50
	Physical Demand	0	10	0	0	10	0	0	45	0	2	20	40	1	0	0	5	55	275
	Temporal Demand	3	60	180	5	65	325	4	70	280	2	10	20	0	0	0	0	5	0
	Performance	4	5	20	4	20	80	2	55	110	4	10	40	5	5	25	2	10	20
	Effort	2	15	30	2	50	100	3	60	180	5	25	125	2	5	10	4	25	100
	Frustration	5	55	275	3	40	120	2	60	120	0	5	0	3	5	15	2	15	30

Figure B.4.: NASA TLX raw data part 2



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure B.5.: The rating page of the NASA TLX questionnaire with the 6 scales

Table B.6.: Feedback and remarks given by the subject + observations by the experiment conductor

Feedback/Remarks/Observation	possible solution
Impaired spatial perception lead to substantial problems with reading text displayed in AR	
Scrolling through documents like PDF is very tedious	pagewise skimming with use of buttons
Visibility of tools impaired by hologram	toggle visibility of holograms
Manipulation of windows and other inputs works better and more intuitively using distance manipulation	
Bright overlay blocks vision of the actual working envelope	
"I can already see the next parts/components and can therefore prepare myself"	
Due to the entire set of components being displayed the subject did alter from the procedure for a more efficient way	
"Was a lot of fun", comment on routing harness using AR	
Continous scrolling and manipulating the PDF reader led to exhaustion of arms	Implement voice commands
Depth perception not precise enough to distinguish top and bottom of holograms	
Hand menu appears unintentionally and blocks view	careful use of hand movements to access certain functionalities
Coordinate system of 3D model would improve orientation within the holographic representation	Implementing a coordinate system from the CAD input that can be displayed if necessary
Displaying a virtual line similar to a laser used in construction to aid in tasks as possible tool	
Buttons/inputs required for positioning of model automatically placed near QR-code	
Manual positioning of model in reference to QR code after each robot movement too time consuming	
"More parts displayed than needed is confusing"	Funtionality to display or hide individual
Small dropdown menu very hard to interact with	Effort in creating sufficiently large input fields
Applications needs ability to change transparency and visibility of selected holograms	
"HOME" Button to restore initial window position in case of misplaced or buged windows	
Extensive usage of possibility to push visor up and down	
HoloLens visor might effect ability to spot small movements, features or parts	
First signs of headache after around 25-30min of wearing HoloLens	
Actively using the robot to organize workspace by moving it high enough to fit tables underneath model for easier access	