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Bachelor Thesis

**Towards Augmented Reality as a
supporting tool for exoskeletons in
fabrication tasks**

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Commenced:	May 10, 2021
Completed:	November 10, 2021

Abstract

This project will investigate how tasks performed with an exoskeleton can be supported by augmented reality (AR). When two workers with passive exoskeletons perform a group task (such as lifting and placing large beams), clear and precise coordination between the persons must be ensured. We will investigate whether visual cues displayed in AR can optimise workflows to support the execution of the task.

We implement different visualisations and perform an informal evaluation of a prototype. The focus is on displaying visual cues to improve the beam placement. As well as on motion guidance to help workers move in a way that is beneficial to them in terms of time efficiency and ergonomics. We will also highlight the necessary steps on how data collected in real time should be handled for AR visualisation and how visual information can be projected over real and dynamically moving objects.

In addition, a user study will be conducted to analyse the benefits of AR support in combination with exoskeletons. The results collected will show that AR can indeed attract users' attention and make them adapt their behaviour according to the information provided. However, it will also become clear that more technical tuning will be needed to realise the full potential of this technology combination.

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1 Introduction

The digitization of industries is a trend that grows with the development of more efficient computers, and it tends to become more and more present in fields like construction and architecture as human-robot techniques evolve. With the integration of this technology, it is more than useful to put some awareness into the question, how humans might safely interact with computers and robots in a work environment. One of the areas where this awareness still needs to be better developed, for example, is the integration between humans and exoskeletons, especially in its regards to ergonomics.

As industries become more complex due to digitization and the development of more advanced manufacturing types and techniques, skilled workers who are familiar with working in such environments are becoming increasingly rare, and therefore more valued by their companies. This development also raises the need for companies to protect their employees from potential injuries of any kind in order to preserve their human capital.

1.1 Work environment problems

Besides decreasing work accidents ([Anj17]) in the past two centuries, more challenging tasks require even more challenging solutions to protect employees. A reduction in workplace accidents does not mean that workers do not face other problems that could lead to serious injuries. According to a 2013 study by the German Federal Statistical Office [Anj17], physical stress was most often due to “difficult posture” (12.4%), followed by “handling heavy load” (4.6%). Exoskeletons can be beneficial in such manufacturing environments, helping workers lift heavier objects and do intensive upper head tasks whilst avoiding serious injuries or muscular fatigues.

In 2013 16,5% of employees said that their perceived physical stress mostly arose (15,3%) from time pressure and work overload. The most common occupations, apart from managers, which experienced this physical stress were technicians and equivalent non-technical occupations with 19.6% [Anj17].

One of the possible ways to reduce this problem is looking for solutions that delivers a vital contribution for concerned workers that can help the persons involved to perform these tasks in a better i.e. humane way way. In the last decade, the use of Augmented Reality(AR) became increasingly popular, especially in the gaming industry. In addition, applications in health, training and marketing are also being developed and becoming more mainstream. Since most modern mobile phones now have AR capabilities, it's easy for consumers to have more contact with this kind of technology. Wearable devices, however, are still in an early stage of development, being more focused towards business than final users.

AR devices, in turn, can provide information to workers to improve their work processes or warn them of potential problems.

A combination of both systems (mechanical + visual) might therefore provide both physical and mental support for people in fabrication tasks.

1.2 Goal

This work provides an overview of the challenges and criteria to consider when developing an integration between the two previously described technologies: Exoskeleton and AR. We present and overview of different types of approaches related to attention and visualization of information for motion guidance.

Since there are multiple ways to guide the movement, we design and conduct a user study to evaluate whether this technical combination actually creates a benefit for users, and to try determining which guidance is better for our scenario. In our user study, we want participants to perform a task with and without AR support in order to compare the results firsthand. The task itself must be suitable for the use of an exoskeleton. We expect that users will complete this task in less time with AR support and that they will find the displayed information valuable and adjust their behavior accordingly. We also aim at providing relevant information to participants so that they can perform the task in a way that is appropriate for their posture.

2 Background and State-of-the-art

When implementing and working with new technologies, it is always good to have a brief idea about their use case and already existing application areas. And since working with AR is primarily about the meaningful presentation of information, the following will also provide an insight into how information should be presented with AR in order to catch the interest of users.

2.1 State-of-the-art

Besides the lack of related work on the combination of exoskeleton and AR, the subsequent parts provide a brief overview of the use of both technologies in their own regard. The outlined capabilities were the driving factor for the development of this work.

2.1.1 Exoskeletons in the industry

As the name suggests, Exoskeletons describe an additional outer (from greek, exo = external) skeleton structure [Dav12]. This structure can be used as a wearable devices that work in tandem with the user. Exoskeletons are placed on the user's body to act as amplifiers, augmenting, reinforcing or restoring human performance. The opposite would be a mechanical prosthetic, such as a robotic arm or leg that replaces the original body part. They can consist out of rigid materials such as metal or carbon fiber, or they can be made entirely out of soft and elastic parts and as such be classified in different categories such as upper limb, lower limb or full body, depending on where they are actually supporting the user. Exoskeletons can range from covering the entire body, just the upper or lower extremities, to a specific body segment such as the ankle or the hip [Mar].

With regard to the way the exoskeletons support the muscles, a distinction is made between two types. Passive exoskeletons, which apply their force with the help of mechanical springs, and active exoskeletons, which use motors to apply an assisting torque.

Their main role is not to replace humans in certain tasks, as robots could do, but to assist humans by reducing muscle strain and allowing them to perform heavier tasks that they would not be able to do without the suit.

2.1.2 Augmented Reality

“Augmented Reality (AR) is the synthesis of real and virtual imagery. AR overlays extra information on real scenes: Typically computer generated graphics are overlaid into the user's field-of-view to provide extra information about their surroundings, or to provide visual guidance for the completion of a task.” [Kle06]

Extensive development in recent years has brought many new AR-enabled devices to market. There are multiple smart glasses available like Microsoft's HoloLens¹, the Oculus Quest 2² or Google Glass³. They're all wearable devices that cover a portion or the user's field of view. The way that these smart glasses project information can be mainly separated into two categories. The first one is called virtual reality or VR for short. "VR glasses are completely closed off from the real, physical world, and instead present only a virtual world." AR on the other hand only overlays digital content onto the real world [RAAR15]. This way the user can still interact with the real world and can use the additional information projected by the smart glass.

2.1.3 Areas of application

Exoskeletons on their own were firstly being used as military devices to increase mobility and reduce fatigue of their users [Loc]. "Modern soldiers need to convey from 40 to 300kg. Military exoskeletons enable soldiers to carry up to 117 times more weight than normal" [Sch18]. But they have also proved to be useful as medical devices to help people with disorders walk again [Sui] or alleviate the burden and reduce the amount of workplace injuries in the fabrication sector where heavy or repetitive tasks need to be performed [Eks].

AR is used in many applications such as gaming, medicine, architecture or education. Architects can use it to visualize future building projects and let people walk through them when they have not even been built yet [Yod]. It can assist nurses in finding veins easier or even assists surgeons in operations [Fut].

Since both technologies have not been available for long, there are not many research studies about the advantages of combining both. Efforts have been made to advance the exoskeleton rehabilitation by AR gamification to keep users motivated [OAAM]. But no major study focusing on the fabrication sector has been conducted so far.

¹<https://www.microsoft.com/de-de/hololens>

²<https://www.oculus.com/quest-2/>

³<https://www.google.com/glass/>

2.2 Information Conveyance

As the main part of this thesis relies on visualizing information in a way that is beneficial for the users, the displayed data must be meaningful and intuitive. The information will be displayed by the HoloLens via AR overlaying the real environment.

But the users can only benefit from the projected data if it is understandable so that they adjust their performance accordingly. It is not helpful, if the information is not used by the participants at the end. So, it must be shown in a way that raises interest and attracts the attention of the users.

2.2.1 Attention

“Attention is the behavioral and cognitive process of selectively concentrating on a discrete aspect of information, whether considered subjective or objective, while ignoring other perceivable information” [W90].

People will focus their attention on something if they are interested in it. Since the people taking part on the user study have for the most part never worked with a HoloLens before and were willing to participate, they are probably more interested in the topic.

There are different types of attention, which can be divided into the following types

- Divided: The ability to attend to two or more different stimuli at the same time
- Sustained: The ability to attend to a stimulus over long periods of time
- Selective: The ability to intentionally ignore certain details of a stimulus we are attending to
- Alternative: The ability to switch attention between two or more stimuli [Cla]

The divided type, also known as multitasking, makes people open to perform several tasks at the same time. It has been shown, however, that people then perform their tasks more slowly and with less efficiency as [Gor09] states.

In order to achieve maximum attention, you have to display as little information as possible at the same time to trigger only one stimulus and make use of the sustained and alternating effect.

But there are still design choices to be made to gain the user attention on specific displayed information. A few of these are:

- Developing a narrative: Keeping the user engaged in a compelling story
- Creating stimulating visuals: Using motion to trigger prehistoric reflexes
- Avoiding overloading: Avoid overstimulation with too much displayed information

[Cla]

These ideas could be implemented in the augmented reality environment in the following ways:

- Animating objects [San]
- On-screen hints to point toward the direction of an off-screen element [San]
- Playing with transparency to highlight specific elements or regions [San]
- Keeping the HoloLens field of view clean to avoid overloading

Since the practical part of the experiment will not last longer than a few seconds, it is almost impossible to build up a narrative. However, it should be possible to implement all of the other aspects.

2.2.2 Learning

Once the user's attention has been captured, it is important to ensure that the user actually understands the information being displayed so that it can be used to adjust and hopefully improve their own behaviour.

As with the different types of attention, there are also different types of learning.

- Habituation: Is the response reduction to a repeated stimulus.
- Sensitization: Is the progressive reaction amplification of a repeated stimulus. [J10]
- Operant conditioning: A reinforcement or a punishment is given after a stimulus, changing the behaviour on future stimuli of the same type. [SC03]
- Observational Learning: Learning by mirroring the behaviour of others. [Sto17]
- Play: Gaining own experience through trial and error with the possibility of making mistakes.

Repetition often ensures that the later participants will perform the task more and more efficiently through sensitization. To be able to offer an actual advantage through the HoloLens, learning the task could be accelerated through positive feedback or by playing the task from a third person perspective.

In addition, it may be helpful to address several stimuli. In the case of the HoloLens, this can be done by displaying information or playing sound. A combination of both increases the attention and thus the learning ability of the user. [RBB11]

3 Implementation

The AR device used for this task is the HoloLens 2 from Microsoft. The main application, which is then executed on the HoloLens, is created using Unity¹. Unity is a cross-platform engine that makes it easy to target multiple platforms at the same time. Its extensive use in games and architecture also provides multiple ways to create 3D environments, display information or play sounds.

3.1 Evaluation

To see the influence of AR in combination with exoskeletons, an experiment is needed that can benefit from the help of the exoskeleton alone and the additional AR assistance. The task should also be feasible without AR support to allow a direct comparison of iterations with and without the assist.

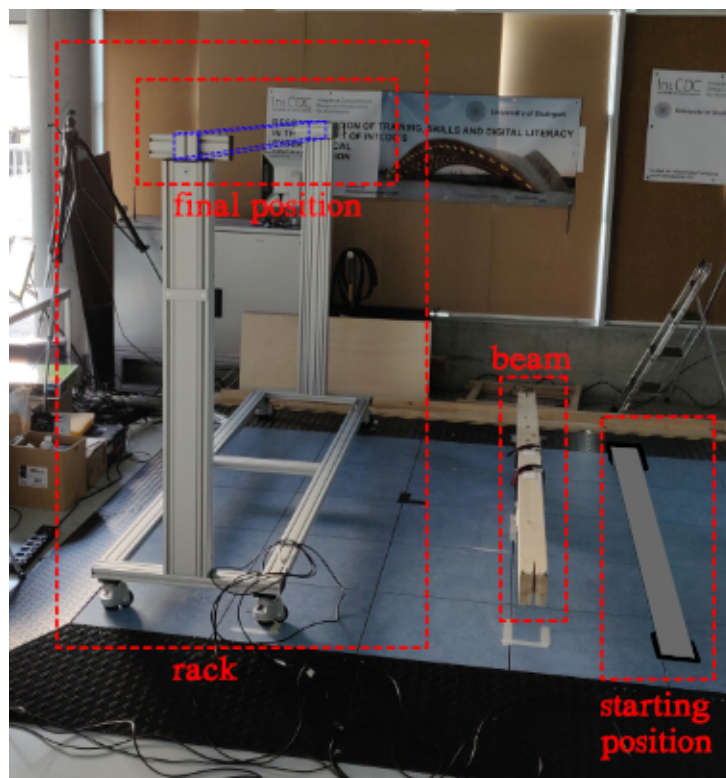


Figure 3.1: Experiment Setup

¹<https://unity.com/>

The corresponding task consists of lifting a 2.5m long wooden beam into a metal rack. Two participants in the final user study are considered to stand on either side of the beam and lift it together towards its destination.

The rack itself is fixated on the floor and can't be moved. In order to place the beam inside of the rack it must be inserted from above into the final position. The beam itself has a carved out slid on each side while the rack has a corresponding counterpart with a metal plate on each side. This enables the beam to be inserted only in a vertical movement.

Both participants will wear the HoloLens 2 from Microsoft as AR device. Plus a passive upper limb exoskeleton that supports the upper arms.

3.2 Coordinate systems

Since the idea of this HoloLens is to test AR in combination with exoskeletons, a reference point that is known in the virtual world as well as in the real world is key to precisely overlay information at the desired positions. This would not be the case when using VR, as only the one virtual coordinate system is used there.

Once the application is initiated on the HoloLens, any virtual content remains at its current position in the real world. For example, if a cube is placed at the world origin (0,0,0), the cube will always be visible at the position where the Unity application is launched. This is because this start position determines the origin of Unity's own virtual coordinate system. And even if you walk around with the HoloLens, a virtual object then always remains at the same position in the real world.

To generate exact results with multiple repetitions, you would have to start the app at the same position each time. Since this is almost impossible to achieve due to variations in the actual positioning of the device as well as offsets of the app itself, another reliable connection is needed to link the real world with the virtual world.

One unit of length in Unity corresponds to a length of one metre in the real world. If a reference point in the real and virtual world would now be known, any virtual content could always be placed exactly where it is wanted in the real world by simply measuring the offset towards that reference point and adjusting the setting in Unity.

Therefore the Vuforia² marker recognition system is used. Vuforia uses the image of target markers and calculates the offset from Unity's world center to the position of the scanned marker relative to the real environment. This position can then be used as an offset to overlay virtual data precisely over real objects.

Since the distances of the objects needed for the later experiments in the real world are known, such as the start position of the beam on the floor and the end position on the rack, the distances can also be adjusted in the virtual world within Unity.

The remaining task is to link the two together. Since the first link is crucial for any subsequent projection, several markers were used at this point to increase accuracy through triangulation.

²<https://developer.vuforia.com>

$$p_{triangulated}(x, y, z) = \left(\frac{1}{n} \sum_{k=1}^n p_{marker_{k_x}}, \frac{1}{n} \sum_{k=1}^n p_{marker_{k_y}}, \frac{1}{n} \sum_{k=1}^n p_{marker_{k_z}} \right)$$

Since we can assume that the floor in the final experiment is even only the rotation around the normal vector of the floor (positive y in Unity) has to be triangulated as well. Each other rotation simply can be set to zero.

$$r_{triangulated}(x, y, z) = \left(0, \frac{1}{n} \sum_{k=1}^n r_{marker_{k_y}}, 0 \right)$$

However, triangulation only increases accuracy if the distance between the markers is relatively large. So it is important for the later experiments, that they are spaced out in the room as much as possible.

This link now allows virtual data to be overlaid on real objects, such as the display of virtual rack over the real rack for example.

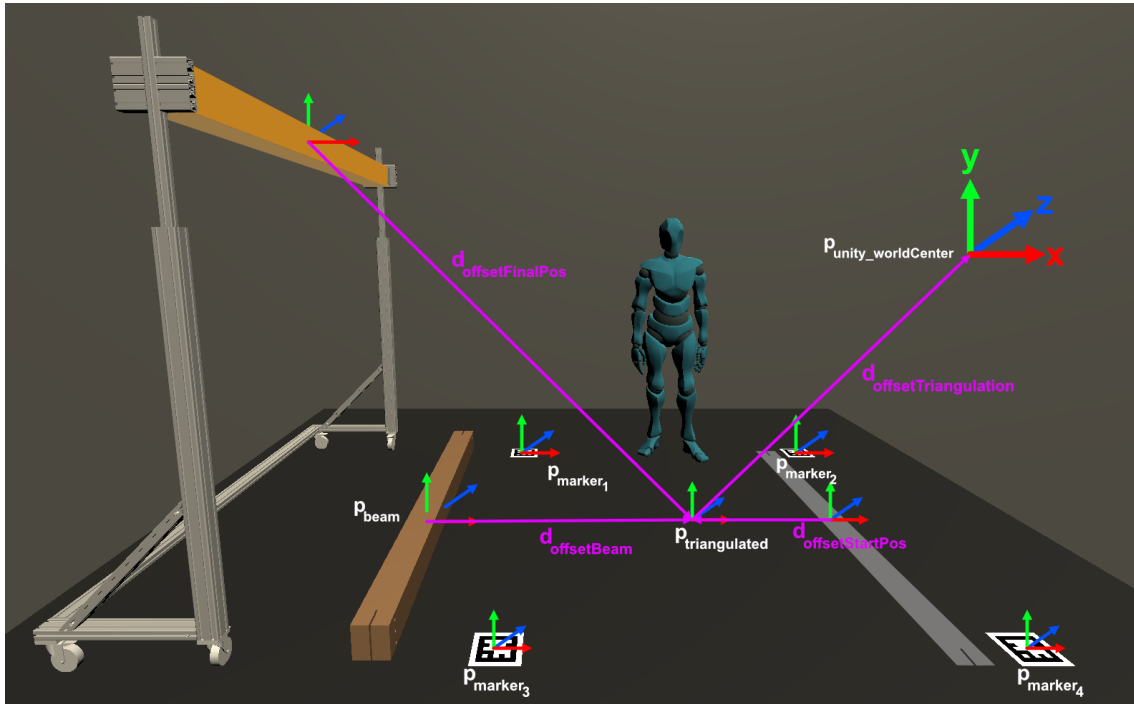


Figure 3.2: Unity coordinate system offsets

After scanning the markers and calculating the triangulated position, any virtual content can be displayed across multiple HoloLens devices at the same position in the real world. However, the scanning of the markers only needs to be done at the beginning when the Unity application is launched.

To display virtual content at a desired position in the real world, the offset from the desired position towards the triangulated position is needed. This can then be used to adjust the position of the virtual content inside of unity. The virtual content will now appear at the desired position in the real world.

3.3 MQTT Transmission

3.3.1 MQTT System

In order to start the experiment on both HoloLens at the same time during the later user study and to maintain the distance according to the Corona requirements, it is necessary to find a way to do this wirelessly. Here this is achieved by an MQTT connection.

“MQTT is an OASIS standard messaging protocol for the Internet of Things (IoT). It is designed as an extremely lightweight publish/subscribe messaging transport that is ideal for connecting remote devices with a small code footprint and minimal network bandwidth” [20].

This lightweight design makes it ideal for the HoloLens not to consume unnecessary CPU power.

The MQTT architecture is based on clients and brokers. Clients can publish data and/or receive data. The broker itself only ensures that incoming data is forwarded to each subscribed client.

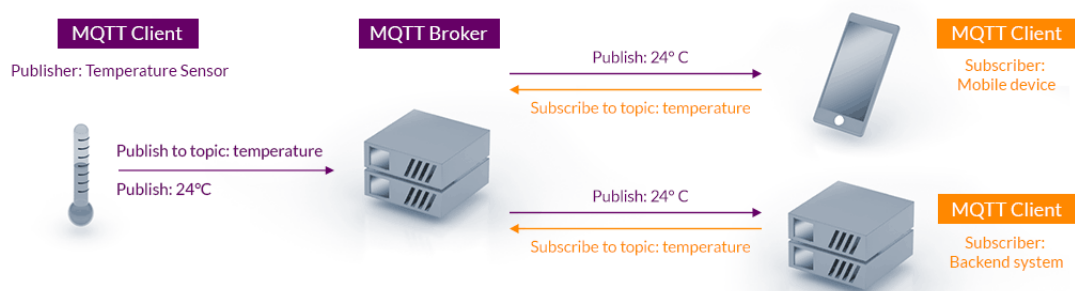


Figure 3.3: MQTT publish/subscribe architecture³

MQTT has 3 defined quality of service levels (QoS) that determine how often a published message arrives at a subscriber:

- QoS 0 : at most once
- QoS 1 : at least once
- QoS 2 : exactly once

[20]

³<https://mqtt.org/assets/img/mqtt-publish-subscribe.png>

3.3.2 MQTT Network

For the final user study the MQTT broker will be emulated on a laptop via Node.js⁴. There are also online brokers. But a broker directly on the local network improves performance due to the unnecessary added latency of an internet connection. Since every connected device that wants to send or receive data via MQTT must be connected to the same network, a router is used to create an independent local network where no data traffic is blocked.

As for the connected devices, the two HoloLens devices and another smartphone client, which acts as the main controller, are connected to this network. The smartphone client runs a controller app that manages the connected HoloLens devices and can start and stop the experiment described later.

For it to work properly, the controller app must first be started before the Unity apps are launched on the HoloLens devices.

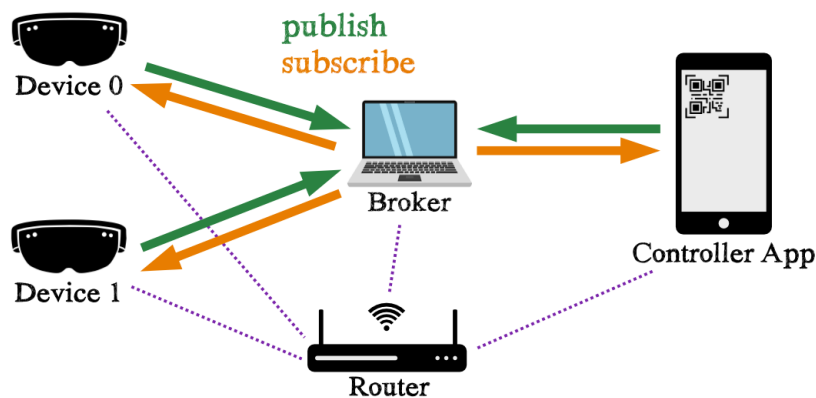


Figure 3.4: MQTT network architecture⁵

The image above summarizes the MQTT network described. The laptop acts as an MQTT broker and the connected HoloLens devices and the controller app are MQTT clients.

3.3.3 Connection Handshake

Since it is important to control the connected HoloLens directly and as a group, each device must be assigned a unique identifier (ID). This process takes place at the start of the application on the HoloLens through a handshake.

To do this, the HoloLens sends the current timestamp to the registration topic. The administrator application (app) tracks each connected device and generates a unique ID for each registration request and sends this ID back to the name topic along with the device's timestamp. Each HoloLens

⁴<https://nodejs.org/en/>

⁵<https://static.thenounproject.com/png/816211-200.png>,
<https://static.vecteezy.com/ti/gratis-vektor/p1/636084-laptop-symbol-auf-weissem-hintergrund-vektor.jpg>

listens to the name topic. Only if the Hololens has not yet received an ID, the data published in the name topic will be processed. If the timestamp then matches the one previously generated, it is guaranteed that the correct device has been addressed and the handshake was successful.

These messages, which are necessary for the handshake, as well as all administrative commands or user update requests are sent with a Quality of Service level (QoS) of two. This ensures that the corresponding data always arrives exactly once.

This procedure only works well if the connecting devices do not send the registration message at exactly the same time with the identical timestamp. However, since the timestamp is given in milliseconds, this is very unlikely and can be ruled out by a minimal waiting time between the app starts.

Once the connection is established each device can then be addressed independently by its set device ID. This is achieved by sending the information, for example, about the detection of a bad posture to the corresponding topic. The MQTT message additionally contains the corresponding device ID, and each receiving device checks whether its personal ID matches that of the message. If so, the message was received by the targeted device.

Since the MQTT message is basically a single string, the data components are separated by semicolons, and the receiving devices split the messages according to these separators to retrieve the individual components of the message again.

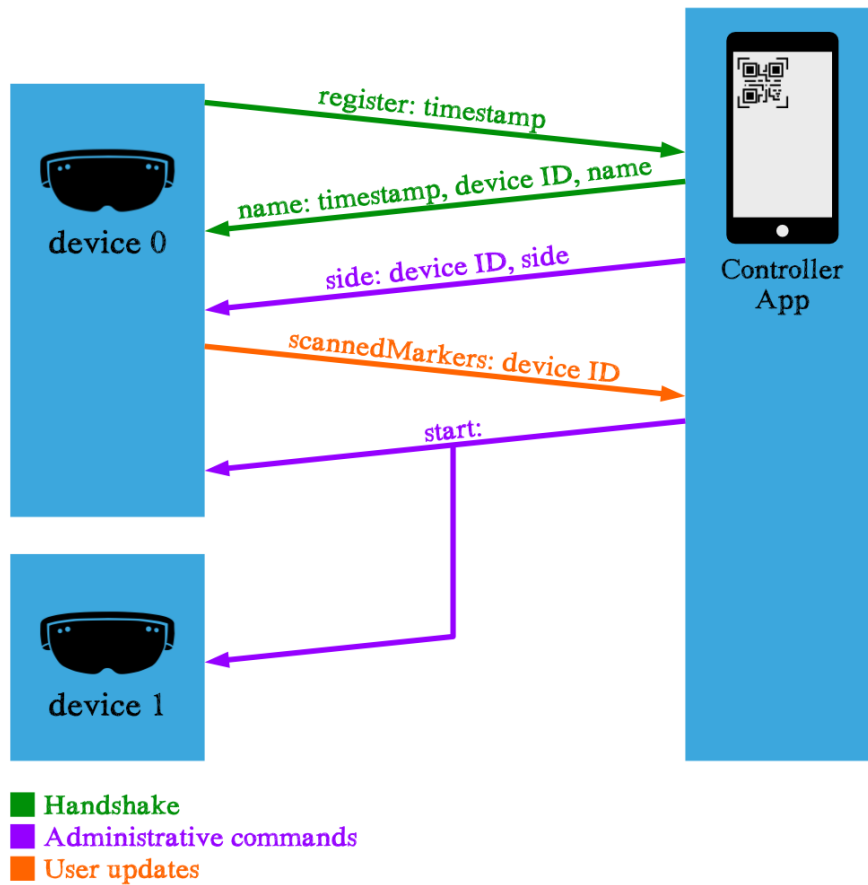


Figure 3.5: MQTT administrator - HoloLens connection

3.3.4 Interface

The graphical user interface of the controller app additionally allows to provide direct assistance in the event of problems with the user study, as the current states of the connected devices are displayed automatically.

Throughout the app, the beam side can also be adjusted, which is essential for displaying the correct data in the final user study. Additionally the logging of data can be en- or disabled, so whereby the corresponding HoloLens will then store the measured beam trajectory in a ".csv" file for later usage.

The controller app itself is also programmed with Unity and could be ported to more than just Android devices.

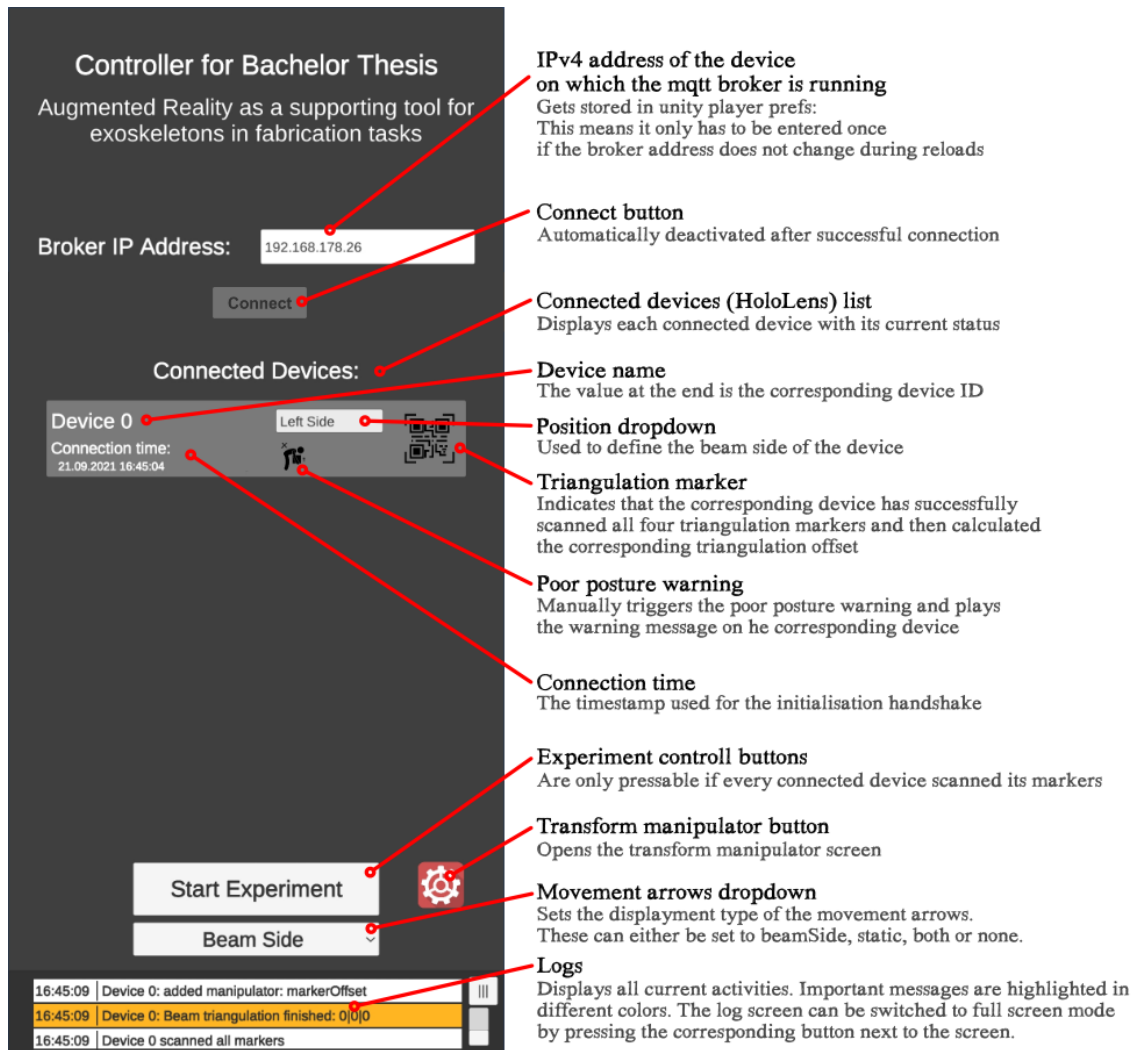


Figure 3.6: MQTT App Controller

3.3.5 Logging

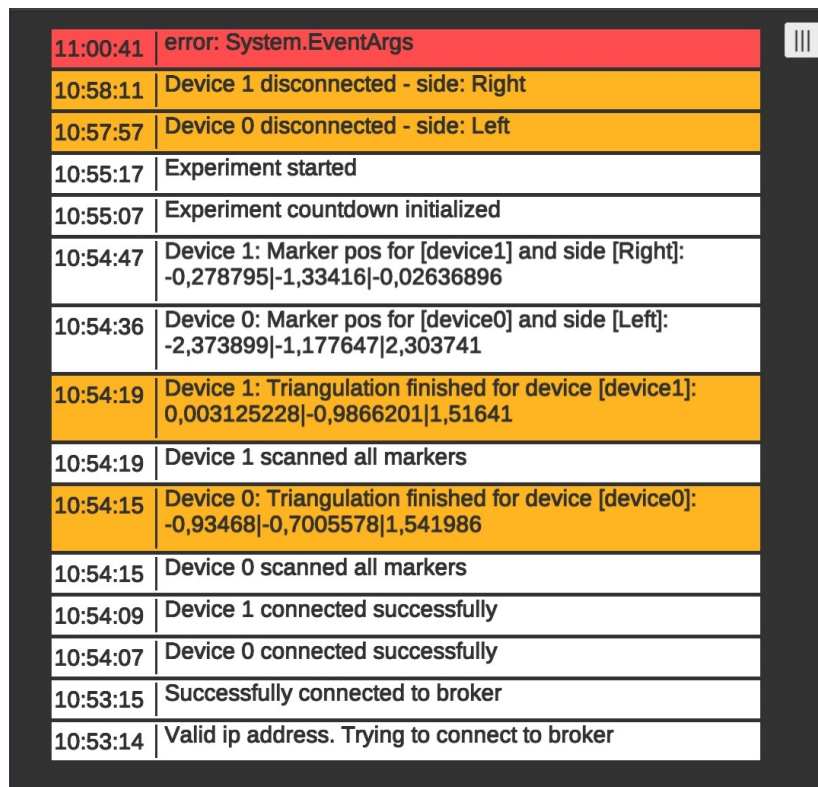
When a Unity application is running in the corresponding editor, logs or error messages are displayed right inside that editor. When the same program is run on HoloLens, there is no direct way to see these logs or error messages. This makes troubleshooting very difficult. Therefore, the logging screen has been integrated into the controller app.

The implemented logging screen makes development for the HoloLens much easier, as every triggered log entry (or exception) on the HoloLens is sent directly via MQTT and displayed in the controller app.

The color of the log corresponds to the log type of the thrown log or exception on the HoloLens.

- Red: Error or exception
- Orange: Assert or warning
- White: Log

As each connected HoloLens has already been given its custom name and ID during the handshake process, this can be used to distinguish between devices and see which one has thrown corresponding exception.



11:00:41	error: System.EventArgs
10:58:11	Device 1 disconnected - side: Right
10:57:57	Device 0 disconnected - side: Left
10:55:17	Experiment started
10:55:07	Experiment countdown initialized
10:54:47	Device 1: Marker pos for [device1] and side [Right]: -0,278795 -1,33416 -0,02636896
10:54:36	Device 0: Marker pos for [device0] and side [Left]: -2,373899 -1,177647 2,303741
10:54:19	Device 1: Triangulation finished for device [device1]: 0,003125228 -0,9866201 1,51641
10:54:19	Device 1 scanned all markers
10:54:15	Device 0: Triangulation finished for device [device0]: -0,93468 -0,7005578 1,541986
10:54:15	Device 0 scanned all markers
10:54:09	Device 1 connected successfully
10:54:07	Device 0 connected successfully
10:53:15	Successfully connected to broker
10:53:14	Valid ip address. Trying to connect to broker

Figure 3.7: MQTT App Controller - Log Screen

3.3.6 Transform Manipulator

For this project it was necessary to calculate several positions and rotations to adjust objects in different coordinate systems. As explained in the previous subsection, debugging on the HoloLens is not trivial. Trial-and-error method had to be used to achieve the desired results. Since the building in Unity and the subsequent package building in Visual Studio can take up to 10 minutes until the final launch on the HoloLens, this approach is quite time-consuming.

The Transform Manipulator allows any Unity's object transform (position, rotation and scale) to be adjusted wirelessly and live via the MQTT controller app. This enables adjustments as a result of incorrect triangulation due to a slightly shifted marker position without having to restart the application directly or the placement of virtual content relative to the triangulated position without taking direct measurements in the real world.

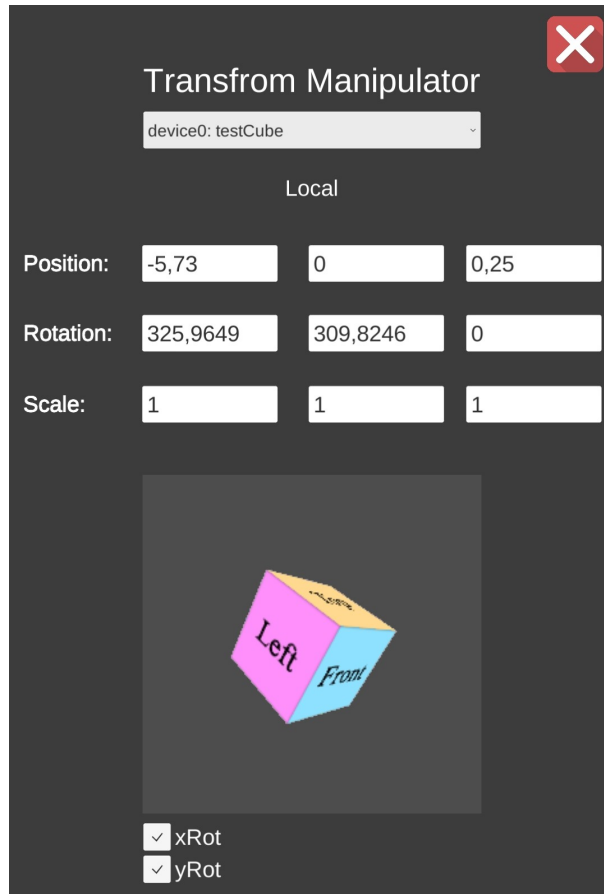


Figure 3.8: MQTT App Controller - Transform Manipulator Screen

To use this system all that is required is to add a script to the corresponding game object in Unity. The MQTT controller app automatically adds each incoming request to the drop-down menu. Any adjustments made to the objects are then transferred directly to the connected HoloLens and the changes are applied to the game object.

If the connected HoloLens now exits its Unity application, the previously connected transformation manipulators should no longer be available and are therefore removed from the drop-down menu.

3.4 Beam Position Tracking

In order to be able to display information on the side of the beam in real time, the exact position and rotation of the beam must also be known in real time. Therefore, different types of tracking were tried out to determine the best variant for this project.

3.4.1 Tracking with side markers

The idea behind this method is based on the fact that in the final user study a participant always looks at one side of the beam. If the position of each side would be tracked now with markers, the information of both sides could be used to calculate the actual beam position and rotation.

Since only one participant knows the position of one side of the beam, they would have to pass on his beam position to the other participant and vice versa. This is achieved by using the MQTT system (3.3).

Of course, this only works if both participants keep a constant eye on their marker. If only one side loses track, the calculated beam position would not be correct anymore.

For this position sharing to work properly, the exchanged position data must refer to the same coordinate system in all devices. This is where the triangulated reference position comes into play again. To change the position from the random Unity world center to the triangulated one, the triangulation offset can simply be subtracted from the tracked marker position. The same applies to the rotation.

$$markerPos_{triang}(x, y, z) = markerPos_{Unity} - triangOffsetPos$$

With the quaternions used in Unity to store rotational data, a simple subtraction is not possible. To achieve the same result, the first quaternion must be multiplied with the inverse of the second one.

$$markerRot_{triangulated}(x, y, z, w) = markerRot_{Unity} \cdot triangOffsetRot^{-1}$$

The adjusted $markerPos_{triang}$ and $markerRot_{triang}$ can then be used to calculate the final beam position and rotation.

$$beamPos_{triang} = \frac{markerPosLeft_{triang} + markerPosRight_{triang}}{2}$$

$$beamRot_{triang} = Quaternion.Lerp(markerRotLeft_{triang}, markerRotRight_{triang}, \frac{1}{2})$$

The "Quaternion.Lerp" command from Unity is used to calculate the mean of the two quaternions.

Testing has shown that this system does indeed work. But Vuforia only detects the markers correctly in a certain field of vision. So you have to keep your heads position and rotation at the correct angle and distance from the beam in order to recognize the corresponding marker. This feels fiddly and counterintuitive and therefore should not be used in the final user study.

3.4.2 Tracking with cuboid markers

Instead of adding only two markers to the beam, the maximum available space could be used with 6 markers covering each side of the beam. The previously used Vuforia system supports exactly this kind of application. The advantage here is that no manual offset calculations need to be done from each marker to the centre of gravity of the beam, as Vuforia already manages this, and the need to send the position of the markers to the other participant is eliminated, as one person can track up to three sides at the same time and the information of the opposite face is no longer needed



Figure 3.9: Cuboid Marker

This tracking system was tested with a sample cube of 7cm x 7cm x 7cm. The results showed that the tracking is functioning as intended, but similar to the double-sided marker tracking, it is still quite difficult to find the right angle of view on the marker for Vuforia to successfully detect it.

The detection often fails and one has to concentrate permanently on keeping a perfect angle of view. However, this would distract too much from the actual task during the future user study. Therefore, this variant is unsuitable as well.

These two tracking options based on image markers made clear that dynamically moving objects cannot be tracked easily via Vuforia. This technique should preferably only be used for static objects.

3.4.3 Tracking with Cameras

Instead of using the HoloLens' internal cameras for beam detection, an external system can also be used. With Optitracks motion capturing system, multiple cameras track the position of passive reflective markers. By grouping several markers of this kind into a rigid body, the rotation of this object can also be captured.

The advantage of our approach compared to printed markers is that the HoloLens is not used to track the position of the beam and therefore the final participants do not have to worry about aiming at the markers at the right angle. On the other hand, Optitrack again arrives with its own relative coordinate system that needs to be mapped to the previously triangulated coordinate system. This mapping can again be done using printed markers and Vuforia. Knowing the position of the beam in the triangulated coordinate system and in Optitracks coordinate system, it is possible to calculate the offset and adjust the beam position and rotation accordingly.

On the beam itself 4 more markers are attached and the same triangulation system as for the main coordinate system is used to determine the beams position and rotation relative to the main coordinate system. After this triangulation for the beam is completed, the current position and rotation that comes from Optitrack is used as an offset, so that the triangulated beam position will be the new center point for future incoming Optitrack data.

Sending the beam's transformation data from Optitrack directly to the HoloLens is not possible due to the blocking of ports on the HoloLens. However, since MQTT streaming is possible, the outgoing data from Optitrack can be streamed to another computer using Optitracks system, which then sends it to the HoloLens via MQTT.

As the beam position and rotation data now has to be streamed through another Unity client and is independent from the HoloLens this client can also be used to store this data even when the participants are not wearing the HoloLens. This allows for direct comparison of the way the beam was lifted in the final user study.

The additional usage of two more computers increases the previously described MQTT network (chapter 3.3.2). Optitrack itself uses the transmission control protocol (TCP) to broadcast the position and rotation of the beam to the Unity streamer client.

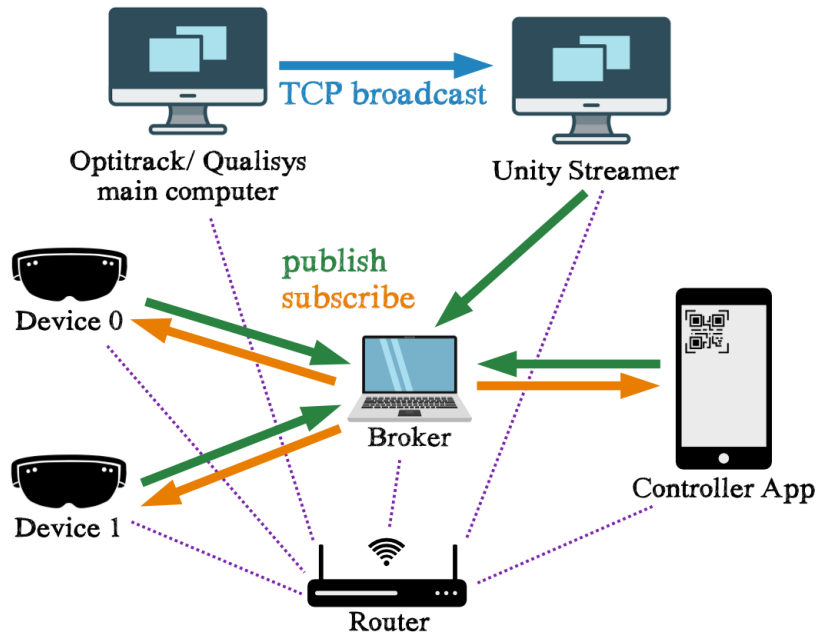


Figure 3.10: MQTT advanced network architecture⁶

The HoloLens itself can then perform the necessary calculations to determine the beam transform in its triangulated main coordinate system.

$$beamPos_{triang} = p_{triang} - beamPos_{marker} - optitrackPos_{initialOffset} + optitrackPos_{actualData}$$

This calculation is obligatory every time the HoloLens receives new data from Optitrack. But this can be made easier by using Unity’s hierarchy.

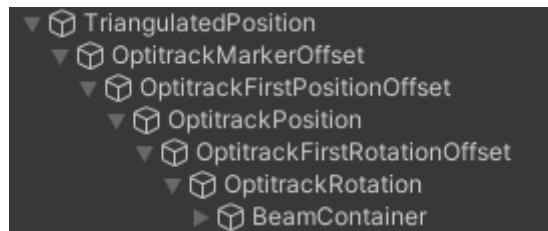


Figure 3.11: Unity beam offset adjustment hierarchy

“Unity uses the concept of parent-child hierarchies, or parenting, to group GameObjects. An object can contain other GameObjects that inherit its properties. You can link GameObjects together to help move, scale, or transform a collection of GameObjects. When you move the top-level object, or parent GameObject, you also move all child GameObjects” [21b].

⁶<https://static.thenounproject.com/png/816211-200.png>,
<https://static.vecteezy.com/ti/gratis-vektor/p1/636084-laptop-symbol-auf-weissem-hintergrund-vektor.jpg>,
<https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcS6YAhg5OdUmh1-57-jYwhxSSPIPxzq2tTbmAusqp=CAU>

The highest parent object here is the triangulated position. This means that all lower-level objects will have their central position at the triangulated position. Unity uses local and global positions and rotations. Changing the global position sets the object to these coordinates in the Unity global coordinate system, despite any offsets of parent objects. Local, on the other hand, only sets the current transformation of the object at its place in the hierarchy.

By first defining the `TriangulatedPosition`, the `MarkerOffset` and the `OptitrackFirstPositionOffsets`, the actual Optitrack data can be applied later as local positions and rotations. This parent-child chaining ensures that the `beamContainer` object is always set to the center of the beam relative to the triangulated coordinate system. Each content that should now be displayed next to the beam can simply be added as a child of the `beamContainer` object.

It is also important to note that the shift of position must take place before the rotation is set. The rotation of the motion capturing cameras describes the rotation around the center of the beam. Therefore, the position shift must be performed first so that the rotation will only rotate the beam around its center of gravity. If the rotation were performed first, the beam would rotate around the axis of the triangulated position rather than around the center of the beam.

3.5 Poor Posture Detection

Another major part of this project is to prevent poor posture of participants and therefore possible muscular fatigues. The task on itself is mainly a lifting task. The main poor posture that can occur in such a scenario is the lifting of the beam without being in a squatting position.

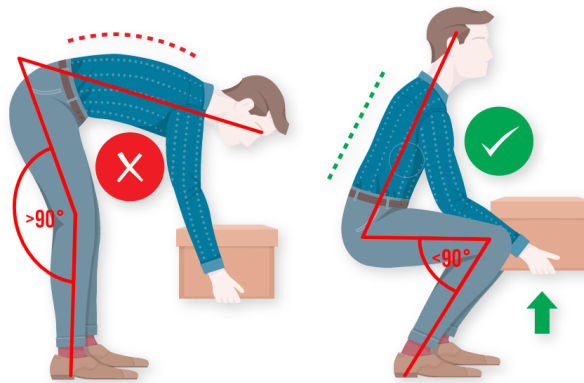


Figure 3.12: Poor Posture⁷

In order to prevent participants from this unwanted position the occurrence of this bad posture must be detected. Multiple system can be used here again:

⁷<https://www.arthritis-advisor.com/exercise-prevention/how-to-improve-posture>

3.5.1 Xsens - Inertial Measurement Units (IMU's)

By attaching multiple Xsens⁸ IMU sensors to a participants body the whole body can be tracked. During the lift, the knee bending can then be checked to see if the angle is less than 90°. If so, the participant is in a good lifting posture. If not, a warning tone raises awareness about this problematic posture.

3.5.2 Hip tracking

Since only the occurrence of poor posture shall be detected, tracking the entire body as Xsens is not actually necessary. By only tracking the participants' hips with straps to which the Optitrack markers are attached, the hip height is known throughout the experiment. Once the experiment is started, the current hip height can be stored, and as soon as the beam is raised slightly, the current hip height can be compared to the original one. If the current hip height is lower than the original by a certain factor, the participant lifts the beam in a squat position. If this is not the case, the participant is in poor posture and a warning sound is played to alert the participant that they need to adjust their posture.

This detection of poor posture is carried out by the Unity client that receives the Optitrack data and streams the beam position to the HoloLens devices. To reduce the network utilisation the Unity client only emits a MQTT message to the HoloLens's to play the warning sound once for each experiment if poor posture was actually detected.

⁸<https://www.xsens.com/>

3.6 Optimal Trajectory

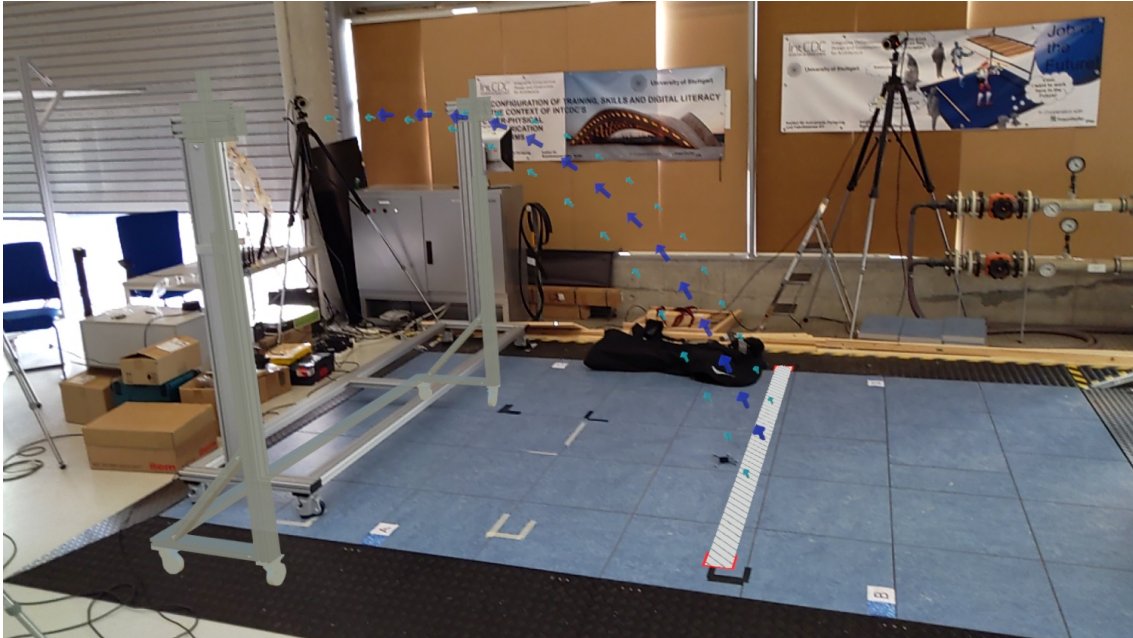


Figure 3.13: Example trajectory

This image shows an example trajectory. Note that the virtual rack is not displayed in the final user study, as it does not provide participants with any further information that would not have been available before.

The whole movement of the beam can be divided into three different sections:

- 1 : The lifting of the beam from the ground
- 2 : The movement towards the rack
- 3 : The lifting of the beam above the users heads onto the rack

To reduce muscle strain, the lifts should be performed as quickly as possible. The second movement phase therefore takes the most time out of the three. The beam must be carried in such a way that it is easy for the participants and does not require much muscular effort. In this case that requires a position where both arms are fully extended.

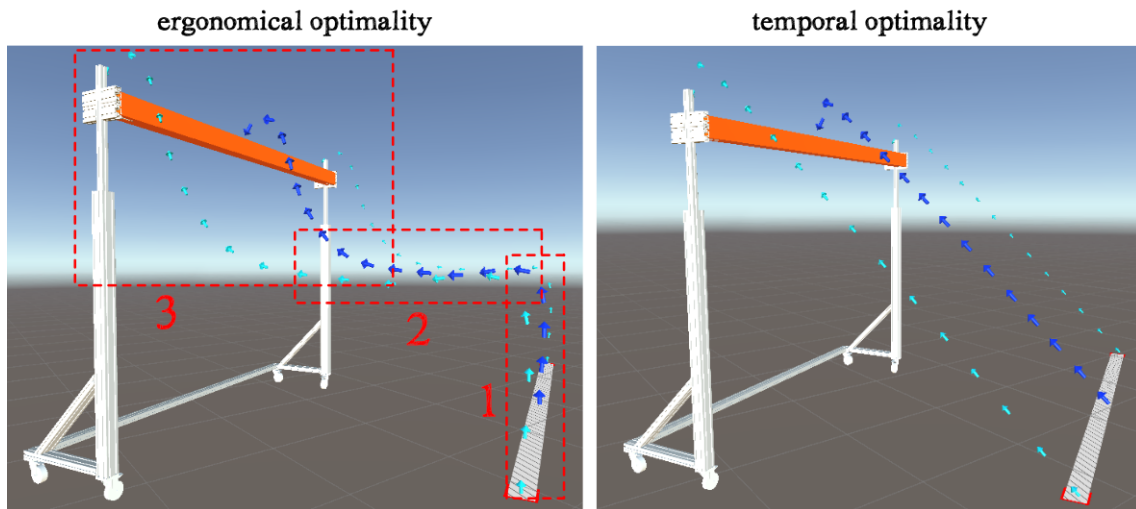


Figure 3.14: Optimal trajectory in terms of ergonomics and time

This picture shows the theoretical optimal path for the participants in terms of ergonomics and time. The ergonomically optimal path contains the three previously described path sections.

Since the time-optimal path requires that the path itself to be as short as possible, it is linear. The previously described three path sections also can't be distinguished with this trajectory.

As the ergonomic aspect of the participant is valued higher than the actual time efficiency of the experiment, the left path is further used in this project. Because constantly moving sideways and lifting the beam would put more strain on the body of the participants.

The trajectory also shows how the beam must be lifted onto the rack. The beam itself has a slot on each side and the rack has the corresponding counterpart. In this way, the beam can only be inserted to the rack by moving it downwards.

3.7 Tools

3.7.1 Marker Design

The whole project is based on several markers that need to be recognised by Vuforia. To make the marker scanning and tracking process easier and faster, it is important to have good markers. Vuforia itself has a rating system for markers between 0 and 5 stars. “The higher the augmentable rating of an image target, the stronger the detection and tracking ability it contains. A rating of zero indicates that a target is not tracked at all by the AR system, whereas a star rating of 5 indicates that an image is easily tracked by the AR system” [21a].

Vuforia uses features for the image recognition. Features can be described as a “sharp, spiked, chiseled detail in the image” [21a]. In order to be rated with a higher rank, the marker image should contain more features. It is also worth mentioning, that those features should not be repetitive in any pattern.

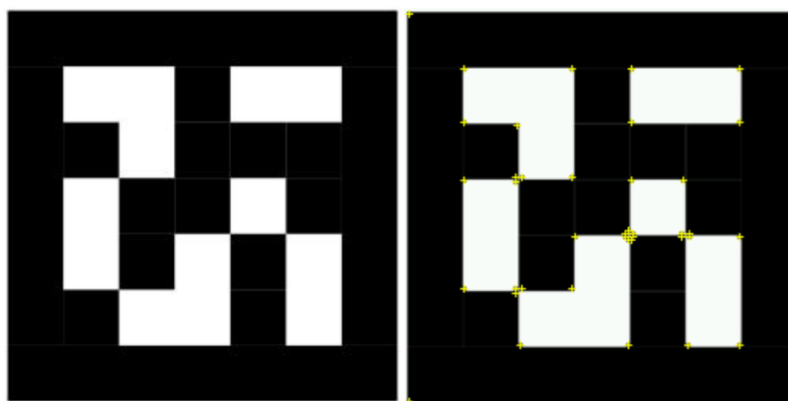


Figure 3.15: Old marker design

The small yellow crosses in the image on the right indicate these features that Vuforia uses for the recognition process.

The old used marker design is based upon various other designs that are often used in image recognition processes. But apparently those designs were only rated with 3 stars by Vuforia. And the actual scanning process with these markers on the HoloLens were also noticeably difficult.

Since the previous markers were still created manually and several were needed for the project, it was clear that the manual process would be too time-consuming due to the requirements of Vuforia to have several reference points. Therefore we developed a tool that generates better markers based on the marker design of Dario Mazzanti, which are mostly rated with 5 stars by Vuforia [Maz].

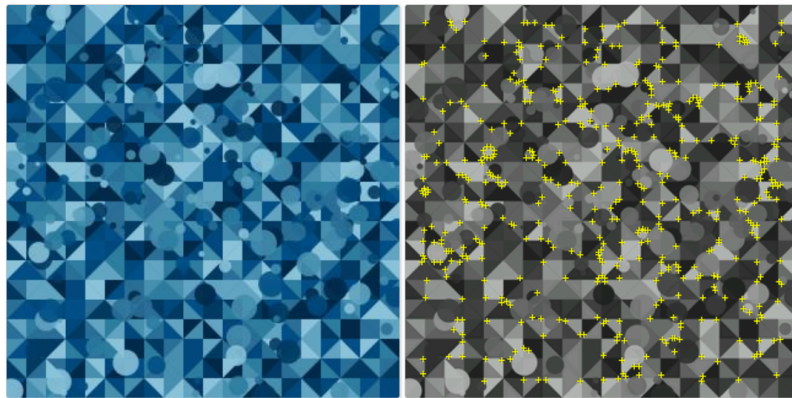


Figure 3.16: New marker design

Mazzantis marker design uses a repeating triangle pattern as a background with randomly generated circles over it, creating multiple random intersections that are perfect for Vuforia as a feature.

The written marker creator itself can be accessed at <https://legendsofmechatron.de/marker>. Do not be put off by the web page taking a few seconds to load. The server shuts down automatically if it has not been used for 30 minutes and must first boot up again.

Other features can also be adjusted when generating the images, such as the size of the marker, the number of rows and columns of triangles and the desired color palette.

If the provided four vanilla color palettes are not enough or other things shall be customized, the code itself can also be found on GitHub⁹ <https://github.com/JayKay135/markerCreator>.

Mazzantis algorithm is written with Processing¹⁰, whereas our generator mentioned above is written with Node.js®.

⁹<https://github.com>

¹⁰<https://processing.org/de/>

4 User study design

The following describes how the implemented systems are used to display data in the interface design and how user studies were conducted to analyse the benefits of the visualizations.

4.1 Interface Design

Design choices and visualizations of information are based upon the chapter about information conveyance (chapter 2.2). The succeeding subsections describe the information displayed with AR for the previously outlined task.

4.1.1 Trajectory

The optimal trajectory (chapter 3.6) based on time and ergonomics was predefined and displays the optimal path of the beam being moved from its starting to its final position. It is displayed once the experiment is started.

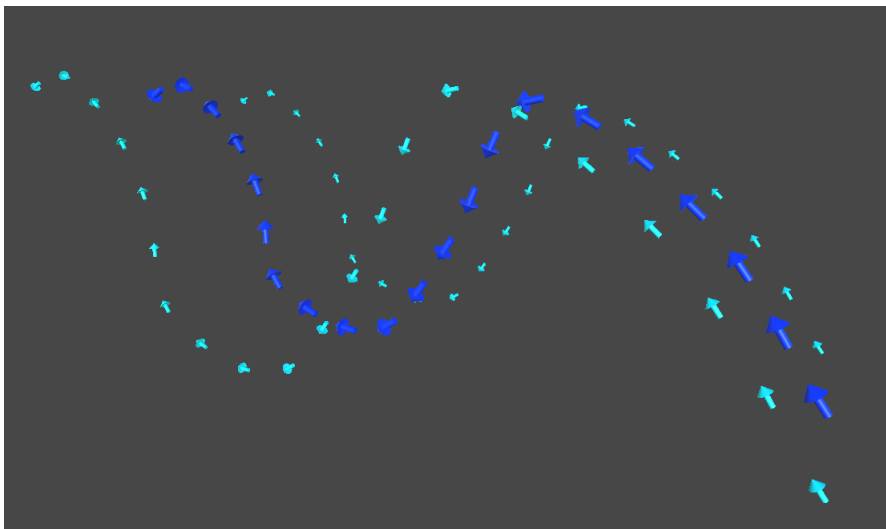


Figure 4.1: Unity trajectory arrows

Note that the above figure only shows an example trajectory and not the optimal (chapter 3.6) one used in the later user study.

The dark blue arrows indicate the centre of the beam, while the light blue arrows are shifted to the two ends of the beam to provide better guidance for the participants. Due to the narrow field of view of the HoloLens, participants likely won't be able to see the light blue arrows displayed at their beam side. Therefore the two other parallel trajectories can be used for the beam movement.

4.1.2 Beam movement force

The main part that participants are expected to perform is the actual movement of the beam. To help them doing this task more efficiently guidance arrows are displayed at the corresponding beam side where the participants are standing showing how to move the beam.

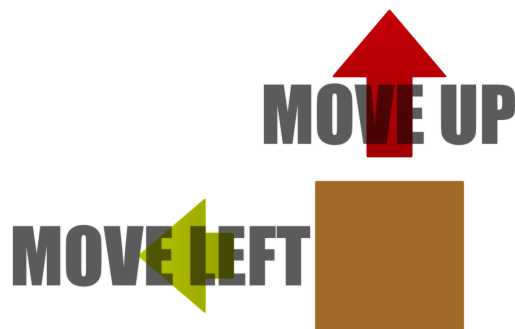


Figure 4.2: Unity movement force arrows

The movement strength is indicated by 4 arrows that specify whether the beam should be moved to the left, right, up or down. But only 2 can be seen at a time. The colors and the size of the arrows visualize the actual strength of movement in the respective direction.

The example above signifies that the beam should be moved strongly upwards and less strongly to the left. The cross on the beam indicates that the beam should be pushed slightly in the direction of the paper. If instead a point would be displayed at the same location, the beam shall be pulled out from the same axis.

These arrows always point to the nearest of all waypoints that make up the optimal trajectory. If the participants were to move the beam so that several waypoints of the optimal trajectory were skipped, these waypoints would automatically be removed and the arrows would again point to the nearest waypoint.

The arrows can be displayed either directly next to the side of the beam or as a static overlay. In the first case, the participant must look to the side of the beam to receive the information, while in the static version it is constantly available regardless of their viewing direction.

As a consequence to the previous chapter, the data displayed must be intuitive and easy to understand. To exclude possible misinterpretations a text is placed directly above the arrows explaining the interpretation of the arrows by displaying the corresponding action. These texts are only showed in the first 5 seconds after the start of the experiment.

4.1.3 Final Position Highlighting

As the beam has to be placed into the rack from above, the final position of the beam may be occluded by the participants' viewing angle. Therefore, the final position is highlighted.

The highlighted final position in the rack has the same shape and size as the real beam, so participants should intuitively understand the idea behind the projection, that the beam should be moved into the position of the virtual beam.

4.2 Main Experiment

This first user study aims to find out how the different types of movement arrows improve the behaviour of the participants. And if the detection of bad posture and informing participants of them leads them to adjust their movement in future runs.

4.2.1 Scenario

The experiment will be conducted by two participants at the same time. Both will be wearing an exoskeleton. The task is the lifting of a wooden beam that's approximately 2.5m long into a provided rack that is roughly 1.5m above the ground. The beam must be placed into the frame from above. Therefore the participants have to work together on either side of the beam to perform this task.

After the start of the experiment, the position and the rotation of the beam that was tracked via Optitrack, as well as the time stamps at which a posture warning was issued, are stored.

The movement behaviour can be later compared to previous tests where the optimal trajectory for the movement was evaluated.

The participants have to repeat this process for different scenarios.

- Without the HoloLens
- With the HoloLens and movement arrows next to the beam
- With the HoloLens and static movement arrows

At the beginning of the test, we ask participants to fill out a demographic questionnaire and present them with the conditions they must agree to if they participate in the experiment. In addition, we give them a NASA TLX¹ questionnaire to answer after each round.

Ideally both participants do not know each other before they take part in the test to avoid advantages of already existing social interactions in their communication behaviour.

¹<https://humansystems.arc.nasa.gov/groups/tlx/>



Figure 4.3: Main user study setup

4.2.2 Study Design

The main idea of this study is to show if the AR technology improves the workflow of working with exoskeletons. Two user groups will be needed to compare both in their efficiency performing the provided task. One of them with and the other without the HoloLens. The group with the HoloLens will get additional information projected via AR.

The information consists out of:

- an arrow trajectory showing the optimal path to move the beam
- a non viewing occluded highlighting of the final position in the rack for easier recognition
- beam movement force arrows either displayed on the side of the beam or as a static overlay
- a warning information if bad posture was detected that could lead to muscle fatigues

At the end, a direct comparison can be made if the assistance of the HoloLens improved the task performance. The efficiency can be evaluated using the complete time taken to complete the task and comparing it with the results of the questionnaires.

4.2.3 Procedure

Each participant first fills out general consent forms and a questionnaire (see Appendix questionnaire A 6.1) on gender, age and previous experience with AR. After putting on the exoskeleton and HoloLens, they have to scan four markers placed in the room at precise positions on the floor to create the main triangulation coordinate system. This process is then repeated with additional 4 markers placed on the beam.

After these first initializing steps are completed, the lifting of the beam can be started.

Participants are given a trial run of the beam lift to help them understand what the user study is about and how to perform the task. During this trial run, the movement arrows are not displayed and the participants only see the arrows of the optimal trajectory. If they were to see the movement arrows already in the trial run, the later results with activated arrows would no longer be objective.

They start the first round with the HoloLens and the movement arrows next to the beam. The experiment itself is started wirelessly via the MQTT control app and each participant sees a 5-second countdown on the HoloLens. Once the beam has been lifted to its final destination, the HoloLens plays a success tone and participants can move the beam back to its original position and repeat the same process again. After the first round, they are given some time to complete the NASA TLX (see Appendix questionnaire B 6.2).

This process is now repeated with the HoloLens but with static movement arrows and once more without the HoloLens. In the last case, the start of the experiment has to be counted down manually.

During the experiment the participants are not allowed to verbally communicate with each other. The connection of both holding the beam should be sufficient to accomplish the task as a team.

4.2.4 Hypotheses

These are the hypotheses we aim to prove with an analysis of the data obtained from the above experiment:

- **H1** - In the trials with AR, the participants will perform the complete task in less time.
- **H2** - The participants will prefer using the setup with the AR assistance.

4.2.5 Study Results

Due to technical difficulties resulting from the changes in the motion camera system, the user study could not be conducted as planned. Therefore, the study design was reduced to a fit around an actual working environment in the following reduced experiment.

4.3 Reduced Experiment

This reduced user study aims to find out how the different types of movement arrows can assist the participants through a more complex trajectory without wearing exoskeletons.

4.3.1 Scenario

According to the main experiment, this experiment is also carried out by two participants at the same time. This time not with a wooden beam, but with a shorter, wider and lighter cardboard box. The cardboard box itself must be picked up from the floor, lifted over a chair, under an obstacle hanging from the ceiling and then placed on a table.

The participants take the course for different visualizations:

- Without movement arrows
- With beam-side movement arrows
- With static movement arrows

They wear the HoloLens during the whole experiment, and therefore see the optimal trajectory, the highlighted starting position on the floor as well as the final position highlight on the table.

The following image shows a setup very similar to the final setup for this study. However, the obstacle hanging from the ceiling and the chairs are in the wrong order, the waypoints defining the path of the trajectory are still visible, and the static as well as the beam-side movement arrows are both visible at the same time. But the start and end positions are correctly highlighted, as is the trajectory itself, and the reference markers for triangulating the starting position can be seen too on the table.

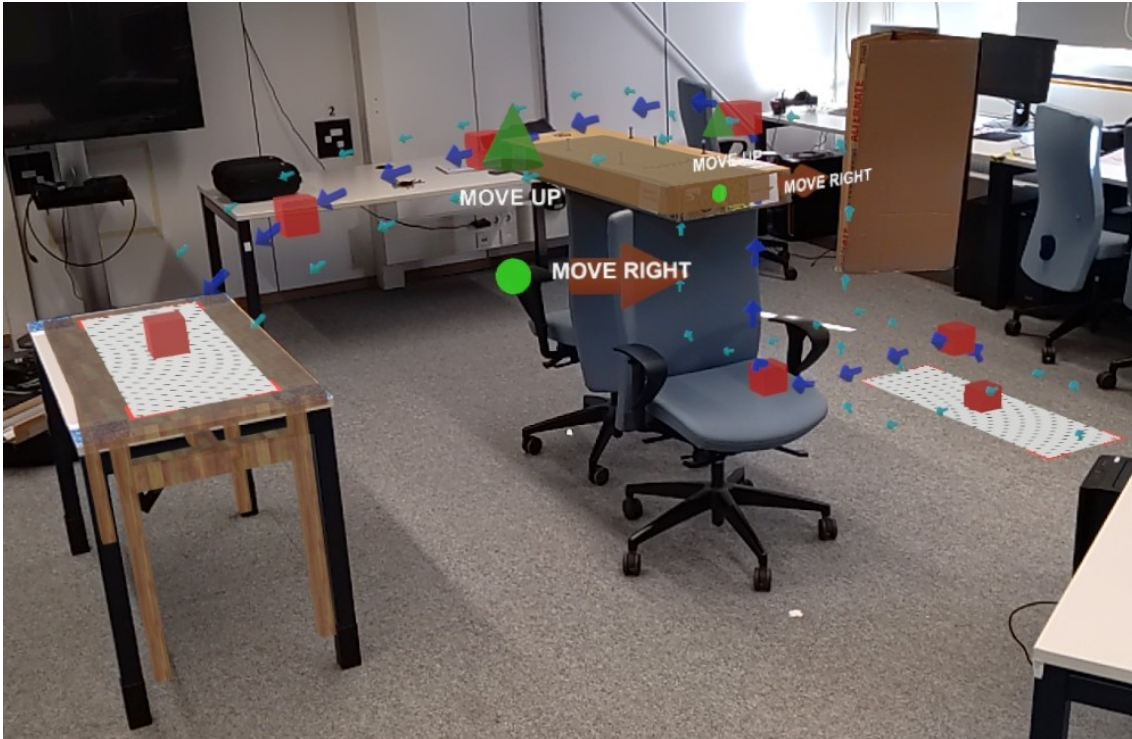


Figure 4.4: Reduced user study setup

4.3.2 Experiment Design

The idea of this study is to see if the motion guidance can be more beneficial if the trajectory is more complex and takes longer to follow. The results of the two movement arrow display types can be later compared to the iterations with no movement arrows.

4.3.3 Procedure

The participants will get a brief introduction of what the user study is about. Afterwards they have to fill out general consent forms and a questionnaire (see Appendix questionnaire C 6.3) on gender, age, previous experience with AR and their expectations of the task.

Next they will initialize the unity project by scanning the 8 markers like in the previously described user study. Then they perform the task twice without movement arrows, twice with beam-side movement arrows and twice with static movement arrows. After each new movement arrow type are asked to fill out another questionnaire (see Appendix questionnaire D 6.4) about their experience of the visualization and if it was beneficial for them.

4.3.4 Study Results

Four groups consisting of five men and three women participated in the user study. Their average age is 23 years and they rated their average AR experience before the study as 3.25, with 1 being the lowest and 5 the highest possible score.

Most of them expected the task to be simple and straightforward. One wondered why AR support was needed at all, and another saw the difficulty in performing the task without communication with the team partner.

Question	no movement arrows	beam side movement arrows	static movement arrows
The displayed information was easy to understand	5	4 ↓	4 ↓
I've used the displayed information to adjust my behaviour	4,167	4,75 ↑	4,25 ↑
AR helped me overall to perform the task	3,667	3,5 ↓	3,875 ↑
The cooperation with my partners was really easy and intuitive	5	4 ↓	4,375 ↓
The AR support increased my time efficiency of the task	3,833	2,75 ↓	3,25 ↓
The AR support helped me to move in a way that was beneficial for my posture	3	3,125 ↑	3

Figure 4.5: Questionnaire D results

The image above shows the average results of the user study after each iteration. The colored arrow visualizes whether the value of the beam side or static movement arrows increased or decreased compared to the iteration without movement arrows. It is clear to see, that the participants did not easily understand the two different types of movement arrows. However, it is interesting to notice that in these cases, the additional information of the movement arrows had a positive impact on the participants' behavior. Since information must first be understood before it can help to adjust someones behaviour, the other way around would have made more sense. Still it seems like participants tried to adjust their behaviour even without getting the idea behind the provided information. Besides that, the additional movement arrows slightly decreased team collaboration and overall time efficiency.

Speaking from the experience of conducting the user study, almost every team spent more time on the final two iterations than on the comparison benchmark run. The time taken for each iteration by the participants was not directly measured. However, it was clear that the additional information displayed made participants more curious to find out what it meant, and so the focus shifted from completing the task as quickly as possible to finding the clue behind the additional information.

After performing the task for the first time, participants mentioned that they liked the arrows for the trajectory and the highlighting of the final placement position on the table. Some also particularly liked the sound design. They criticized that they would have preferred fewer arrows and a more complex course with more obstacles. One person thought that the trajectory arrows should dynamically adjust to the current position of the box.

These initial impressions changed when participants performed the task again with beam side movement arrows. Most participants understood that the movement arrows meant that the box should be moved in the indicated direction, but they did not understand how this information was

correlated. Whether it was related to either the trajectory or the movement of the team partner. They also indicated that they now focused their attention mainly on the newly displayed data and not so much on the other projected information.

Participants were also curious why the movement arrows sometimes pointed backwards from the final position on the table. "I understood that the arrows indicate where to move the box, but I did not get why they sometimes point away from the target." This occurred mainly when the box was not moved exactly to the position of a waypoint. The waypoint was then not marked as reached, and if the box was now moved to the next waypoint, the movement arrows still pointed back to the old waypoint, since it was still closest to the box.

They also didn't like that the movement arrows sometimes changed quickly. Since the movement arrows always indicate movement to the next waypoint, when one is reached and thus marked as reached, the next closest waypoint is targeted. This can lead to quick jumps in the indicated movement arrow strength.

It is also worth noting that while most participants noticed that the arrow color indicated the movement strength, they did not see that the arrows also changed size accordingly.

As for the last iteration, not too much changed compared to the previous round. However, it was positively noted that the static overlay did not force the participants to constantly look at the beam side, but allowed a free field of view. "It was fun. You did see the arrows way better and therefore the task was easier to perform."

Overall the participants did not feel stressed at all by the task and enjoyed the process of exploring the meaning of the new displayed information.

One person stated that they felt the movement guidance itself would be more beneficial if the weight of the beam was increased, as participants would then be forced to actually carry the heavy box and focus on how they move it. By using a lightweight box, the guidance itself is not really necessary.

In summary, it can be said that the participants definitely noticed the provided movement clues and tried to adjust their behavior respectively. However, it is important to note that the data collected is not really meaningful, as only a small group of people participated. The results should rather be seen as general indications and should not be taken too seriously.

But to adapt to the given feedback for future work, a dynamic approach might be more suitable for the displayed trajectory, so that the arrows would always adjust to the current position of the box. This would also prevent the backward arrow scenarios. In line with the rapidly changing arrows, a smoothing animation between different strengths could also improve the visual appeal.

5 Challenges and Conclusion

Even though we faced many challenges with the initial project, and had to adapt it a lot over time, we were able to gather feedback from the users and draw some conclusions about it.

5.1 Challenges

The following subsections list the most severe challenges and how they were solved during the technical development of the thesis.

5.1.1 Decimal Separator

The established MQTT network transmits several types of information between the connected devices. Apart from strings, decimal values are mostly sent as part of vector3s or quaternions that describe the position or rotation of objects. The separator used to indicate the end of the number part and the beginning of the fraction part varies in different regions. In Germany, for example, the ","(comma) is used, while in the United Kingdom the "."(dot) is the defined separator [17].

If both HoloLens are not set to the same regional separator, the problem can arise that decimal values are way larger than they should be due to automatic conversion. This can be prevented by setting both devices to the same regional separator which secures that the interchanged data always has the correct format.

5.1.2 MQTT Messages arriving too often

The version of the MQTT library compatible with the .NET¹ framework unfortunately did not always work as expected. As explained in the section on the MQTT system (3.3), messages can be sent with three different quality levels. For important messages such as start/stop of the experiment or detection of poor posture errors, the highest quality level 2 was used. This should mean that the subscribed clients will only receive this message once.

However, due to inconsistencies in the library, it arrived several times over a period of about 10-20 seconds.

To ignore future messages and only respond to the first message, each message that had QoS 2 also added the current timestamp in milliseconds at which the message was sent. The receiving client would then hash the message based on the timestamp, topic and content and would try to find this

¹<https://dotnet.microsoft.com>

hash in a dictionary. If the hash was not available, the message had not yet been sent and the hash was added to the dictionary. If the hash was available, the message was already sent and simply ignored.

To prevent the dictionary from being flooded with hashes, the dictionary automatically deleted old entries when a threshold of 1000 hashes was reached.

This workaround made sure that important messages would only arrive once as expected.

5.1.3 MQTT Library runs in different Thread

The previously mentioned MQTT library runs in a different thread than the main Unity thread. This becomes problematic if, for example, elements of the Unity hierarchy are to be changed when an MQTT message has been received. Such changes can only be made from the main Unity thread. Therefore, a thread dispatcher was used to ensure that the necessary code sections are executed from the Unity main thread. This does cause a slight delay before the corresponding sections of code are executed, but it was essentially negligible.

5.1.4 Availability

Throughout the technical construction phase multiple system were tested and used. This happened mainly when the system no longer met the requirements or when it was simply no longer available.

Due to availability difficulties of technical systems, such as the previously tackled motion capturing system Optitrack², already functioning solutions had to be ported to a completely different system (Qualisys³).

The same happened with the initially used Xsens system, whereby this system was completely replaced by the hip tracking approach.

These changes increased the complexity of the project and unnecessarily required additional time.

5.1.5 HoloLens Blockage

Multiple tests have shown, that its not directly possible to stream data from either Xsens, Optitrack or Qualisys directly onto the HoloLens. The HoloLens' non-adjustable firewall blocks this data transfer. Therefore, the data always had to be sent to a separate Unity application first, which could then forward it to the HoloLens via the MQTT network.

²<https://optitrack.com>

³<https://www.qualisys.com>

5.2 Conclusion and Outlook

5.2.1 Conclusion

The basic idea of this project intends to find out if AR can be beneficial in combination with exoskeletons. Due to the adjustment of the user study by the removal of the exoskeleton a direct answer can not be given. However, the motion guidance visualization tested showed some evidence that dynamic tasks, where exoskeleton assistance is used, could possibly benefit from AR support. People are able to adapt their behaviour in dynamic task with constantly changing information.

As stated in our goals, we showed in a reduced user study that participants adapted their own behavior to the provided motion guidance data. However, they did not manage to complete the task in less time and did not find the information displayed to be intuitively understandable overall. Due to the fact that the poor posture checker in the lifting phase of the beam was not used in the reduced study, a definitive answer to the intended goal of showing a reduction of such bad postures cannot yet be given. And since the focus of this project was on the combination of exoskeletons and AR, and the final user study was conducted without the use of the exoskeletons, further research is needed to achieve the set goals.

As this project entirely focused on a specific task in the field of fabrication, the gathered results are only representative for this specific use case. In addition, as the used exoskeletons are only passive upper limb exoskeletons the field of usage was already limited to tasks above the participants hip. For these reasons, there are many more possible scenarios where AR could add value in collaboration with exoskeletons that are worth of more investigation.

AR for the exoskeleton should be seen as a tool to provide useful information to the user. It depends entirely on the type of information and how the information is presented to be beneficial. Additional equipment, such as those used in this study, may be needed to collect this information.

5.2.2 Outlook

We believe there is a wide field of possibilities for future work. AR could be used to display real-time information about the environment for example in showing the shortest path of movement to another destination. Or the visualization of objects that would normally be occluded.

Since the HoloLens used as AR devices for this project has its own central processing unit (CPU) and is thus independent of a main server, projects with multiple people performing tasks and sending their status to others similar to swarm behaviour could be interesting for future investigation. It could also be used for instance for house construction to display work steps. The manner of execution could then be directly displayed and any error in performing the task directly reported. Moreover, if all work processes were stored digitally the processes could be carried out simultaneously by several people.

In summary, this project has shown that AR motion guidance adds value to dynamic tasks, but it definitely indicates that future work is needed to reveal the potential in combination with exoskeletons.

5.2.3 Acknowledgments

I would really like to thank my supervisors Aimee Sousa Calepso and Nelson Enrique Bances Purizaca for their generous support throughout my thesis.

Providing me with the necessary equipment, their time and expertise.

Bibliography

- [17] *Number Formatting*. 2017. URL: <https://docs.microsoft.com/en-us/globalization/locale/number-formatting@online>. accessed: 21.09.2021 (cit. on p. 45).
- [20] *MQTT: The Standard for IoT Messaging*. 2020. URL: <https://mqtt.org>. accessed: 02.08.2021 (cit. on p. 18).
- [21a] *Best Practices for Designing and Developing Image-Based Targets*. 2021. URL: <https://library.vuforia.com/features/images/image-targets/best-practices-for-designing-and-developing-image-based-targets.html>. accessed: 08.08.2021 (cit. on p. 33).
- [21b] *The Hierarchy window*. 2021. URL: <https://docs.unity3d.com/Manual/Hierarchy.html>. accessed: 25.09.2021 (cit. on p. 28).
- [Anj17] K. M.-P. Anja Crößmann Lisa Günther. “Qualität der Arbeit - Geld verdienen und was sonst noch zählt 2017”. In: (2017). URL: <https://www.destatis.de/DE/Themen/Arbeit/Arbeitsmarkt/Erwerbstaetigkeit/Publikationen/Downloads-Erwerbstaetigkeit/broschuere-qualitaet-arbeit-0010015179004.pdf>. accessed: 01.10.2021 (cit. on p. 9).
- [Cla] V. Claypoole. *Maintaining attention in AR*. URL: <https://uxdesign.cc/attention-attention-fe7f3e2e45d5>. accessed: 14.06.2021 (cit. on p. 13).
- [Dav12] T. Davidson. *Chamber’s twentieth century dictionary of the english language*. 2012. URL: <http://eremita.di.uminho.pt/gutenberg/3/8/5/3/38538/38538-h/38538-h.htm>. accessed: 20.10.2021 (cit. on p. 11).
- [Eks] EksoBionics. *The leader in exoskeleton technologie*. URL: <https://eksobionics.com>. accessed: 30.04.2021 (cit. on p. 12).
- [Fut] T. M. Futurist. *Augmented Reality in healthcare will be revolutionary*. URL: <https://medicalfuturist.com/augmented-reality-in-healthcare-will-be-revolutionary/>. accessed: 01.05.2021 (cit. on p. 12).
- [Gor09] A. Gorlick. *Media multitaskers pay mental price, Stanford study shows*. 2009. URL: <https://news.stanford.edu/2009/08/24/multitask-research-study-082409/>. accessed: 12.05.2021 (cit. on p. 13).
- [J10] S. S. J. *Cognition, Evolution and Behaviour*. 2nd. New York: Oxford, 2010 (cit. on p. 14).
- [Kle06] G. Klein. “Visual tracking for augmented reality”. In: (2006). URL: <https://www.robots.ox.ac.uk/~gk/publications/Klein2006Thesis.pdf>. 26.10.2021 (cit. on p. 11).
- [Loc] LockheedMartin. *Exoskeleton Technologies: Military*. URL: <https://www.lockheedmartin.com/en-us/products/exoskeleton-technologies/military.html>. accessed: 01.05.2021 (cit. on p. 12).

Bibliography

- [Mar] B. Marinov. *What is an exoskeleton?* URL: <https://exoskeletonreport.com/what-is-an-exoskeleton/>. accessed: 12.05.2021 (cit. on p. 11).
- [Maz] D. Mazzanti. *AR Image Target Generation (Vuforia)*. URL: <http://www.dariomazzanti.com/uncategorized/ar-image-target-generation-vuforia/>. accessed: 08.08.2021 (cit. on p. 33).
- [OAAM] M. Omar, F. Alnajjar, B. Alsinglawi, A. Marmud A. *Exoskeletons with Virtual Reality, Augmented Reality, and Gamification for Stroke Patients' Rehabilitation*. URL: https://rehab.jmir.org/2019/2/e12010?utm_source=TrendMD&utm_medium=cpc&utm_campaign=JMIR_TrendMD_0. accessed: 30.04.2021 (cit. on p. 12).
- [RAAR15] Rauschnabel, P. A., B. Alexander, Y. K. Ro. "Augmented Reality Smart Glasses: Definition, Conceptual Insights, and Managerial Importance". In: (2015). URL: https://www.researchgate.net/profile/Alexander-Brem-2/publication/279942768_Augmented_Reality_Smart_Glasses_Definition_Conceptual_Insights_and_Managerial_Importance/links/5721ec2e08aee857c3b5dd6c/Augmented-Reality-Smart-Glasses-Definition-Conceptual-Insights-and-Managerial-Importance.pdf. accessed: 12.05.2021 (cit. on p. 12).
- [RBB11] S. Rasul, Q. Bukhsh, S. Batool. "A study to analyze the effectiveness of audio visual aids in teaching learning process at university level". In: *Procedia - Social and Behavioral Sciences* 28 (2011). World Conference on Educational Technology Researches - 2011, pp. 78–81. ISSN: 1877-0428. DOI: <https://doi.org/10.1016/j.sbspro.2011.11.016>. URL: <https://www.sciencedirect.com/science/article/pii/S1877042811024554> (cit. on p. 14).
- [San] S. M. Sanchez. *How to attract the user's attention in an AR environment*. URL: <https://www.use.design/en/how-to-attract-the-users-attention-in-an-ar-environment/>. accessed: 14.06.2021 (cit. on p. 14).
- [SC03] J. E. R. Staddon, D. T. Cerutti. "Operant Conditioning". In: *Annual Review of Psychology* 54.1 (2003). PMID: 12415075, pp. 115–144. DOI: [10.1146/annurev.psych.54.101601.145124](https://doi.org/10.1146/annurev.psych.54.101601.145124). eprint: <https://doi.org/10.1146/annurev.psych.54.101601.145124>. URL: <https://doi.org/10.1146/annurev.psych.54.101601.145124> (cit. on p. 14).
- [Sch18] P. van der Schaft. *Exoskeleton strengthen in uses beyond healthcare*. 2018. URL: <https://www.roboticsbusinessreview.com/robo-dev/exoskeletons-uses-beyond-healthcare/>. accessed: 01.05.2021 (cit. on p. 12).
- [Sto17] S. M. Stone. *Observational Learning*. 2017. URL: <https://www.britannica.com/science/observational-learning>. accessed: 15.06.2021 (cit. on p. 14).
- [Sui] Suitx. *Phoenix medical exoskelton technologie*. URL: <https://www.suitx.com/phoenix-medical-exoskeleton>. accessed: 01.05.2021 (cit. on p. 12).
- [W90] J. W. *The principle of Psychology*. Henry Holt, 1890, pp. 403–404 (cit. on p. 13).
- [Yod] J. Yoders. *What is Augmented Reality, and how can it help Architects and Contractors*. URL: <https://redshift.autodesk.com/what-is-augmented-reality/>. accessed: 01.05.2021 (cit. on p. 12).

6 Appendix

6.1 Questionnaire A

Augmented Reality as a supporting tool for exoskeletons In fabrication tasks user study

Please answer the following questions accurately

What is your age?

Which gender do you identify with?

Female Male Diverse

What is your experience with augmented reality?

Low 1 2 3 4 5 High

Do not fill in this part

Beam Position Left Right

Id

6.2 Questionnaire B

Augmented Reality as a supporting tool for exoskeletons In fabrication tasks user study

Answer according to your experience with the task you have just performed

Mental Demand

How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?

Low 1 2 3 4 5 High

Physical Demand

How much physical activity was required? Was the task easy or demanding, slack or strenuous?

Low 1 2 3 4 5 High

Temporal Demand

How much time pressure did you feel due to the pace at which the task or elements occurred? Was the pace slow or rapid?

Low 1 2 3 4 5 High

Performance

How successful were you in performing the task? How satisfied were you with your performance?

Low 1 2 3 4 5 High

Effort

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low 1 2 3 4 5 High

Frustration

How irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task?

Low 1 2 3 4 5 High

Additional Notes

Do not fill in this part

Display Type Beam Side Static Without HoloLens

Distance Short Long

Id

6.3 Questionnaire C

Augmented Reality as a supporting tool for exoskeletons In fabrication tasks user study

Please answer the following questions accurately

What is your age?

Which gender do you identify with?

Female Male Diverse

What is your experience with augmented reality?

Low 1 2 3 4 5 High

What are your expectations of the task?

Do not fill in this part

Beam Position Left Right

Id

6.4 Questionnaire D

Augmented Reality as a supporting tool for exoskeletons In fabrication tasks user study

Please answer the following questions accurately

The displayed information was easy to understand

1 2 3 4 5
Completely disagree Strongly Agree

I've used the displayed information to adjust my behaviour

1 2 3 4 5
Completely disagree Strongly Agree

Augmented reality (AR) helped me overall to perform the task

1 2 3 4 5
Completely disagree Strongly Agree

The cooperation with my partner was really easy and intuitive

1 2 3 4 5
Completely disagree Strongly Agree

The AR support increased my time efficiency of the task

1 2 3 4 5
Completely disagree Strongly Agree

The AR support helped me to move in a way that was beneficial
for my posture

1 2 3 4 5
Completely disagree Strongly Agree

What did you particular like/ find helpful?

What would you change?

Additional thoughts

Do not fill in this part

Display Type

None

Beam Side

Static

Id

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

Filderstadt, 08.11.2021

A handwritten signature in black ink that reads "Jan Wolberg". The signature is written in a cursive style with a large, prominent 'J' and 'W'.

place, date, signature