



Bachelor's Thesis

**Concept and development of a
human robot interface
using parametrised Augmented Reality**

**Konzept und Entwicklung einer
Mensch-Roboter Schnittstelle
mit parametrisierbarer Augmented Reality
(GERMAN)**

Author:	Eric Vollenweider
Supervisor:	Prof. Dr.-Ing. Birgit Vogel-Heuser
Advisor:	Dr. Pantförder Dorothea
Issue date:	Februar 26, 2019
Submission date:	August 26, 2019

Table of Contents

1	Introduction	1
1.1	Reasons for- and challenges with Human-Robot collaboration	1
1.2	Parametrised development to solve AR-development challenges	2
2	State of the Art	5
2.1	Augmented Reality and its standardisations	5
2.2	AR in Robotic applications	6
2.2.1	AR during development and testing	6
2.2.2	Operating robotic systems with AR support	7
2.3	Parametrised Development	8
2.4	Current methods programming industrial robots	9
2.5	Combining Technologies to mitigate AR Development Challenges	10
3	Concept	11
3.1	Goal, Requirements and Use Cases	11
3.1.1	Requirements	11
3.1.2	Use-Case example: Factory Maintenance	13
3.2	PARRHI Concept	14
3.2.1	Preparation of Parameters	18
3.2.2	Parametrised Program	19
3.2.2.1	Variables	20
3.2.2.2	Points	20
3.2.2.3	Holograms	22
3.2.2.4	Events	23
3.2.2.5	Program example	26
3.2.3	Core Routine	26
3.2.4	I/O Modules	27
4	Implementation	29
4.1	PARRHI Hardware	29
4.2	PARRHI Software	30

4.3	PARRHI Library	30
4.3.1	Parametrised Program objects	32
4.3.2	Importing and interpretation of the Parametrised Program	36
4.3.3	CR-i7A Forward Kinematics	36
4.4	Unity	38
4.4.1	Image Tracking	38
4.4.2	AR-Toolkit	39
4.5	Robot Library	39
4.5.1	Robot Communication Architecture	39
4.5.2	Robot Communication KAREL Host	41
4.5.3	Robot Communication TP Program	42
4.5.4	Robot Motion Group Management	43
4.5.5	Robot Communication Outcome	44
4.6	Parametrised Program Implementation and Validation	45
4.6.1	Parametrised Program XML Structure	45
4.6.2	XSD generation and validation	47
5	Evaluation	49
5.1	Evaluation 1: Comparing PARRHI with traditional methods	49
5.1.1	Evaluation 1: Use Case Definition	49
5.1.2	Evaluation Manual Attempt	50
5.1.3	Evaluation PARRHI Attempt	51
5.1.4	Conclusion Evaluation 1	51
5.2	Evaluation 2: New Developers	52
5.2.1	Evaluation 2: Use Case Definition	52
5.2.2	Summary Evaluation 2	53
6	Conclusion	55
6.1	Summary	55
6.2	Solution to Problems found in Evaluation	56
6.2.1	Solution to Problem 1: Overview and Program Complexity	56
6.2.2	Solution to Problem 2: PARRHI's Limitations	57
6.3	Technology Transfer	58
6.3.1	Replacing the Target Machine	58
6.3.2	Replacing the AR / 3D Engine	59
6.3.3	Replacing AR Device	60
6.4	Future Work - A generalised Concept	60
7	Bibliography	63

1 Introduction

1.1 Reasons for- and challenges with Human-Robot collaboration

Today's world is highly automated in each and every aspect of our lives. One of the most important advancements within the last 30 years were robots. They allow us to minimize costs, while maximizing output, quality and efficiency. With the rising need of agile production plants, non-collaborative classic robotic systems do not seem to fulfil all requirements any-more, since they lack the ability to cooperate with humans on the required level. This collaboration is essential to combine the agility and intelligence of humans, with the speed, precision and strength of robots. Current industrial robots' main strength is not to adapt quickly to changing environments. In contrast, the human's strength always was exactly that - to learn quickly. This is one of many reasons why Human-Robot (HR) collaboration is an inevitable step towards the future of robotics.

Robotics needed to adapt to the new situation, where humans and robots share a perimeter, thus compliant robots were developed. It is not enough to be compliant and not hurt humans for machines to feel natural. As Gary Klein et al. stated, communicating intent is a key issue in effective collaboration within teams [1].

This crucial component (communication with robotic systems) can be supported by Augmented Reality (AR). With rapid advancements in the field of robotics during the last few years [2], innovative ways to program, develop and operate these highly complex systems need to be researched. Also the field of AR has been heavily worked on for the last 20 years, but the combination of AR and robotics has mostly remained untouched. Lately though, it has become a new focus area in research. While it is known that AR can improve communication in certain use cases [3], actually developing them is not as easy, since there is a big variety of challenges to solve. From 3D modelling to image tracking, performance and more. Since most development environments rely on source code to be written, the reusability is quite low, which may result in re-doing the same steps over and over again, requiring software

engineers along the way to do everything. Thus, the time-to-market is long and expenses are high.

According to the U.S. Department of Labour, there is a massive hunt for talent in the software industry [4]. The department reported an expected growth of job employment in this industry of over 30% within the next 10 years. One possible reason for the lack of talent could be, that acquiring the necessary skills to develop software applications takes a long time and is not viewed as an easy path. The lack of programming talent is also seen in the robotics industry, which requires its developers to possess an even wider set of skills, including software development, mechanical and the basics of electrical engineering. Due to the scarcity of developers the speed of innovation and time-to-market may either be slowed down or the companies will have to pay about 20% above market value for their employees [5].

Furthermore, employees that might become responsible for developing such AR apps, might be professionals in their field (e.g. factory logistics), but do not know how to develop AR applications. This domain interdisciplinarity further contributes to the challenge of finding employees to reach one's AR specific goals.

1.2 Parametrised development to solve AR-development challenges

In conclusion, AR applications can play a crucial role in effective collaboration between humans and robots. Unfortunately, it is not easy to find employees, who have the domain specific knowledge required for the task and are capable of developing AR applications. If non-programmers could setup, configure and thus develop Human-Robot interfaces, involving AR and robot controlling all by themselves, without the need to write a single line of source code, the cost efficiency and speed of innovation can be improved.

Today, many industries use a strategy called *parametrised development* (see 2.3), which has many great advantages. Amongst them are, that changes can be made relatively easy, since only the input parameters have to be updated and one can also create easy to use application interfaces, which generate these parameters. Both mitigate the challenges involved in AR application development, making it easier for more people to contribute.

This bachelor thesis aims to research the feasibility and practicability of such an abstract development environment, which helps to develop Augmented Reality interfaces for robotic applications without any knowledge about AR itself. First there will be a "State of the Art"

section, where current research and progress is displayed. From there some gaps will be identified, a concept proposed, implemented and tested in a real application.

2 State of the Art

The State of the Art chapter will highlight technologies and products, which contributed to this field of research. First, Augmented Reality itself will be explained and some basics will be laid out, which is followed by a paragraph about current AR-Standardisations, which is important since they help developers to speed up their processes because many decisions do not have to be made repeatedly. Later, the combined field of AR and Robotics will be described in detail. How it can use Augmented Reality technology, which projects succeeded in doing so and what benefits it brought. A part about parametrised thinking and other disciplines that already work as such, represents the last component of this chapter. A final remark describes how this thesis tries to combine all explained technologies or principles into an innovative way of programming AR applications.

2.1 Augmented Reality and its standardisations

This bachelor's thesis evolves around AR and its use cases. It is important to clearly define some terms before using them thoroughly. AR technology must not be confused with Virtual Reality (VR). Whereas VR completely immerses users, AR still allows the real world to be seen together with superimposed 3D objects projected into the user's view. T. Azuma crafted a very general definition of AR-Systems very early on [6]. He wrote that, in order for a system to be classified as an AR system, it has to fulfil three characteristics: The system has to combine real and virtual objects, be interactive in real time and spatially map physical and virtual objects to each other. The term Augmented Reality is often used as a synonym for the also commonly used expression "Mixed Reality".

There are different underlying principles in AR technology. Two types of AR technologies are in use today. Firstly, there are see through displays with strong user immersion and secondly monitor based approaches like smartphones with cameras. A large variety of producers [7] release new AR-Devices regularly.

Standards often contribute to the development and usage of technologies substantially. Firstly by unifying used technology stacks, thus potentially reducing complexity and secondly by helping new members to navigate in a complex environment. There are not many international standards on AR since the field's popularity still is very young. Nevertheless, C. Perey et al. [8] examined existing standards and some best-practice methods for AR and identified some gaps in the AR value-chain, where, as they state, are interoperability problems between different components. Another conclusion was, that there are some existing standards from other domains that could be used for AR, but there is too little agreement on which ones to use. The researchers lay out numerous standards for low level implementations such as geo-graphic location tracking, image tracking, network data transmission etc.

Figuerola et al. [9] researched about a "Conceptual Model and Specification Language for Mixed Reality Interface Components". They want to lay a foundation for other developers to standardize 3D interface assets, for others to build upon. The team developed an xml based data structure called "3DIC" that defines the look and some smaller behaviour actions of UI control elements. Although their work features useful components, it lacks certain features that robot-human AR interfaces need, and contains unwanted components like pseudo-code. "3DIC" cannot be fully processed automatically, since pseudo-code is not executable.

Concluding from this general overview about AR technology, there does not seem to be an existing standard for HR Interfaces utilizing parametrised Augmented Reality, that allow the development of complete HR-AR-applications that can be automatically processed, executed and used.

2.2 AR in Robotic applications

2.2.1 AR during development and testing

Wolfgang Hönig et al. examined three different use cases of Augmented Reality [10]. The research team primarily focused on the benefits offered by the co-existence of virtual and real objects during the development and testing phase. They documented three individual projects where the implementation of AR as a main feature resulted in lowered safety risks, simplified debugging and the possibility of easily modifying the actual, physical setup.

Another important dimension of development and testing is of financial nature: upfront investments and operating costs. For example, robotic aerial swarms tend to be quite expensive due to the high cost of drones. Hönig et al. successfully scaled up the number of

objects in their swarms without adding physical hardware, thus, saving money and space [10]. However, it is stated that this approach might not be applicable to all experiments since simulations are never perfect replicas of actual systems. This small delta in physical behaviour might be enough to raise doubts regarding the correctness of the experiment results.

For human robot cooperation, behaviour induced doubts would cause great issues in the perception of the visual augmentations. Misplacing a warning hologram for example, could really harm humans near by. According to Hönig and his colleagues, one has to put extra emphasis on this aspect.

All projects by Hönig et al. focus on isolating certain aspects of the system to analyse and test them more flexibly, cheaply or with improved safety for all participants involved (humans and machines). Similarly, Chen et al. have created a software framework for simulating certain parts of robotic systems [11]. These researchers worked on methods to combine real world and simulated sensor data and navigate a real-world robot in the combined environment. Their approach was to intercept the raw sensor data originating from the real robot, and mixing it with the simulated data, before publishing it to the clients.

For the to be built AR-Human Robot Interface system, this approach could not only be used to combine the simulated virtual world and the real world data and then use it for the system's logic components, but also to fully simulate the robot during the development of the system.

2.2.2 Operating robotic systems with AR support

A well-known bottleneck in robotics is the controlling of and thus, the communication with robots [12]. In all previously cited cases, Augmented Reality was not used to enhance the interaction between humans and robots but to mitigate the current challenges in developing robotic systems. Early work by Milgram et al. [13] shows that even the most basic implementations of AR technology, with the objective to improve the information exchange, enhance the bidirectional communication in multiple ways. The team proposed means to relieve human operators by releasing them from the direct control loop and using virtually placed objects as controlling input parameters. This replaces direct control with a more general command process.

As Gary Klein et al. stated, communicating intent is a key issue in effective collaboration within teams [1]. Whenever robots and humans collaborate in a close manner, it is critically important to know each other's plans or strategies in order to align and coordinate joint

actions. For machines lacking anthropomorphic and zoomorphic features, such as aerial and industrial robots, it is unclear how to communicate the before-mentioned information in natural ways.

In order to solve this problem, Walker et al. [14] explored numerous methods to utilize Augmented Reality to improve both efficiency and acceptance of robot-human collaborations via conveying the robot's intent. The group of researchers defined four methods of doing so, with varying importance being put on "information conveyed, information precision, generalizability and possibility for distraction" [14]. The conclusion was that spatial Augmented Reality holograms are received much more intuitively than simple 2D projected interfaces.

For the to be built system this means, that there have to be tools in place for the developer, to explicitly communicate the robot's intent to the operator.

2.3 Parametrised Development

Numerous disciplines utilize parametrised development environments heavily. For example the CAD software *CADENCE* (integrated electrical circuits) offers parametrised cells to optimize the development process [15]. Users can place these cells and adjust certain parameters. For example spiral inductors can be configured via a simple UI that sets the parameters in the background. Aspects like outer dimensions, metal width, number of layers etc. can be set. The software then calculates its properties and behaviour at runtime. Generally there is no coding skill required.

In architecture Parametric Design is taking overhand since the late 2000s. New capabilities in computer rendering and modelling opened up a whole new world for architects at the time. Using parametrised mathematical formulas with boundary constraints allows architects to generate building structures easier and more efficient [16]. Adapting to a changing environment during the design process is much easier, since a substantial portion of work can be completed by algorithms and software applications. Additionally the reusability of components increases massively due to the very formal way of representation. Architecture studios also begin to include Virtual and Augmented Reality technologies actively in their design processes to further incorporate and better understand these new design styles called *Parametric Design* [17]–[19].

2.4 Current methods programming industrial robots

To understand where and how the content of this research project fits into the world of robotics, this chapter will describe the current workflows with robots, how they are configured and programmed. It is important to know that almost all industrial robots are programmed in three distinct ways.

- 1.) Teaching Pendant
- 2.) Simulation / Offline Programming
- 3.) Teaching by Demonstration

According to the British Automation & Robot Association over 90% of all industrial robots are programmed using the Teach Pendant (TP) method [20]. These devices basically are touch-tablets fitted for industrial use with emergency stop buttons, more durable materials and so forth. They allow the operator to jog (term for steering the robot manually using the TP) the robot into certain positions and offer a number of other possibilities. For easier tasks some manufacturers (e.g. Fanuc) offer specific User Interfaces where the operator simply enters parameters and positions. More complex goals can also be achieved with the Teach Pendant by programming in a textual manner, using each manufacturer's own language. This type of programming needs a substantial amount of training and can generally not be done by untrained people.

Teach Pendants are great for trivial and simple tasks, that do not require lots of collaboration between factory components. Reprogramming the robot using this method leads to a partial downtime, since the actual real robot has to be used. Important to note is, that parametrised programming already is an industry standard in industrial robotics for some brands of robots.

Offline programming is most often used for more complex tasks and production lines. While Offline Programming is very precise and powerful, it does require a substantial amount of schooling time for the operator. Teaching by Demonstration on the other hand is the exact opposite. Most people could succeed quickly, but the complexity of achievable tasks and the precision is limited.

The planned Augmented Reality Robot Human Interface could be attributed to the Offline Programming category, but also interacts with the Teach Pendant mode, since the operator should be able to take over control of the robot when necessary.

2.5 Combining Technologies to mitigate AR Development Challenges

One can now take the mentioned technologies and principles from above, and combine them for an attempt to mitigate AR development challenges. The above sections of this chapter shortly describe each area of this research project's topic and analyse how and what could be used for this thesis.

Many industries adopted Augmented Reality in their daily process already. It's advantages and challenges are clearly known and being worked on. There are numerous examples of AR helping in different environments and tasks [21]–[23]. Developing AR applications is generally speaking still a very costly task. On the other hand there is the design principle of "Parametrisation", that may involve increased initial investment, but can lower the cost of changes and adaptations to changing environments. Combining the perks of both AR technology and parametrised architecture may bear great potential.

In conclusion, there has been work done on most aspects of this bachelor's thesis' topic, which is a parametrised Augmented Reality Robot Human Interface. Some discussed frameworks ('3DIC', [9]) allow the textual definition of AR interfaces, but lack the ability to control robotic hardware and contain unwanted components like pseudo code. The latter does not allow automatic interpreting, since pseudo code is not executable. Other projects showed the feasibility to combine simulated and real world data to control robotic systems, but had to be programmed and developed by professional software engineers. As far as my search showed, there are no systems to be found that allow a simple, text based and parametrised representation of AR interfaces, that are able to communicate with robots and allow reasonably complex applications to be built.

3 Concept

This chapter will explain what requirements were defined for the to be built system and how it will be designed and setup. At first, I will define a goal of this project before writing about the user and system requirements. Then an example Use-Case should help to further understand the goal and purpose of this project. For further reading the system will be called "Parametrised Augmented Reality Robot Human Interface" (*PARRHI*).

3.1 Goal, Requirements and Use Cases

As described in section 1.2 this thesis presents a possible approach to solve the previously described problems (see section 1.1), which were the difficulty of developing AR applications in the robotic industry due to interdisciplinary context. It is the main target of this research project to remove the necessity of high software engineering skills to develop reasonably complex Augmented Reality Robot Human Interface applications, maintaining the quality of the outcome and even increasing the degree of resuability. This might result in lower development costs, lower struggle to gather software engineering talent and even in a shorter time to market.

To succeed in achieving this goal, a specific set of requirements has to be defined and documented in a formal way.

3.1.1 Requirements

Before defining the system's requirements, the end user has to be defined first. The end user is the person, who develops Augmented Reality applications for robotic systems with the PARRHI system. This might be a person, who is currently employed at a factory to design and implement user interfaces for certain machines, or also somebody that crafts

schooling literature for robots. The end user has a technical background, but does not have any experience with Augmented Reality development or is no software engineer at all.

This person requires the PARRHI system to fulfil the following aspects:

- 1.) Create AR Applications without any knowledge about AR development (Image Tracking, AR hardware, corresponding engines and frameworks)
- 2.) Involve their domain specific knowledge in the application's workflow, content and appearance
- 3.) Superimpose the real world with three dimensional Holograms to describe, highlight or mark real and virtual objects.
- 4.) Reuse previous work easily
- 5.) Build applications for multiple platforms (Desktop, mobile devices, tables, head mounted AR devices)
- 6.) Have the tools necessary to create medium complex applications for use cases such as tutorials, maintenance instructions or similar tasks.
- 7.) Have the possibility to control the robot, but also to let the operator take over the controlling at runtime.
- 8.) Be able to simulate the real and virtual world, to allow development without any hardware being present.

Deriving from these user requirements, one can define what the PARRHI system itself should fulfil. The system should:

- 1.) handle all Augmented Reality aspects without any developer input. This includes position recognition of the AR end user and the robot, the corresponding image and motion tracking and the build process for different hardware platforms.
- 2.) allow programming and parametrisation in a simple and intuitive, which allows the developer to reuse code from other projects.
- 3.) allow the definition of 3D objects including the utilisation of the robot's position via simple parameters.
- 4.) deliver human readable and intuitive feedback on the written program, comparable to compiler error messages.
- 5.) support building for multiple platforms such as hand held mobile devices and head mounted Augmented Reality glasses.

- 6.) make applications with medium complex workflows (Values in the range of 1-15 following the McCabe Metric [24]) possible. Event based systems, conditions and actions should be offered.
- 7.) allow the combination of simulated and real world data to be used for the application's workflow and its logical operators.
- 8.) allow the sensing and commanding of the robot's position both relatively and absolutely in joint and task space.
- 9.) allow documentation of the application's workflow via comments

These basic requirements should be a guideline for further conceptualisation and therefore for the implementation. The next section will visualise one possible use case of the PARRHI System and why it might be interesting to utilise it here.

3.1.2 Use-Case example: Factory Maintenance

I will now give an example use case, where the PARRHI system might come into play. Bear in mind, that one could find more use cases, since the PARRHI system is a development environment, which allows a wide variety of workflows and content. Examples could be AR applications for educational/training purposes, factory workflow processes, investigation and analysis tasks and process profiling.

The Use Case will be explained on the example of an automotive company, which produces its personalised car-bodies in an agile factory. The factory wants to increase the safety and efficiency of different steps during the assembly, and decides to use AR supported applications for that. These applications should then be distributed to the corresponding employees.

The factory is highly automated with different machines and robots. One of their assembly lines contains a robot, which is tasked to prepare the customised seats of the car. Every car might have a different type of seat built into it. The process of mounting these seats is not fully automated and still needs employees to be completed.

An application engineer is now tasked with developing an Augmented Reality application, that supports the collaborative process of humans and robots during this assembly step, to increase the safety and efficiency. The engineer has never built an AR application before, but has a substantial amount of experience with robot assembly lines and corresponding surveillance applications. The engineer needs this application to communicate the intent of the robot to the surrounding humans, control the robot to perform its next movement and

also make sure, that the collaboration between all parties stays safe, so that neither the human nor robot get damaged. This should be achieved by visually augmenting real world objects, but also by directly taking over the control of the robot.

This engineer now uses the PARRHI system to setup an AR application, which has multiple tasks. The application constantly monitors the human's distance to the robot's moving parts and warns the employee visually if they gets too close. At the same time, it always visualises the robot's range of motion and a danger perimeter around its axes, so that the employee has more contextual information to work with. In the case of the employee getting too close to the robot, the application immediately stops the robot and commands the user to move away.

This use case is a realistic depiction of what is possible with the PARRHI system. This specific application would not even take that long to develop (in the range of one hour), since the engineer does not have to care about the Augmented Reality aspects of it. The engineer can focus on their specific domain knowledge and fill the application with important information, without spending a substantial amount of time with any system setups or framework installations.

There are numerous other use cases that one could think of. Of course, an application like this could easily be developed for any other machine in the same factory, by simply expanding the PARRHI system to be able to communicate with it. Certain modules would have to be expanded or adapted for PARRHI to be able to communicate with other machines. A precise explanation of possible technology transfers can be found in section 6.3.

Theoretically, the automotive company could also use PARRHI applications to perform lectures and training on new employees. It is important to notice, that for these use cases no AR specialist was needed, since the system takes care of these components. Also reproducing an application for a similar workflow would be easy, since the text based program could simply be copied over.

3.2 PARRHI Concept

The following chapter will now explain the concept of the PARRHI system. I will first start with a general overview of the concept and how each requirement can be addressed, before shortly explaining each component. After that, the information flow in the system will be clarified.

Relieving the developer from AR efforts (Reqmt. (1)) means, that the system needs to have all the AR logic implemented on its own, without the need of any developer input. Thus, the architecture has an input and output module, which handle the Augmented Reality aspects. The input module will have to use the AR device's camera to perform the image and motion tracking, and the output module will have to generate the corresponding holograms. The developer's input into the system has to be a text document (Reqmt. (2)), which allows the definition of parametrised 3D objects (Reqmt. (3)) and logic components (Reqmt. (6)). Since the developer needs feedback on their work (Reqmt. (4)), the input document has to be validated. Combining real and simulated world data (Reqmt. (7)) demands the input module to intercept the data stream of the real world, and feed the simulated data into the stream before passing it on. Finally, the in and output modules have to communicate with the robot (Reqmt. (8)).

Fig. 3.1 depicts PARRHI's concept, which attempts to fulfil the given requirements and consists of three main parts. The left hand side shows the developer, the grey box in the middle is the PARRHI system itself and the right side visualises the environment that surrounds the PARRHI system in both virtual and real space. I will now go into detail and systematically explain each component from (0) to (8), before describing the information flow between them.

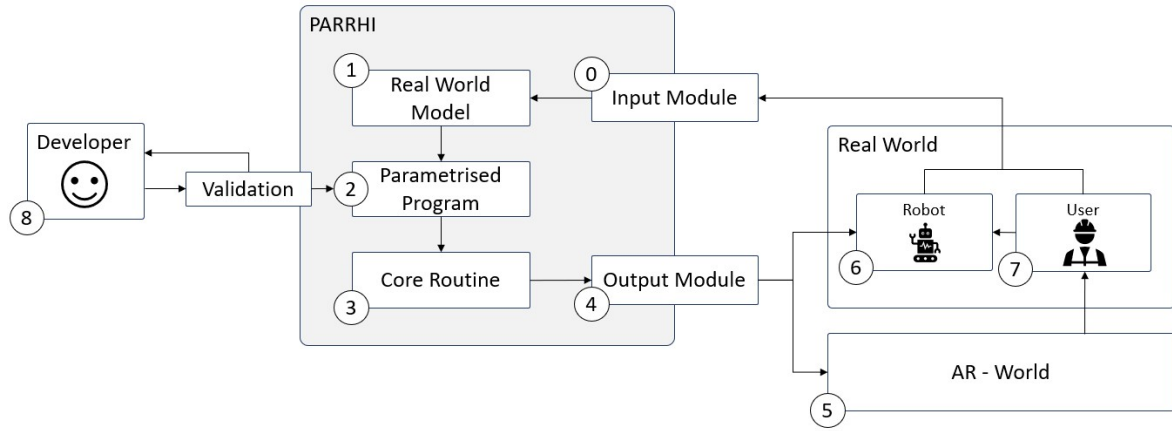


Figure 3.1: PARRHI general concept

- 0.) Input Module: The Input Module (0) is responsible for collecting data needed from the real world. In this specific case, it receives the robot's (6) joint angles and the user's (7) position.
- 1.) Real World Model: Since the data from the Input Module (0) might not be in a usable format straight away, it has to be processed first. The Real World Model (1) has a deeper understanding about the real world and helps to extract useful information from the

data inflow. In this specific case, its outputs are the robot's (6) joint positions and the user's (7) location represented as parameters that are available for the Parametrised Program (2).

- 2.) Parametrised Program: This is a document that defines the AR application's behaviour and workflow. Its syntax is parametrised, meaning, that it makes use of placeholders (parameters) whose actual value is managed by PARRHI itself at runtime. There are two types of parameters. First, there are the ones that are provided by the Real World Model (1) (for example the discussed robot's (6) joint positions) and secondly any object defined in the Parametrised Program itself (2) can act as a parameter for other objects in the program. These objects can be 3D AR-Hologram definitions, logical instructions or a variety of events and actions. For a more thorough explanation of the Parametrised Program see section 3.2.2.
- 3.) Core Routine: The Core Routine (3) is an interpreter for the Parametrised Program (2), and acts on its instructions. It generates the output of the application, which can either be commands to the robot (6) and thus real world, or instructions for the AR-World (5).
- 4.) Output Module: This component manages the outgoing communication with PARRHI's environment.
- 5.) AR-World: The Augmented Reality World is the space, where the AR part of PARRHI's output is displayed. It can create holograms like spheres and cylinders, but also written text for instructions. The AR-World (5) augments the Real World and is thereby seen by the User (7) through an AR Device.
- 6.) Robot: It is a Real World object that can be controlled by the User (7) themselves, or by the PARRHI system.
- 7.) User: This is the person that would use the finished application.
- 8.) Developer: This person develops the application's workflow and behaviour. Their output is the Parametrised Program (2) as a text-based document, which is validated before being fed into the PARRHI system.

It should now be clearer what each component is responsible for. The following paragraphs will track the information flow between the components. I will first start with the Developer (8) crafting the Parametrised Document and then continue with the standard runtime cycle of the PARRHI system.

After having defined what the AR-HR-Interface application should achieve, the Developer (8) crafts the Parametrised Program (2). At this point, the Developer pours his domain specific knowledge and expertise into the system, so that other people like the User (7) can

profit from it. The text-based hierarchically built document will be validated first, before it is granted access into the PARRHI system. If the validation fails, the Developer (8) receives error messages accordingly and can reiterate over their document until it validates successfully and behaves as the Developer (8) wants it to.

The runtime loop starts with the Input Module (0). It not only collects the robot's (6) joint angles, location and gripper-state but also the User's (7) position. This input data is then fed into the Real World Model (1), which uses its Real World understanding to extract/calculate more useful information. In this specific case, it applies forward kinematics onto the robot's (6) joint angles to calculate their 3D position and transforms the User's (7) location coordinates into PARRHI's internal coordinate system.

After transforming the input data into a usable format, the Parametrised Program (2), which is written using placeholders (parameters), comes into play. The latter are now filled with information by the PARRHI system. For example, the Parametrised Program (2) could use the robot's tool centre point (TCP) for a definition of some AR-holograms, without knowing where exactly the TCP is during development. At runtime, PARRHI inserts this information it received from the Real World Model (1) into the parameters.

The Core Routine (3) then interprets the now-filled-in Program (2). It first updates its internal state with the new parameters, before updating all AR-Holograms. At last it evaluates all events, and triggers their actions if needed. These actions might be commands for the AR-World (5) (for example to show or hide holograms, or to change UI text) or commands for the Real World Robot (6) (e.g. to move or stop the robot). These commands are passed into the Output Module (4), which is responsible for executing them. It has the required tools to communicate with the Robot (6) and with the AR - World (5).

At this point, the User (7) sees two things. They see the Real World in front of them. There is the Robot (6) and a surrounding environment. The Robot (6) might be instructed to do something by the Output Module (4) already. Superimposed onto the Real World, they also see the Augmented Reality World (5), which contains all visual information that the Output Module (4) constructed. There could be cylindrical translucent holograms marking a danger zone around the robot's (6) axes. The AR-World's (5) content influences the User (7) to do certain things. He could be instructed by holograms to move into a safe-zone. At the same time, the User (7) might control the Robot (6). At this point it is to mention, that the Output Module (4) enjoys priority over the User's (7) input when commanding the Robot (6).

As Fig. 3.1 depicts, the Input Module (0) then finally closes the feedback loop by receiving fresh data from the Real World. The information flow that was followed in the paragraphs above, changed the environment either by direct commands or indirectly by commanding the User (7) via the AR World (5). These changes will now be reflected in the input data and are thus available for the next cycle. The presented loop repeats itself, where every iteration only takes a fraction of a second, until the *PARRHI* system is terminated for some reason.

The preceding paragraphs should give a relative detailed overview about the concept behind *PARRHI*. The following chapters will now explain each part in an even higher degree of detail, with the goal being, that almost no questions about the concept stay unanswered. The order will be similar to the explanation of the information flow in the *PARRHI* concept, meaning, that the Input Module (0) and the Real World Model (1) will be explained first, followed by a very thorough explanation of the Parametrised Program (2) with all its objects and definitions. In the end the Core Routine (3) and the Output Module (4) with the Real and AR-World (5) will finish off the concept chapter.

3.2.1 Preparation of Parameters

One main strength of the *PARRHI* concept is its disclosure of its knowledge of the outside world to its inner components via parameters. Two steps are necessary to do that. First, an Input Module (0) has to automatically retrieve real world information. Since the latter is hard to comprehend for computer programs and might not be usable for the Developer's purpose, the Real World Model (1) processes the input data in some way.

The complexity of collecting Real World data strongly depends on the use case. I decided to limit my scope to the collection of three information pieces, since it is not the main focus of this thesis. These three pieces are the user's position, the robot's joint angles and it's gripper state.

Gathering the user's position relative to the robot is the first step. For AR applications, it is utterly important for the AR device to know its six dimensional orientation (position and rotation). Otherwise superimposed holograms would not make any sense to the viewer, since they appear misplaced. As soon as misplacements of visual augmentations happen, they are more a distraction than an assistance. To get this relative position, the robot's position has to be received first. This could be done via image tracking. To synchronise all coordinate systems, the centre of origin for *PARRHI* applications is always the robot's base. From this vector (user to robot) *PARRHI* calculates the user's location in the robot's coordinate frame with its Model of the Real World.

Then the robot's joint positions are needed for the application program to offer the possibility to fully integrate the robot in the application's workflow. Since most robots do not offer their individual joint positions in 3D vectors via some interface, but only their joint angles, a corresponding robot model is needed to calculate each joint's position from their joint angles. This is called forward kinematics, an old challenge in robotics with known mathematical tools and ways to solve it (at least in the case of basic industrial robots). In principle, one can calculate a robot's tool point via every joint angle and some knowledge about the robot's configuration. The latter is specified by the types of joints (degrees of freedom (DOF)) and the distance between consecutive joints. A mathematical model then outputs each joint's three dimensional location, which is offered to the Application Program (2) via parameters. To get an example of how the joint's position might be used in a parametrised way see section 3.2.2.2.

3.2.2 Parametrised Program

The Parametrised Program is the document, which the Developer ((8) in Fig. 3.1) of the *PARRHI* system crafts. It contains parametrised, hierarchically structured data, that defines the behaviour, feel and look of the final AR-HR-application. This document is responsible of fulfilling the defined requirement number (6) in section 3.1.1, which requires the *PARRHI* system to allow complex application workflows to be depicted.

The Parametrised Program contains instructions and definitions which from now on will all be called to "objects". All these objects have a certain set of parameters that are needed to fully define their function, visual appearance or behaviour. These parameters can either be previously defined objects, data from the Real World Model or constant values. By using other objects as parameters, one can create an interconnected program with links to other components, where instructions might be able to manipulate other objects in the program at runtime. To reference these other objects, every single object has to have a unique name.

The following chapters explain the set of tools that are available to the developer, how they work and interconnect. Table 3.1 displays the different categories of objects. Each section will describe what exactly is parametrised in their definition and how they can be used as parameters to define other program parts.

Table 3.1: *Input Data* structure

Name	Section	Explanation
Variables	3.2.2.1	Integer variables in a traditional sense
Points	3.2.2.2	Different kinds of 3D Point definitions (fix, relative to the robot, relative to the user)
Holograms	3.2.2.3	3D virtual augmentations like spheres and cylinders
Events	3.2.2.4	Tools for logic operations to define workflows

3.2.2.1 Variables

Variables are storage locations for numbers and have a symbolic name. When using Variables as parameters, they can be the input and target for instructions and thus take part in the application's logic. With the help of Variables an application could keep track of something by counting events, or also implement state machines that jump between modes.

3.2.2.2 Points

Points essentially are a three dimensional vectors (X , Y , Z), with their coordinates being defined using parameters. Depending on the type of Point, different parameters for the definitions are used. There are three types of Points.

- 1.) Fix-Point
- 2.) Robot-Point
- 3.) Camera-Point

Points are probably the best example of parametrised information in the *PARRHI* system. At runtime the data from the Real World Model (see (1) in fig. 3.1) is directly fed into the definition of all points that use the according parameters. Thus, the system updates these objects repeatedly with Real World information, that was fed through the Real World Model. Although points are defined using parameters in some way, points themselves are parameters to other objects in the Parametrised Program.

The **Fix-Point** has static coordinates and thus fixed values are used to define their coordinate parameters (see figure 3.2). It could be used to setup holograms that visualize certain spacial

environmental constraints that do not move.

Definition Parameters: *name* : *string*, *X* : *float*, *Y* : *float*, *Z* : *float*.

Robot-Points are defined by two indexes of the robot's joints and one scalar value that will be explained later (see figure 3.3). The application's developer does not have to understand the robot's kinematics and simply uses the joint-indexes as parameters. At runtime, the *PARRHI* system retrieves the robot's joint position, uses the Real World Model to calculate each joint's position ($J_0 - J_5$) and then feeds this data into the Robot-Points. The final point's position P is calculated as follows (with s being the scalar value and J_n the position vector of Joint n):

$$P = J_1 + (J_2 - J_1) * s \quad (3.1)$$

As it can be seen, the scalar value linearly interpolates between the two joint positions and thus allows for a wider variety of Robot-Points.

Definition Parameters: *name* : *string*, *J1* : *int*, *J2* : *int*, *Scale* : *float*.

Camera-Points are a way to involve the user's position in the application. Similarly to the Robot-Points, the *PARRHI* system retrieves the camera's coordinates via the Input Module, feeds it through the Real World Model to map it onto the internal coordinate systems and finally periodically updates the Camera-Points with the new location data of the head mounted AR-Device. Since there is only one Camera in the PARRHI system, its only parameter is the point's *name* : *string*.

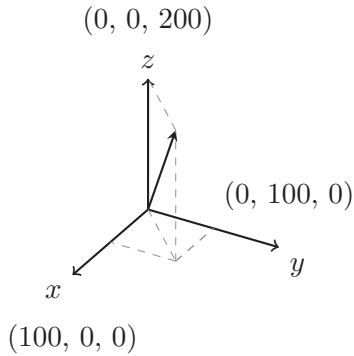


Figure 3.2: Fix-Point example

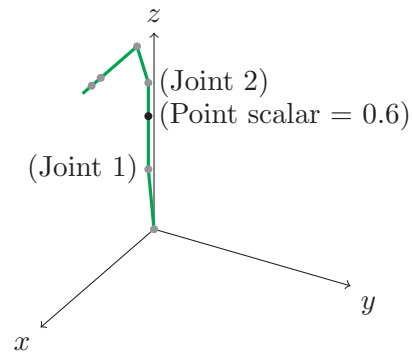


Figure 3.3: Robot-Point example

3.2.2.3 Holograms

The AR World can be filled with numerous holograms. In the Parametrised Program these holograms are defined using parameters. In this case, Points from section 3.2.2.2 are used to define the Hologram's location and orientation. Since Points are parametrised themselves, and are thus updated by the data from the Real World model, holograms are indirectly also updated regularly.

Holograms in the PARRHI system have a number of attributes (see table 3.2). Currently *PARRHI* supports two types of holograms. There are spheres and cylinders, respectively taking one or two points and a radius as input parameters to define its size and position. Other attributes describe its visual appearance.

Table 3.2: Hologram attributes

Attribute	Possible values	Explanation
name	any text	Used to identify the object
visibility	visible, hidden	Sets the hologram's visibility
renderMode	normal, transparent	normal: Hologram is rendered as a solid object transparent: Hologram is rendered translucent
radius	number	The radius of the sphere or cylinder
point1	name of any defined point	Used for the holograms position definition
point2	name of any defined point	Used for the cylinder's position definition (not available for spheres)

A Sphere's centre is always set to the point it was defined with (point1), whereas a cylinder always connects the two points of its definition (point1 and point2). All described types of points in section 3.2.2.2 can be used as input parameters for the location. This is the first example of Parametrised Program internal use of objects as parameters.

Holograms have an attribute called *renderMode*, which if set to "transparent", renders the hologram in a half transparent way, allowing holograms to be used for boundary or zone visualizations. Furthermore the visibility of holograms can be changed by setting the *active* parameter, which is done by actions as described in section 3.2.2.4.

3.2.2.4 Events

All previous elements (variables, points and holograms) exist to define the scene and to set up assets that can be utilized by events, which now actually describe the application's workflow. There are two subtypes in this category. There are event-triggers and event-actions (or short *triggers* and *actions*). Triggers have a boolean expression, which is checked each cycle. As soon as the boolean expression evaluates to *true*, the attached actions will be executed and the trigger will be disabled, avoiding multiple executions. One could say that if triggers are *PARRHI*'s sensors, then actions are its actuators.

Although there are different types of triggers, all definitions of them have some attributes in common, which are listed in the table 3.3. Of course, specific trigger types have additional parameters to define their function. Almost all trigger need other objects as parameters for their definition.

Table 3.3: Trigger attributes

Attribute	Possible values	Explanation
name	any text	Used to identify the object
canTrigger	true, false	Enables/Disables the trigger
actions	multiple names of actions	Defines the payload of the trigger

To reach a reasonably capability numerous different but easy to understand triggers are available for the application's developer. In table 3.4 is a complete list of all defined triggers.

Distance trigger are mainly defined using two Points and a distance value. They trigger, as soon as the euclidean distance of the two points is below the distance parameter. They can be used for two main purposes. First the application can use the robot's movement as an input using a *Robot-Point*. An action could be triggered as soon as the user jogged the

Table 3.4: Trigger types

Name	Input Parameter	Trigger expression
Distance trigger	Two Points $\mathbf{P}_1, \mathbf{P}_2$, distance d	$ \mathbf{P}_2 - \mathbf{P}_1 \leq d$
Variable trigger	Variable v , trigger value v_{tr}	$v = v_{tr}$
Time trigger	trigger time t_{tr} , time since enabling $t_{enabled}$	$t_{tr} \geq t_{enabled}$

robot's TCP into a wished position by using a *Fix-Point* and waiting for them to come close to each other. Second the user's movement can be monitored by utilizing a *Camera-Point* as an input parameter. The application can thus ask the user to move to a specific location (e.g. a safe-zone).

Definition Parameters: *name:string, canTrigger:bool, point1:Point, point2:Point, distance:float, actions:[Action]*

Variable triggers are defined using a variable parameter, and one *trigger value* parameter. They trigger, as soon as the given variable equals the *trigger variable*. One could implement a counter for certain events, and trigger an action when a threshold value is reached. It can also be used for workflows that need states or steps.

Definition Parameters: *name:string, canTrigger:bool, varName:Variable, triggerValue:int, actions:[Action]*

Finally the **Time trigger** allows the application to involve timers. These triggers are defined using a *timeSinceActivation* parameter and trigger, as soon as the time passed since setting *canTrigger* to true is equal or greater than the *timeSinceActivation* value. If *canTrigger* is true from the beginning on, the timer starts immediately. The user could be given a maximum time for a task or holograms can be hidden after a few seconds.

Definition Parameters: *name:string, canTrigger:bool, timeSinceActivation:int, actions:[Action]*

Whenever a trigger's boolean expression evaluates to true, its actions are invoked and the trigger gets disabled. There are numerous different types of actions - each serving a specific purpose. As with triggers, actions have a set of input parameters they need to fulfil their task and to be completely defined. The table 3.5 gives a quick overview about all actions that *PARRHI* currently supports.

Table 3.5: Event Actions

Action Name	Input Parameter	Explanation
Increment Counter	Variable <i>v</i>	Increments the value of <i>v</i> by 1
Set Hologram State	Hologram-names, State to set	Enables/disables all specified holograms
Set Trigger State	Trigger-names, State to set	Enables/disables all specified triggers
Change UI Text	Text to set	Sets the UI Text
Move Robot	Point <i>P</i>	Moves the robot to <i>P</i>
Set robot-hand State	State to set (open/close)	Opens or closes the robot's gripper

Increment-counter actions increment the value of the Variable parameter by 1. If a developer wanted to count the number of times a user jogged the robot into a specific region, an Increment-counter action could be used as a payload of a Distance trigger. After a threshold value is reached, a Variable trigger could change the UI text and display a hint. Definition Parameters: *name:string, intVar:Variable*

The **Set-Hologram-State action** enables setting the visibility of holograms at runtime. If a hologram represents a region for a tutorial step, it can be hidden after the user's task is completed. The new scene can then be setup by displaying new holograms that guide the user's way. Another possible scenario would be, to display a warning boundary, if the user moves into a forbidden zone. This can be achieved by combining Distance trigger and Set-Hologram-State actions.

Definition Parameters: *name:string, onHolograms:[Hologram], offHologram=[Hologram]*

When using *PARRHI* the user is presented a GUI that shows text and some other few options. The **Change-UI-Text action** allows to change this displayed text. There are numerous obvious use-cases where this is useful. Whenever it is of value to inform the user about something that cannot be achieved by holograms, this is a simple way to do so.

Definition Parameters: *name:string, text:string*

To create meaningful and longer applications, enabling and disabling triggers is an essential tool. This is what the **Set-Trigger-State action** is for. Triggers can only invoke their payload actions, if their attribute *canTrigger* is true. Triggers can either be defined as disabled from the beginning on, or get disabled by triggering as described above. The Set-Trigger-State action has the ability to (re)activate disabled triggers. There is a speciality in the case of *Time triggers*. Their inner timer starts ticking, whenever they get enabled. This allows for timers to be used in the middle of applications, relative to other events.

Definition Parameters: *name:string, triggerName:Trigger, canTrigger:bool*

The last two actions are designed to take active control over the robot. The **Move-Robot action** moves the robot to the specified coordinates. It is important to note, that this action has two different modes defined by a *mode* parameter. If *mode* is *'t'*, then the coordinates will be interpreted as absolute euclidean task space coordinates, and if *mode* equals *'j'* then PARRHI will assume that the coordinates are defined in joint-space and will act accordingly.

Definition Parameters: *name:string, target:Vector6, mode:char*

The **Set-Robot-Hand-State action** behaves as one would expect and simply open or close the robot's gripper according to its parameters *state*.

Definition Parameters: *name:string, state:bool*

3.2.2.5 Program example

To further explain the parametrised program, I want to give a short example of how such a small program might be set up. The following program will wait for the user to move the robot's tool centre point (*TCP_Point*, line 3) to the *Target_Point* (line 2) at some static coordinates and visualise both points with Sphere holograms (lines 6,7). Upon reaching the target with a certain tolerance (line 10), it will display a success message to the user (line 14).

```

1 <!-- Define Points -->
2 <PointFix name="Target_Point" X="200" Y="200" Z="200" />
3 <PointRobot name="TCP_Point" J1="6" J2="6" scale="0" />
4
5 <!-- Define Holgorams -->
6 <Sphere name="Target_Area" radius="15" point="Target_Point" />
7 <Sphere name="TCP_Area" radius="15" point="TCP_Point" />
8
9 <!-- Define Trigger -->
10 <DistanceTrigger name="d_trigger" point1="TCP_Point" point2="Target_Point"
    actions="SetUI_Success" distance="15" />
11
12 <!-- Define Action -->
13 <ChangeUITextAction name="SetUI_Success" text="You have reached your target
    successfully!" />

```

3.2.3 Core Routine

The Core Routine's responsibility is, to interpret and execute the Parametrised Program. It's input is the Parametrised Program with all data from the Real World Model already set, and it's outputs are commands to the Real or AR World. At the very beginning of each cycle in the Core Routine, all Parameters are resolved (see (0) in fig. 3.4). This means, that the interpreter finds all parameters that are used in the Parametrised Program, and inserts all values from the referenced objects. For example, if a Hologram is defined using a Point object, the interpreter looks for the point, and fetches its momentary coordinates to fully define the hologram. Similarly, all other parameters are found and processed.

After that, the Core Routine updates its inner state (1). This means, that it updates all Holograms and Triggers with newly received data. Holograms are moved to their new position, and Triggers receive their new input values depending on the Trigger type. Distance Triggers for example receive their new coordinates, that they have to monitor.

With all new values set, it can now check all Triggers whether or not their boolean expression evaluates to *true* (2). Whenever a trigger does evaluate to true, it invokes all actions of that trigger(3). The executing actions result in a group of commands, that will be sent to the Output Module, which then handles them from now on.

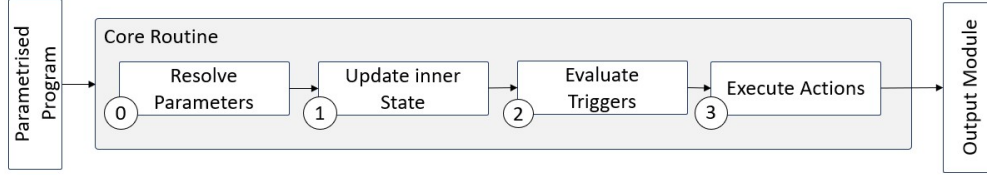


Figure 3.4: Core Routine Workflow

3.2.4 I/O Modules

The last step in the PARRHI runtime cycle is to send all generated commands to their receivers. As described, there are two types of commands. Firstly, there are the ones that are directed to the AR-World and secondly there are commands that are directed towards the Real World. I will now shortly explain the difference in their nature, and why AR-commands are much easier to process conceptually than Real World commands.

The AR-World is *only* software that runs on the same device, that hosts the complete PARRHI system. That means, that sending commands to the AR-World is as simple as actually calling some methods in the Back-End. Real World commands on the other hand, are much more complex because they have to be sent to other hardware devices, with possibly different operating systems (OS) that run on different programming languages. This is why, some network protocols have to be defined to communicate with these Real World objects.

In my case, the Robot (see (6) in fig. 3.1) is the only Real World object, that does not run on the same OS as the AR-Device. This means, that a OS neutral protocol has to be defined for this type of communication. In addition to that, operating systems on Robots tend to be sealed towards the outer world making it safe against unwanted access but at the same time hard to interconnect to other systems. This is why, Florian Leitner (AIS at TUM) and I defined a custom protocol for the bidirectional communication between the PARRHI system and the Real World Robot. To get more information about the implemented protocol and system to communicate between PARRHI and the Robot, refer to section 4.5.

4 Implementation

In this chapter I will write about some implementation aspects that were interesting or problematic during the development of the PARRHI system. For that, I will use a top down strategy, meaning, that I will talk about the general setup of the implemented system, and then drill down into the components. I will explain what software was used, why I made these decisions and whether or not they were good or bad in hindsight.

4.1 PARRHI Hardware

For the Augmented Reality purposes, I decided to use the first version of Microsoft's Augmented Reality glass called HoloLens [25]. The HoloLens has all needed capabilities like cameras for image and environment tracking, simple hand gesture recognition, a reasonably good field of view and was programmable with the 3D game engine Unity. Thankfully, the TUM chair of "Automation and Information Systems (AIS)" supplied me with this product.

The second main hardware component in the PARRHI system is the Robot. The robot manufacturing company Fanuc [26] was gracious enough to gift the TUM chair "Automation and Information Systems (AIS)" a free CR-7iA/L collaborative, 6 DOF, industrial robot [27] and a R-30iB controller [28]. The R-30iB controller can either be programmed in Fanuc's TP-Language or in Fanuc's KAREL language. KAREL offers many possibilities with network sockets, reading and writing data from and to the robot's controller, whereas TP programmes are fit for moving and steering the robot.

The last component is a gripper provided by SCHUNK. The company gifted us a collaborative Co-act EGP-C [29], that seamlessly integrated into the Fanuc robot with a hardware interface for exactly that purpose.

At this point I would like to thank Fanuc, Schunk and the AIS massively for their supplies, so that this bachelor's thesis could be realised.

4.2 PARRHI Software

Software Implementation wise, the PARRHI system is split up in three big components. First there is the PARRHI library, secondly the Robot library and lastly the Unity engine. The PARRHI library is the most intelligent component, since it contains all the logic for the Real World Model, the Parametrised Program, the Core Routine and commands the Input and Output Modules (see fig. 3.1). The Robot library has the tools necessary to communicate with the Robot in the Real World and is used by the Input and Output Modules. The third component *Unity* hosts the PARRHI runtime library, and handles the AR-World, network communication etc.

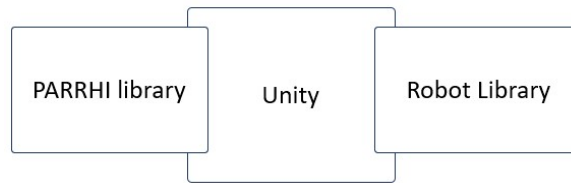


Figure 4.1: PARRHI implementation setup

4.3 PARRHI Library

The PARRHI system was programmed in Microsoft's .NET framework version 4.6.1 [30] using C# [31]. This decision was made because the Unity game engine is scripted in the language C#. The PARRHI library itself is a *Class Library* project [32] and has three main tasks.

- 1.) Import the Parametrised Program and perform some operations on it. The Parametrised Program is a XML [33] based document. After importing, it is validated using an XSD [34] document. Finally the PARRHI library has to extract useable C# objects from the deserialized XML document and setup references to resolve parameters.
- 2.) The Real World Model and the logic behind it is a subcomponent of this library. In my specific case, this means, that the PARRHI library contains the Robot's forward kinematics model and the required information to convert the HoloLens' internal coordinates, into the robot's coordinate system.
- 3.) The Core Routine is located in the PARRHI library, meaning, that on every iteration the PARRHI system calls into the PARRHI library to perform its task.

This libraries main interface to the hosting environment or the caller is a container object, that contains all Parametrised Program object references like Holograms, Points etc., but also manages the importing of the Parametrised Program document itself. Fig. 4.2 is a class diagram of the **Container** object. As it can be seen, it basically holds references to all objects of all types, and provides some update methods, that will be called from the library's host.

It is important to note, that all objects inherit from the **PProgramObject** class, which gives them the id property that allows the object to be identified. This is needed to resolve parameters in the Parametrised Program. As soon as an object is instantiated, it calls back to a list of id's which checks all ids for duplicates. In the case of duplicate ids, an error is thrown and displayed to the developer. Whenever an object is used as a parameter in the Parametrised Program, this id is used to find the reference to the target object.

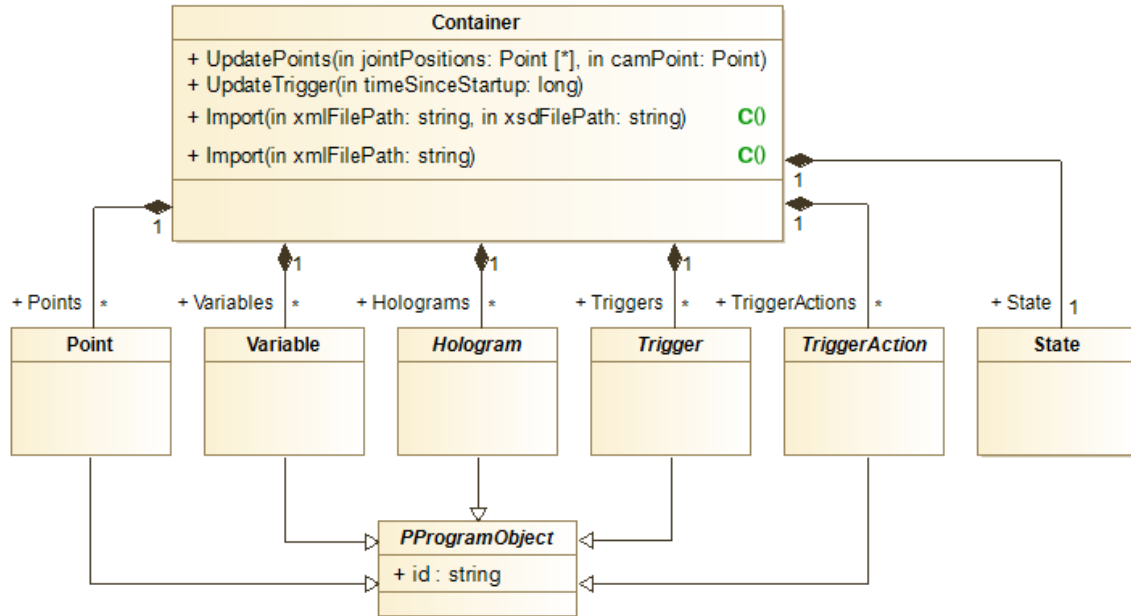


Figure 4.2: Container Class Diagram

All compositions besides the **State** class simply represent the Parametrised Program objects presented in section 3.2.2. The **State** itself is an object, that holds the Real Worlds state data at all times, so that the PARRHI library has access to it. Fig. 4.3 shows that the State object is composed of two other objects - each serving a specific purpose. The **Robot** class handles all operations that have anything to do with the robot. For example the Forward Kinematics. It also contains two delegates. Instead of letting the Robot class have an instance of the robot library (section 4.5), I chose to let this class have two delegates. The PARRHI library invokes these two delegates, which will be configured from the hosting environment.

This creates some independence from the Robot Library, and may allow the PARRHI library to be used with absolutely any robot as long as there is a .NET framework controller for it.

This is not the only advantage of abstracting the controlling of the robot. During the development of the PARRHI system, I wanted to simulate as much as possible since I did not always have access to the robot. So I created an Interface between the PARRHI system and the real world, that was able to simulate all values instead of retrieving them from the real world. In the case of a simulation, I can then simply set this delegate to send the commands into the simulation, and not to the real robot.

The `World` class has attributes that represent the state of the real world and discloses them to the PARRHI library. The `SetUIText` delegate similarly to the `MoveDelta` method from the `Robot` class, is a function pointer that can be configured from the library's host. This was done for the exact same reasons as with the `Robot` class - to create independence from the host.

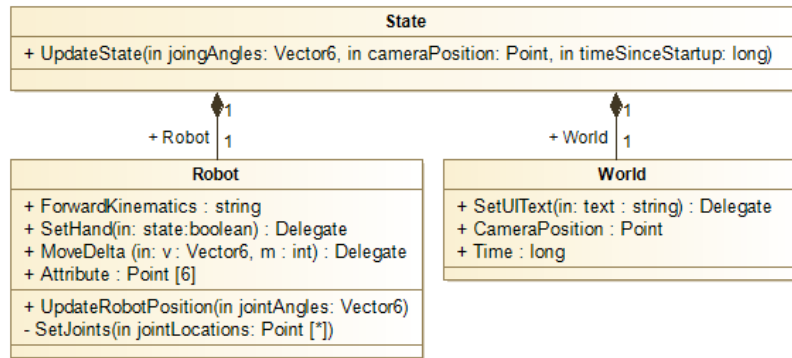


Figure 4.3: UML Class Diagram of State class

These two classes are the main interface to the library's host. They contain multiple sub classes which will be explained in the following section.

4.3.1 Parametrised Program objects

The Parametrised Program contains five different objects: Variables, Points, Holograms, Triggers and Actions. During the implementation, I first created abstract classes of each object type, and then created concrete implementations for each sub-type. The PARRHI interpreter only utilises the public methods that are disclosed in the abstract classes. I chose

this approach, because this way it is not important how the abstract class was instantiated, but only what values they hold.

This approach also allows the PARRHI system, to (for example) use any type of Point for the definition of a Hologram. The abstract Point class provides all data that is needed for the Hologram's definition. It is not important which concrete implementation the given instance is. This section will explain how these objects were implemented and how the inheritance tree is setup.

The Variable class is very straight forward and literally only contains an integer value, hence, it would be too much to draw a class diagram for it. There is also only one type of it, which makes it even simpler.

The Point class on the other hand is a bit more interesting. The abstract Point class contains the 3 dimensional position vector, and some read-only properties, but the inheriting classes define how the position is set. For example the PointRobot class takes two joint indexes for its definition as it was described in section 3.2.2.2. In each cycle, the public method UpdatePoint is invoked, which allows the PointRobot to calculate its new position. The PointCamera and PointFix do not add or overwrite any methods, since the Point class contains all needed functionalities.

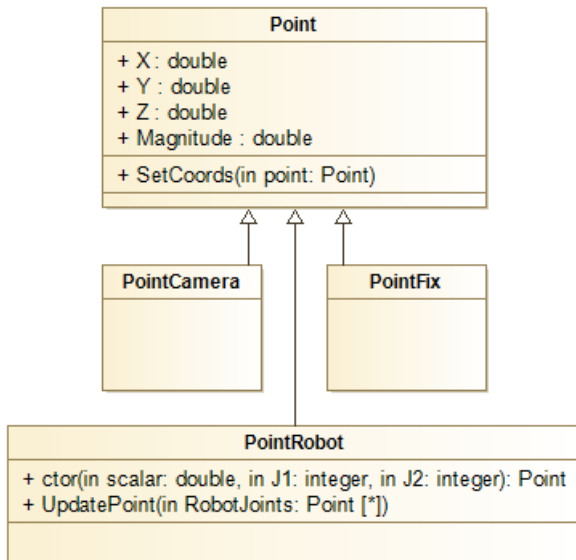


Figure 4.4: UML Class Diagram of the Point class

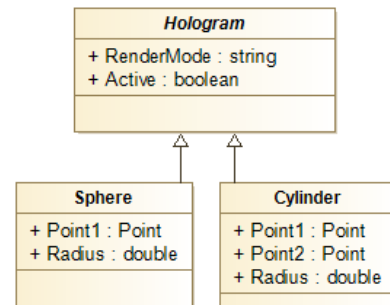


Figure 4.5: UML Class Diagram of the Hologram class

The same principle was applied to the Hologram class (see Fig. 4.5). The two inheriting classes **Sphere** and **Cylinder** provide their specific constructors and hold their values. Since

the `Point` instances in the two different Holograms are references to the real `Point` object, and the way references work, they do not have to be updated each cycle specifically. Only the hosting environment (in this specific case the Unity Game Engine) has to update the 3D objects it generates.

The `Trigger` class (Fig. 4.6) is structured in a similar way. The abstract class `Trigger` has a virtual method called `CheckTrigger`, which evaluates the trigger expression. Since every inheriting class triggers on different data, this method cannot be implemented in the parent class. As it was with the `Point` class, the different inheriting classes have different constructors, and store different data to evaluate their triggers. The `DistanceTrigger` for example takes two references to `Point` objects. It is important to note, that the `Point` object can be any object, that inherits from the `Point` class. This means, that the `DistanceTrigger` can be constructed with `PointCamera`, `PointRobot` or `PointFix`. Each inheriting class provides the `CheckTrigger` implementation, which corresponds to the defined boolean expression in section 3.2.2.4.

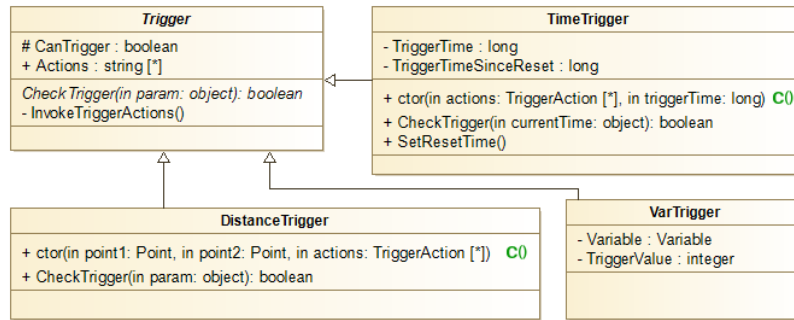


Figure 4.6: UML Class Diagram of the `Trigger` class

The last Parametrised Program object is the `Action` class. In this case, the abstract parent class is not as powerful as in the previous classes. The reason simply is, that all action types are fundamentally different and do not have anything in common, besides one method called `Action`. Figure 4.7 depicts the class structure here. Each inheriting class has to implement the virtual `Action()` method itself, since the parent object does not have the necessary data.

There are some interesting aspects to this implementation. As described, the `World` objects holds a function pointer (delegate) to a method, which prints a given string to the corresponding AR output. The `ChangeUITextAction` takes a reference to the `World::SetUIText(...)` delegate. This way, the hosting environment has to configure the UI delegate only once and it will be applied everywhere in the PARRHI library.

Similarly to the `ChangeUITextAction`, the `MoveRobotAction` holds a reference to the `Robot::MoveDelta(...)` delegate. In this specific case, the class has two different private attributes, which both save the position that should be sent to the robot. This is the case, because there are two different modes this Action can be used. In one case, the input can be a reference to a `Point` object and in the other case a six dimensional `Vector6` object. Remember, that the used Fanuc Robot is six dimensional. Since `Point` objects are only three dimensional, the robot will then approach the coordinates of the `Point` object from above, with the gripper facing downwards. The predefined orientation provides the last needed three coordinates, which completes the command and makes it executable. If a `Vector6` object is given, then the command can be sent without adjustments.

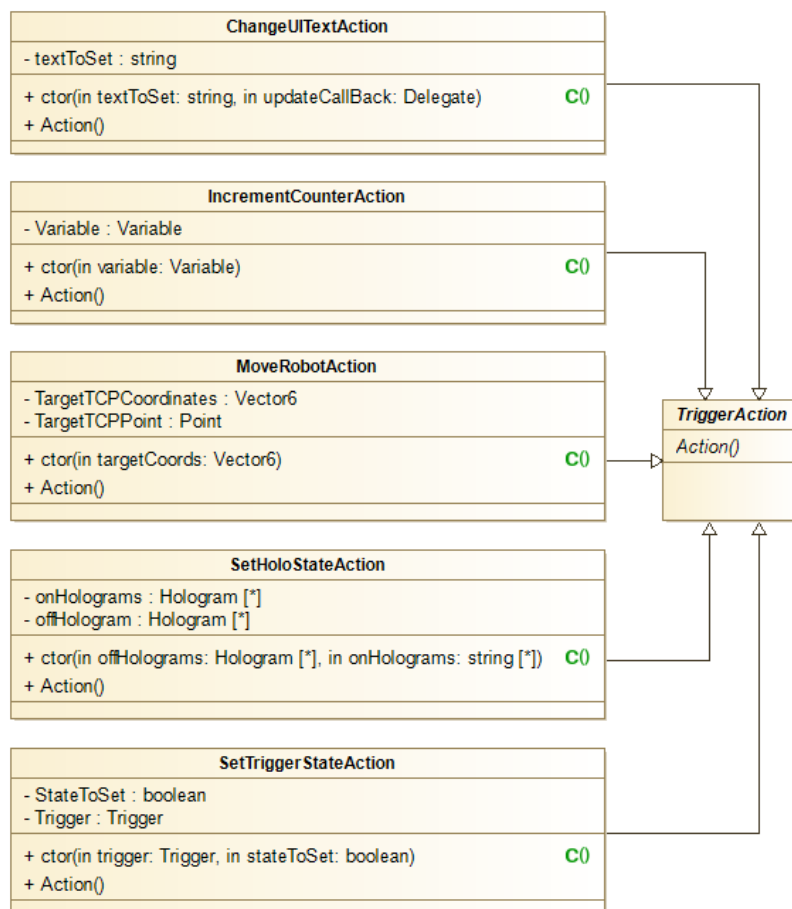


Figure 4.7: UML Class Diagram of the Action class

4.3.2 Importing and interpretation of the Parametrised Program

[This small subsection will describe how the xml is imported, how the needed information is extracted and how the described classes are instantiated - not yet finished, but will be quite short.]

Importing and validating the XML document is very easy, since the used .NET framework natively supports that. The implementation of the PARRHI Core Routine is also quite straight forward, which is why I will not talk about it too much. More interesting is the Robot's forwards kinematics, which will be presented now.

4.3.3 CR-i7A Forward Kinematics

In robotics, a robot can be described in two different spaces. On one hand there is the joint space, meaning that all vectors and matrices depend on the joint positions, velocities or accelerations. Since the robot has six joints, the joint space is six dimensional. In the joint space the position vector is often represented as \vec{q} .

On the other hand there is the task-space. In this space, all vectors and matrices depend on the Cartesian position and orientation (and their first two derivations) $\vec{x}, \dot{\vec{x}}, \ddot{\vec{x}}$ of the robot's TCP. If the joint space is six dimensional, then generally speaking (ignoring cases like singularities) the task space is also six dimensional and represented as follows, with x, y, z being the 3D coordinates, and α, β, γ being the orientation of the tip.

$$\vec{q} = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \end{pmatrix}, \vec{x} = \begin{pmatrix} x \\ y \\ z \\ \alpha \\ \beta \\ \gamma \end{pmatrix} \text{ with } \vec{x}, \vec{q} \in \mathbb{R}^6$$

The forward kinematics now describes the process of transitioning from \vec{q} to \vec{x} . This is done as follows: $\vec{x} = f(\vec{q})$ with $f : \mathbb{R}^6 \rightarrow \mathbb{R}^6$. Where the mapping f depends on the robot's specific configuration and geometric properties. For reference, if f is a mapping from $\mathbb{R}^6 \rightarrow \mathbb{R}^6$ then f^{-1} (if it exists!) with $\vec{q} = f^{-1}(\vec{x})$ is called inverse kinematics.

To calculate f , I first defined local Cartesian coordinate systems after each joint. In fig. 4.8 the green axes represent the robot, the black vector packs of three represent the coordinate systems $\phi_i = (x_i, y_i, z_i)$ and \vec{l}_i represent the axes defined in the coordinate system ϕ_i . In the following paragraph, the notation of $\vec{l}_{a,b}$ will be used to name the a^{th} vector called \vec{l} expressed in the coordinate system b .

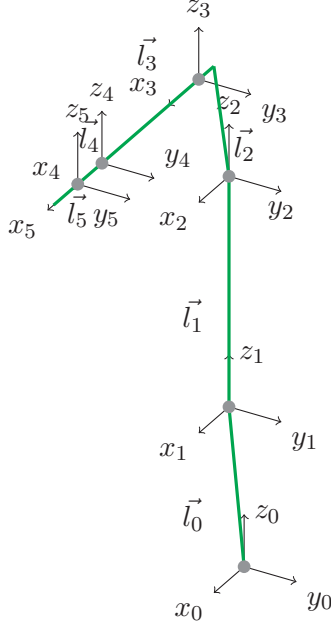


Figure 4.8: Robot forward kinematics coordinate systems

The matrix (ϕ_{n+1}) allows the conversion from vectors expressed in the coordinate system $n+1$ to the expression in system n , with $\vec{l}_{n+1,n} = \phi_{n+1}(q_{n+1}) * \vec{l}_{n+1,n+1}$. After transforming the vector \vec{l}_{n+1} one can add the vector $\vec{l}_{n,n}$ because they are both defined in the same coordinate system. Meaning, that the position of the tip of the vector \vec{l}_{n+1} relative to the origin of the coordinate system n is, $\vec{x}_{n+1,n} = \phi_{n+1}(q_{n+1}) * \vec{l}_{n+1,n+1} + \vec{l}_{n,n}$. Repeating this process from $n = 5$ to $n = 0$, results in the robot's TCP position relative to the coordinate system \vec{O} , which is what we wanted. One has to remember, that only the matrices ϕ_i are variables, since they depend on q_i . The vectors \vec{l}_i are constants. This means, that for each iteration one only has to calculate all matrices ϕ_i and can then calculate the positions (x_i, y_i, z_i) of each coordinate system relative to the base system \vec{O} .

Since the C# implementation of this algorithm is only about 20 lines of code (excluding the definitions of the matrices ϕ_i and the vectors \vec{l}_i), takes only about 4ns to run, and the end results are all joint positions in Cartesian coordinates relative to a base system, I am quite happy with the outcome. If one wanted to add multiple robots into this framework, it could be done quite easily by adding one additional world-coordinate system, where all robot base systems are embedded into.

Adjusting this model to other types of robots would be easy. If the adjusted joints are all 1 DOF and rotational, then only the rotation matrix ϕ_i has to be adjusted, and \vec{l}_i still stays constant. If one included translational, linear joints, the vector \vec{l}_i would depend on some variable, but the mathematical process would stay the same.

Implementation wise one interesting fact is, that Unity (the game engine which hosts the PARRHI library) uses a left-hand coordinate system, whereas my robot forward kinematics was done in a right handed system since that is how I learned it the past few years. This

means, that the last step in the forward kinematics is, to transform all produced vectors into Unity's coordinate system, which is rather easy. I only needed to swap the z and y coordinates of each joint position.

For further reading into this topic see [35].

4.4 Unity

Unity is the host of the PARRHI and Robot libraries. Originally, Unity itself is a game engine that helps developers to develop, publish, maintain and market their games [36]. Within recent years the company behind Unity, called Unity Technologies, made efforts to become a de facto standard for AR and VR development.

There are a lot of third party products for Unity that help the developer with image tracking and general AR interaction. The next paragraphs explain what libraries, and tools were used to handle hand gesture recognition and image tracking.

4.4.1 Image Tracking

For Image Tracking I used the Vuforia Engine [37]. This engine had a rather simple setup in Unity and worked relatively seamlessly in Unity. Compared to other engines and libraries the Vuforia Engine first of all worked, had a good documentation and a user friendly configuration. An important aspect is, that for non-commercial use it is free of charge.

The PARRHI implementation makes use of two image markers. One of them is attached directly at the robot's base and is of course used to synchronise the Real World with the majority of the AR World. Since the centre of origin of the robot was not at its base, but about 30 cm above the first joint, there is a small translation between the image markers position and the AR World's coordinate system. The second image marker is used to display the User's UI. The User is given a small sheet of paper with the said image on it, and the PARRHI system projects the User's tasks, some configuration and debug options onto it.

4.4.2 AR-Toolkit

Interacting with Augmented Reality objects is an essential part of AR environments. Fortunately, Microsoft's open sourced Mixed Reality Toolkit [38] makes this an easy task. The library directly integrates into the Unity environment and allows easy hand gesture recognition (pinching) for clicking and pointing at objects in the augmented space. Since both the HoloLens and the Mixed Reality Toolkit are developed by Microsoft, the library utilises all features and allows for an easy integration.

4.5 Robot Library

Next to the PARRHI library and Unity, the Robot library is the big third component in the PARRHI implementation. The following chapter will explain how we accessed the controller's data, transferred the data to the HoloLens and generally communicated with the robot. The whole Robot library was built together with Florian Leitner, who is currently writing his bachelor's thesis about a virtual programming environment of industrial robots at the same chair as I am. Since his thesis is being written at this very moment, I cannot reference to any source of his.

The Robot Library is responsible for the communication between any system that is capable of executing .NET framework applications, and the robot's controller R-30iB (see section 4.2). It is important to know, that Fanuc's controllers are not easily controllable by non-Fanuc components. Our goal was, to wirelessly control the robot from external devices that run .NET framework applications. Since there were no "plug and play" solutions available, we came up with the system, that will be explained in the rest of this chapter. As it has been done in the concept chapter, I will first shortly explain each component before elaborating on the information flow between them. Finally, I will give some details about the implemented, custom protocol we use. Fig. 4.9 depicts how the system is actually setup.

4.5.1 Robot Communication Architecture

The architecture can be split up into nine individual components, ranging from the actual commanding application to the robot itself. This architecture is tightly linked with the concept of the PARRHI system, thus many components can be recognised.

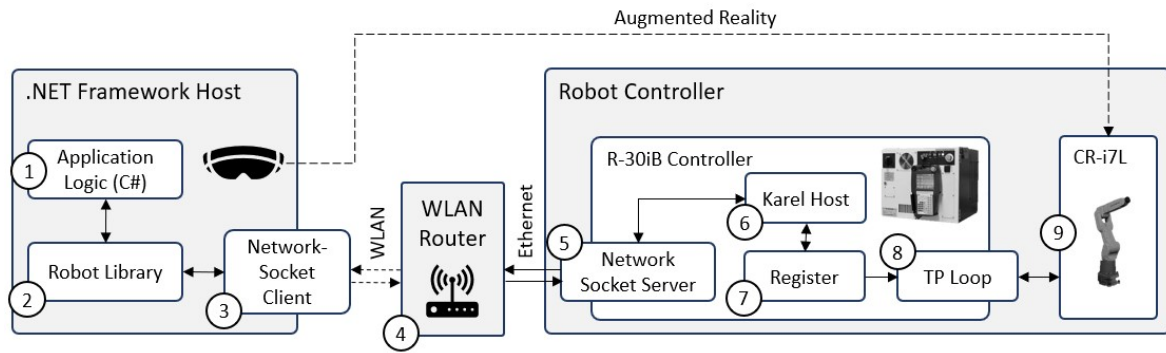


Figure 4.9: Robot library setup

- 1.) Application Logic: This is any application that wants to communicate with the robot. In my case the PARRHI system.
- 2.) Robot Library: A custom library written in *C#* that offers some wrappers around our custom protocol, which simply is a syntax we defined to transfer commands and data over the Network Socket. This protocol follows certain rules, so that both the KAREL Host and the *C#* Library can parse them to extract the important information in a standardised way.
- 3.) Network Socket Client: Standard Network Socket, where the PARRHI library represents the client.
- 4.) WLAN Router: Standard WLAN Router, which is connected to the controller via a standard patch cord.
- 5.) Network Socket Server: Standard Network Socket, where the R30iB controller represents the server.
- 6.) KAREL Host: A programm written in KAREL [39] that receives commands from the network socket, parses them according to the defined protocol and returns the requested data or executes the requested commands.
- 7.) Register: A storage that is used to command the Teach Pendant (TP) Loop (8), which also has access to this storage location. Some registers are used to set different modes like coordinate systems, absolute versus relative and so on, and six registers are used to transfer vectors, that the TP program should process according to the set mode.

- 8.) TP Loop: A program written in TP that scans the Register (7) every cycle, and controls the robot accordingly.

One can now see, that Application Logic (1) is the PARRHI itself. The network socket client(3) is the concrete implementation PARRHI's the in and output module and the complete Robot Controller is the "real world" excluding the end user.

Since researching the difference between KAREL and TP programmes on the internet is rather hard, because one simply does not find a lot of information about it, I would like to summarise our current knowledge about that. KAREL is a programming language, that is similar to Fortran. It was developed by Fanuc itself, and is used internally for a lot of components in the controller. Nowadays, KAREL is most often used for managing tasks like communication, synchronisation, data handling and so on. Teach pendant programmes on the other hand, are specialised on actually commanding the robot's movement and behaviour. TP supports numerous methods to control a robot, that the KAREL language simply does not offer. This is why, we chose to split up the controller-side software in these two programming components.

Now the information flow is as follows: First, the application (1), which wants to send a command to the robot has to call into the Robot Library (2). Besides managing the network socket connection (3), this library offers about 12 commands to the Application. A command could be the wish to fetch the robot's joint position, or to move the robot into a certain position. The Robot Library (2) then sends the command to the network socket (3), which is connected to the controllers server-endpoint. It is important, that the communication between the HoloLens (or a Laptop for instance) is wireless in order to stay mobile. The controller is connected to the WLAN Router (4) via a cable using the Ethernet protocol. There, the network socket server (5) receives the command, and passes it on to the KAREL Host (6). The latter then processes the command, which is described in the following section.

4.5.2 Robot Communication KAREL Host

At the point of reception, the command is only a string following a very specific syntax that we defined. The KAREL Host (6) then parses the command and acts on its instructions. If the command is a simple "Fetch Command", the KAREL Host (6) collects the needed data, constructs the message and sends it back via the network. If the command is targeted at the robot itself, the KAREL Host (6) fills the Register (7) with all necessary data that the TP Loop (8) needs to execute the movement command. This data is a six dimensional vector (coordinates in task or joint space), the mode whether the vector should be interpreted

absolutely or relatively to the current position, the coordinate system which should be used to interpret the six dimensional data and some internal flags.

The KAREL code consists of four main parts. There is the network communication, the command parsing, the data collection/register writing and lastly the response sending. The KAREL language makes it relatively easy to parse strings and write the logic components that are needed for the communication system. We tried to achieve as much as possible within the KAREL Host, and limit the parallel running TP Program to its speciality, which is controlling the robot physically.

4.5.3 Robot Communication TP Program

The TP Loop (8) itself is written in Fanuc's TP-Language. It basically is one large loop, that reads the Register (7) and acts on its instructions. There are some problems that had to be overcome though. For example switching between the relative and absolute movement mode has one very critical aspect: During absolute movements, the values in the Register (7) might be relatively high, since the task space coordinates are defined in millimetres. Values here are in a range from -700 to +700 mm. When interpreting these coordinates absolutely, that is not a problem since they are in the robot's range of motion. But after switching to the relative mode, these values are added to the current robot position, resulting in a huge step, which most probably is not within the range of motion any more.

Another example here is the switching of coordinate systems. When the current data in the register was inserted to be interpreted as joint coordinates, the individual values are in the range from about -360° to $+360^\circ$ (varying for each joint). This range includes values close to zero. A limit error would occur, if these were to be interpreted as task space coordinates suddenly, since Cartesian positions close to zero are not possible in the task space. Cases like these have to be thought of and handled.

Fig. 4.10 shows the TP Loop's Activity Diagram. Of course this is a rather simplified version, since almost every action depends on two register values, which represent the coordinate system and the relative/absolute mode.

Resetting the register's state at the very beginning is crucial, since the data registers are persistent stores, which means, that their value is saved even when the controller is shut down. The initialisation defines a clear behaviour at each launch of the program.

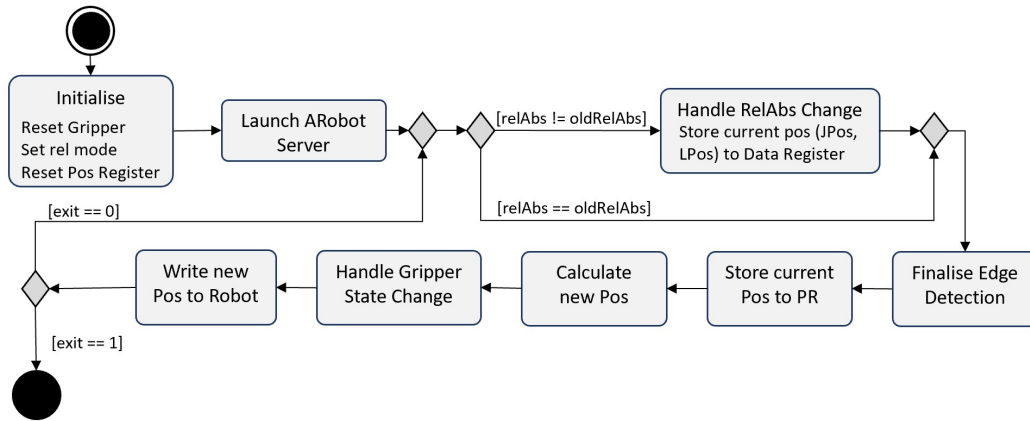


Figure 4.10

The *Launch ARobot_Server* action starts the KAREL Host, which communicates with any potential client via the network socket. After starting the KAREL Host, the program has to check if the relative/absolute mode has changed. If so, it handles this change to avoid unexpected behaviour due to old data in the registers. This is done via an edge detection, which needs an additional variable to store the previous mode.

The action *Store Current Pos to PR* fetches the current coordinate vector in the corresponding system (joint space or task space), which is then fed into the next action, which calculates the new target position vector. This action differentiates between the relative and absolute mode.

After the hand gripper state change is set, the new target position is written to the robot - again within the corresponding coordinate system. At the very end there is an *exit* flag, which can be set to '1' by the KAREL Host. This quits the KAREL and TP Programm and thus allows the client (.NET library) to send an exit command to the robot. This gives the controller an opportunity to safely shutdown the network socket and the TP Loop.

4.5.4 Robot Motion Group Management

One important aspect to mention is the motion control system, which all FANUC robots are subject to. Within the FANUC environment, the robot can be separated into motion groups, which are groups of moveable elements within a FANUC robot. One motion group may for example contain the first three joints, and another motion group could own the second three joints. Or, one group can also contain all joints. At runtime, a motion group can be physically

controlled by only one instance at a time. TP programmes, KAREL programmes and also the Teach Pendant are viewed as instances here. The reason for this is, to avoid cases, where undefined behaviour through double commanding might occur.

Since applications, which were developed in the PARRHI system, should both allow the user to jog the robot and then take over control programmatically through actions, the right to move the robot has to be managed. In this case there are two involved instances: The Teach Pendant and the TP Loop program.

The solution to this problem was, to implement a motion group control ownership management system. By default, the TP Loop would release the motion group control and not be able to move the robot, unless it really needs to execute a corresponding command. This means, that unless the TP Loop actively controls the robot, the Teach Pendant has the ownership over the motion group, so that the user can jog the robot.

Implementation wise, this was achieved by a "pause" flag in the data register. As soon as the KAREL program sets this pause flag to "1", the TP loop starts a second TP program called "Waiter", which does not have any motion control rights and then aborts its own execution - this actually releases the motion control. This waiter program simply waits until the pause flag gets reset to "0" by the KAREL program, and then restarts the TP loop. While the waiter program waits, the motion control rights are owned by the Teach Pendant, and thereby the user can take control over the robot. As soon as the PARRHI system has to control the robot, it activates the TP loop by setting the pause flag to "0", executes its movement command and then releases the motion control by setting the pause flag to "1".

4.5.5 Robot Communication Outcome

Basically, the presented architecture allows us to execute any pre-defined function in a fraction of a second. The whole process is actually so fast, that the PARRHI system fetches the robot's joint position in each iteration.

To finish this chapter off, I would like to shortly explain what the system is capable of doing. The Robot Library can get the robot's joint angles, TCP position and six dimensional force/torque sensor data. It can command the robot to drive to an absolute or relative task or joint space position and set a speed vector for the TCP and joint vector. Finally, there are commands that are mainly used internally at the moment, which release and claim the motion control. Generally, this system could be extended quite easily, by defining new commands in the robot library and the KAREL host.

4.6 Parametrised Program Implementation and Validation

One core component of the PARRHI implementation is the Parametrised Program. The document needs a hierarchical or at least well defined structure, since the content has to be imported (de-serialised). This automatic process only works seamlessly, if certain rules are kept perfectly. This is also why, it makes sense to validate the document before de-serialising it, since the PARRHI system has some presupposed assumptions about the document.

XML [33] seems to fulfil these requirements. XML documents are strictly hierarchically and have the big benefit of being human and machine readable. In PARRHI's case this is exactly what the document in question should be. Written by a human with possibly limited software engineering skills, but interpreted by a machine.

4.6.1 Parametrised Program XML Structure

The content of the Parametrised Program was thoroughly discussed in section 3.2.2. In this section, I would like to present the actual implementation and how a Parametrised Program written in XML would look like.

XML documents must have one root element. In PARRHI's case this is the "<PProgram/>" tag. Similarly to the conceptual train of thought, the actual implementation contains four children.

```

1 <?xml version="1.0"?>
2 <PProgram xmlns="PARRHI">
3   <Variables>...</Variables>
4   <Points>...</Points>
5   <Holograms>...</Holograms>
6   <Events>
7     <Trigger>...</Trigger>
8     <Actions>...</Actions>
9   </Events>
10 </PProgram>
```

Each child element of PProgram can now take their object definitions directly. Only the "Events" element categorises its content in two sub elements "Triggers" and "Actions". It is important to know, that every object defined in the Parametrised Program has to have a unique name attribute to identify it in other parts of the application.

The following block of code exemplary defines each object once. Please note, that this program is not written to actually do something meaningful, it only presents all ways to define objects in the Parametrised Program. Of course the Developer could use every object multiple times and also create multiple instances of the same object types, as long as their name is unique.

```

1 <?xml version="1.0"?>
2 <PProgram xmlns="PARRHI">
3   <Variables>
4     <Int name="Variable0">0</Int>
5   </Variables>
6   <Points>
7     <PointCamera name="CamPoint"/>
8     <PointFix name="FixPoint0" X="200" Y="-300" Z="300" />
9     <PointRobot name="RobotPoint0" J1="1" J2="2" Scale="0.6" />
10  </Points>
11  <Holograms>
12    <Cylinder name="Cyl0" point1="CamPoint" point2="FixPoint0" radius="10"
13      visibility="hidden"/>
14    <Sphere name="Sphere0" point="RobotPoint0" radius="25" renderMode="
15      transparent" visibility="visible"/>
16  </Holograms>
17  <Events>
18    <Trigger>
19      <DistanceTrigger name="DistanceTrigger0" canTrigger='true' point1="CamPoint"
20        point2="RobotPoint0" distance="15.5" actions="HoloStateAction0"/>
21      <VarTrigger name="VariableTrigger0" canTrigger='true' varName="Variable0"
22        triggerValue="2" actions="IncrVarAction0"/>
23      <TimeTrigger name="TimeTrigger0" canTrigger='true' timeSinceActivation="120"
24        actions="TriggerStateAction ChangeUITextAction0"/>
25    </Trigger>
26    <Actions>
27      <IncrementCounterAction name="IncrVarAction0" intVar="Variable0"/>
28      <SetHologramStateAction name="HoloStateAction0" onHolograms="Sphere1 Sphere2
29        Zyl2" offHolograms="Zyl1"/>
30      <SetTriggerStateAction name="TriggerStateAction0" triggerName="Trigger1"
31        canTrigger='true'/>
32      <ChangeUITextAction name="ChangeUITextAction0" text="Tutorial step nr. 4"/>
33      <MoveRobotAction name="MoveRobotAction0" target="100 100 100 45 15 0"/>
34      <SetRobotHandStateAction name="SetRobotHandAction0" state="open" />
35    </Actions>
36  </Events>
37 </PProgram>

```

It does not matter in which sequence all the elements occur. Only the hierarchically structure has to be kept exactly as the example document above. The PARRHI library will at some

point deserialise the Parametrised Program using a standard .NET Framework XML library. For this deserialisation a validation should be performed, in order to find flaws beforehand.

4.6.2 XSD generation and validation

The hierarchy of XML documents can be specified very detailed in XML-scheme documents, which are also called XSD files [34]. These documents define which element can or must occur at which location in the XML document, which attributes these elements can or must have and so on. The XSD file can even specify minimum and maximum values, data types and much more.

Hence, an XSD document is an essential part in the importing / validation process. Since writing these documents can be enormously work intensive, Microsoft has developed ways to generate XML schemes from a set of XML documents. Especially, when the underlying XML document may change repeatedly, it can be very exhausting to update the XSD file every time. For that I wrote a small *C#* application, that takes multiple .xml documents as an input, and outputs one XSD document that defines rules, which fit to all input XML files.

Another application developed by Microsoft called "xsd.exe" [40] allows to convert XSD documents into *C#* class definitions. During the development of this bachelor's thesis, I automated the process of generating the XSD file and from that the *C#* class definition, using the programming language Perl [41].

This means, that whenever an attribute had to be added to some xml element in the Parametrised Program, this attribute had to be added in one of the example input xml documents and the execution of the Perl script would then output new XSD documents and a *C#* class to deserialise the Parametrised Program.

One huge advantage of XSD documents and their validator is, that the latter can output exact error messages with what went wrong in the input xml document. This includes the type of error, line and column numbers, and (depending on the error type) suggests how to fix it. For the PARRHI system this means, that very exact feedback can be printed to the user if any errors occur. This makes it easier for non software engineers to accomplish their task.

5 Evaluation

Having developed the PARRHI system it is now time to ask, whether or not the end goal was actually achieved. For that, I will shortly summarize the requirements collected in section 3.1.1. The Developer (the person that uses the PARRHI system to create applications) has no to little software engineering skills but some knowledge about the robot industry. The person would like to reuse their previous work and create Augmented Reality Applications for other people to use. The application should transfer some knowledge, or give instructions on how to achieve a certain task.

This evaluation will consist of two different parts. First I will try to compare traditional AR programming methods with the PARRHI system, and then I will let other people try to succeed in a specific task that was given to them.

5.1 Evaluation 1: Comparing PARRHI with traditional methods

I will first define a use case for the evaluation, then pose as the "Developer" and actually develop such a AR application. First, it will be manually programmed without the PARRHI system. For future reference, this run will be called the "*manual attempt*". Then, I will attempt to achieve the same goal by using the PARRHI system. This run will be called the "*PARRHI attempt*". Both attempts will be timed and afterwards I will compare the Pros and Cons of each approach.

5.1.1 Evaluation 1: Use Case Definition

The following use case will be the base of my thesis' evaluation. As a context, I will use the same factory as explained in section 3.1.2.

The task, which will be supported by an Augmented Reality Robot Human Interface is the following. First, the employee using the AR application approaches the robot work cell and will then be commanded to walk over to a specific point, that is in a safe distance from the robot. After that, the person has to move the robot's TCP close to his position, so that they can touch the robot's tip. The user will be asked to remove the item in the robot's gripper and jog the robot back into its starting position. Having reached this position, the user will be told to move away into a marked area. The robot will then drive into his "zero" position, where all joint angles are 0 degrees.

This task involves multiple objects in the robot factory, including the robot itself, the user's position, jogging the robot and walking round. To keep the scope of this evaluation at a reasonable level, I will allow myself to reuse the Robot-Library and the image recognition parts for the *Manual attempt*.

5.1.2 Evaluation Manual Attempt

The manual attempt is defined by programming the task described above manually. I used the same programming language and game engine as I did during the development of the PARRHI system, which means, that I could reuse the complete project setup including libraries and tools. It took about 2.5 hours to develop a reasonably good framework that allows for an easy implementation of the task. For that, I reused the Robot forward kinematics model and the robot library that handles the communication between any .NET Framework application and the robot controller.

The implementation of the actual task for the AR application took about 1 hour. I implemented the steps relatively minimalistic, meaning, that I did not invest a lot of work and time into the styling of holograms and kept it at a basic level in general.

I will now summarize the downsides and benefits of the manual attempt, where unfortunately, the developer absolutely must be an experienced programmer, know the basics of forward kinematics, Unity, C# development, AR, Image tracking and more. Although the most complicated tasks like image tracking are done by some third party libraries, the developer has to know how to use them effectively. Also the Unity Engine is not perfectly intuitive, and might need some training time, to get up to speed.

The upside of course is, that any non-trivial task can be achieved. If one step in the application involves complex logic or simply some actions that are not supported by the PARRHI system, the developer can simply add the feature on the fly, because they are developing everything

in source code anyway. The downside of this is, that also the most trivial processes have to be worked out in source code every time they occur. Furthermore, developing the application in Unity itself means, that the product has to be compiled, built and then transferred to the HoloLens every single time something changes. This process takes about 3-5 minutes and is very error prone.

Depending on the project's architecture, one could get into trouble if some task requirements change. Reusing the accomplished work is possible, but it involves a number of steps, where each and every one can cause errors. In order to go into more detail here, I would have to explain how Unity works, which is not within the scope of this thesis.

5.1.3 Evaluation PARRHI Attempt

The PARRHI attempt means, that the same use case as above was be implemented using the PARRHI system. Based on the default template of the Parametrised Program, which contains the basic XML structure and defines the needed objects to animate the robot, it took about 15 minutes to complete the given task. It is important to mention, that I know the PARRHI syntax very well and did not need any time to get used to it. But, the same is true for the manual attempt with Unity.

The Parametrised Program for this task contains four point definitions, eight triggers for the individual steps and 21 actions that are executed by the triggers. This use case was easily achievable with the PARRHI system, because all needed actions are supported.

The structure is very easy. There are eight steps that represent eight individual phases in the task. Each step has one trigger, that marks its end and invokes the needed actions to transition into the next step.

5.1.4 Conclusion Evaluation 1

Comparing the two methods described above, I come to the conclusion, that using the PARRHI system definitely speeds up the development process but at the same time might limit the developer's possibilities.

For trivial tasks, the PARRHI system greatly speeds up and simplifies the development process of these applications. A potential developer needs much less time to get used to the

programming environment, than it would be the case with traditional programming and most importantly does not have to be a software engineer to do so. The developer can invest more time into the applications workflow using their domain specific knowledge, when using the PARRHI system, since all AR and many other aspects are done by the PARRHI system.

But PARRHI's strengths are its biggest weaknesses. As soon as a developer needs a feature that is not supported by the PARRHI system, other solutions have to be found. There is currently no way of extending the trigger/action system with custom objects. This is due to the big simplification that had to be undertaken in the concept of the Parametrised Program, so that non software engineers are able to develop Augmented Reality Robot Human Interfaces.

This limitation really only applies to specific features that are not supported by actions or triggers. The PARRHI system is indeed capable of creating high complexity workflows.. Parallelisation for example is not a problem in the PARRHI system. It would be perfectly fine to have two workflow branches running at the same time.

A solution to the mentioned weaknesses discovered in this evaluation will be proposed in section 6.4.

5.2 Evaluation 2: New Developers

As shortly described in this chapter's introduction, the second evaluation will test the systems usability by letting other people try to achieve a certain task. First, I will again define a Use Case for them to achieve and then summarise their findings and feedback.

5.2.1 Evaluation 2: Use Case Definition

The task for the experimentees will be to create an AR HR Interface with the Parametrised Program that helps the User to do the following task:

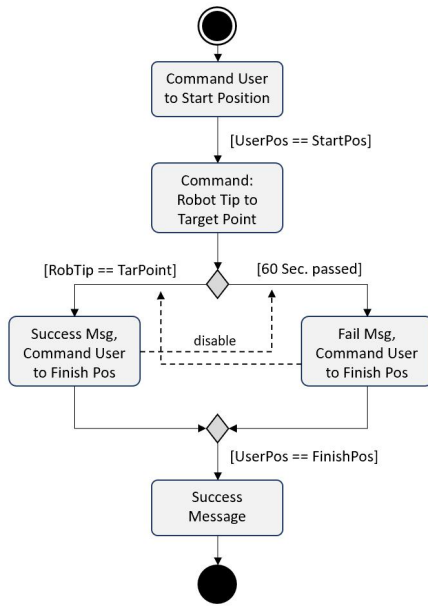


Figure 5.1

- 1.) The User should approach the robot safely by walking to the Start Position.
- 2.) Then, the robot should be jogged into a given position in under 1 minute.
- 3.) The application should then display a success or failure message according to step 2.
- 4.) In both cases, the user should be commanded to move away into the finishing position, such that the robot can not inflict any damage.

The coordinates of the Start, Finish and Robot-Target Points will be given to the experimentees. Fig. 5.1 depicts one solution to the given task as a workflow diagram.

Each experimentee will be given a 15 minute explanation of the PARRHI system, before attempting to succeed at developing the requested application. I will provide them with a cheat sheet, which shortly summarises all commands and object definitions. After they completed their task, they will be asked three questions, the answers of which will be summarised below. Their work will be timed and evaluated whether or not they actually achieved the goal.

5.2.2 Summary Evaluation 2

The second evaluation has been completed by six people, five of which are mechanical engineering and one a software engineering bachelor student. Five out of the six students reached their goal, with the average time being roughly 42 minutes, excluding the student who did not succeed, who took about 55 minutes while omitting the time limit during step 2. It is important to note, that all students heard about the PARRHI system and the parametrised program syntax the first time, and it was their first attempt of actually developing with it.

All students had some minor experiences with different programming languages, and about half of them are very experienced in different programming related technology stacks. None of them had any experience in Augmented Reality development.

Most experimentees took a chronological approach to the task. Most realised rather quickly, that they had to define the triggers deactivated and activate them when appropriate. In some but not all cases, the students lost the overview towards the end, since the given names of the parametrised program objects were not optimal. This resulted in confusion regarding the names of objects and occasionally misplacing some parameters.

After the students debugged their parametrised program within the simulated environment, I uploaded their project onto the used Microsoft HoloLens and let them test their application with the real robot.

All students were asked the same questions after they finished their assignment. The following listing displays the question and directly summarises the student's answers.

- 1.) *"How much experience do you have with AR development and programming in general?"*

All students had some basic experience with C programming. Some were very experienced in some other programming languages, but none of them ever developed an Augmented Reality application nor operated a robot. Only one of them actually used a head mounted Augmented Reality device.

- 2.) *"What do you think is the biggest advantage of the PARRHI system?"*

All experimentees said, that they would never have been able to fulfil the given task without the PARRHI system, since they either do not know C#, Unity or both. The software engineer, who had experience in Unity Game development answered, that it would have taken him much more time to achieve a similar result, even with his knowledge about Unity. Furthermore, they all liked the fact, that they saw immediate success with their first attempt of developing the AR application.

- 3.) *What do you think is the biggest disadvantage of the PARRHI system?*

Generally all students reported, that they either lost the overview (or were very close to do so) towards the end. The reason for that was the strict separation between triggers and their actions in the parametrised program.

Since their use case was crafted in a way, that it was possible to succeed with the PARRHI system, none of them saw a weakness in the PARRHI system's capabilities. During the discussion, they all agreed, that currently it is impossible to solve very specific problems, which require a different kind of trigger or action, since one cannot define custom version.

A solution to both mentioned problems will be proposed in section 6.4.

6 Conclusion

This final chapter will conclude this bachelor's thesis. After summarising the project and its biggest components, I will propose some solutions to solve the evaluated problems from section 5. After that, a section about a possible technology transfer will follow, which describes how the PARRHI system could be fitted to other hardware (robots, factory machines, AR devices), programming languages or also 3D game engines. The very last section outlines some future projects, which could build upon this bachelor's thesis.

6.1 Summary

Developing Augmented Reality applications needs a certain set of skills, which involves knowledge in different frameworks, programming languages and engines. In the industry professionals of their field often do not have any experience with AR development, which either results in no applications being developed, or Software Engineers being hired, which increases communication efforts, costs and possibly the time to market.

The presented system called "PARRHI" (Parametrised Augmented Reality Robot Human Interface) tries to solve the problem of interdisciplinarity by enabling people, who do not have any skills towards AR development or programming in general, to quickly and easily develop and execute AR applications for their specific domain.

The approach is, to create an abstract layer above all technicalities, that handle the Augmented Reality and real world communication components. The developer, which is the person with the specific domain knowledge, who wants to create such an AR application, now can focus on the application's workflow, and let the PARRHI system manage all other aspects like image tracking, AR, wireless communication with the real world and more.

To further support the developer, the PARRHI system follows a concept called "parametric thinking". This means, that the program, which is written by the developer, is parametrised

using placeholders. These placeholders can now be data which the PARRHI system discloses to the program, or also other objects defined in the parametrised program.

In conclusion, the developer's necessary skill set is limited to their specific domain knowledge. The PARRHI system handles all other aspects of AR Human Robot Interfaces on its own.

6.2 Solution to Problems found in Evaluation

The evaluation (see chapter 5) found two major flaws in the current concept of the PARRHI system. Firstly, the experimentees lost the overview of their own parametrised program. Secondly, the possible use cases are limited by PARRHI's predefined capabilities.

6.2.1 Solution to Problem 1: Overview and Program Complexity

This problem might be solvable in two distinct but not exclusive ways.

The discussion with the experimentees from evaluation 2 brought up, that a simple re-organisation of the parametrised program's structure could help to increase the overview. Namely, the separation of triggers and their corresponding actions in combination with the name referencing confused the developers, when their program grew in length.

By allowing actions and triggers to be defined underneath the same XML-parent element, the logical workflow could be represented in the program much better. Furthermore, adding the possibility to define "inline actions" would help to reduce the number of names (and with that the confusion) within a program.

Most of the time, one action was exclusively triggered by one trigger. This one to one relation, could be referenced implicitly by defining the action as xml-children of the trigger. As showed in the example below. A trigger would then invoke all implicitly referenced actions in addition to the ones defined with the `actions` parameter.

These implicitly referenced actions do not need a name parameter, since their execution is defined by their parent trigger.

```

1 <!-- Define Trigger -->
2 <DistanceTrigger name="DTrigger" point1="..." point2="..." distance="15"
   actions="...">
```

```
3 <!-- Define Action -->
4 <ChangeUITextAction text="You have reached your target successfully!"/>
5 </DistanceTrigger>
```

Another possible solution to reduce the confusion and complexity within the parametrised program would be a graphical editor, which generates the xml document. The syntax defined in the parametrised program is an almost perfect fit for UML activity diagrams (for reference, see Fig. 5.1.). A more thorough explanation of such an editor is defined in section 6.4.

6.2.2 Solution to Problem 2: PARRHI's Limitations

With the PARRHI system the developer can only perform actions, which are directly supported by the different types of actions. Whenever an action, which is not available in the PARRHI system, should be performed, the system reaches its limits. The same is true, if the application should display holograms in different shapes than spheres and cylinders.

This problem could be surpassed by allowing the developer to define custom implementations of certain components within the parametrised program. In the simplest case, this implementation could be provided in a specific *C#* source code file. The developer would get access to all parameters provided by the PARRHI system, and would also be able to reference objects defined within the parametrised program.

This way, the developer could setup and solve the simple parts within the parametrised program with the supplied object types, and implement everything else on his own. For example, if the developer needs a very specific trigger to be defined, they could achieve that, by directly implementing them in source code. The developer would still not care about any AR functionalities and can still focus on his domain knowledge.

The defined custom components could then be used in the parametrised program as any other type of trigger, provided they are implemented with the correct properties.

The actual usage could work in such a way, that developers continuously extend their custom implementations, and use them like normal elements in the parametrised program. In larger companies, one software engineer could take over the task of implementing these specific functionalities, and less skilled or specialised developers could use these custom elements in their parametrised program.

6.3 Technology Transfer

This section will describe what measurements had to be undertaken, in order to extend the PARRHI system as it is, for a wider variety of use cases and functionalities. The structure of this section will be grouped by technologies or components within the PARRHI implementation.

6.3.1 Replacing the Target Machine

In the provided implementation a Fanuc CR-7iA/L robot was chosen as a demonstrator for the PARRHI concept. Of course there is a big variety of desirable targetable machines, like other robot types from Fanuc or other suppliers, other machines like industry 4.0 machines etc.

The PARRHI library is written in a very modular manner. This means, that extending or replacing certain parts of it is very easy. To replace the target machine, one would only have to extend the Input/Output modules and the Real World Model, to be able to communicate with the desired machine.

At this point, I have to separate three different cases. Case 1 would be to communicate with another robot in the Fanuc product family. Case 2 is to communicate with an industrial robot of another brand and finally case 3 would be to include machines which are not industrial robots.

Case 1 is very easily achievable, since we built a working communication system for Fanuc controllers. In this case, only the Real World Model has to be updated, since the forward kinematics is based on this specific robot. The modification to involve other Fanuc robots would thereby only mean, to adapt the forward kinematic model's vectors and matrices as defined in section 4.3.3. Currently, this model is defined in source code, since in my specific implementation example I only had one robot to work with. So a generalisation would have been a slight overkill. Theoretically, one could simply expose the forward kinematics model via an Interface, and let knowledgeable developers implement their own robot.

Case 2 is a bit more tricky, since the communication problem has to be solved again. One could reuse the Robot Library (see section 4.5), and only replace the other endpoint of the network socket with the new robot. Of course the actual controlling and parsing of the commands on the robot side, would have to be rewritten on the specific system. Our current

KAREL / TP solution only works on Fanuc Robot-Controllers and not on any other type of industrial robot. Then again the forward kinematic's model would need an adaption to the new robot too.

Case 1 and Case 2 do not require any changes to the PARRHI system itself. The Parametrised Program could be used as it is. In case 3 though, this would likely change, since conceptually another machine is not the same as an industrial robot. The Distance Trigger for example would not make any sense, if the target machine does not have any moving parts. This means, that in addition to the communication module (Input / Output Modules), one would probably have to define new triggers and actions for the target machine, what requires changes to the PARRHI library itself. Since the PARRHI library is implemented with element base classes and inheritance structures, the implementation of custom triggers and actions is rather easy.

6.3.2 Replacing the AR / 3D Engine

The current implementation is uses the Unity Game Engine as a host. Since all the application logic (PARRHI Library) and also the Robot Library is implemented in engine independent .NET libraries, one could easily switch to any other 3D engine, which is capable of building for Augmented Reality Devices, and is able to include .NET dynamically linked libraries (DLLs).

The new implementation would have to implement three main aspects: Firstly, the engine has to host the PARRHI and Robot libraries, which is easy, as long as the engine's scripting environment supports .NET libraries. Secondly, the AR-Output Module has to be rewritten for the new engine. In my implementation, this only took about 30 lines of code. The AR-Output module only instantiates new Holograms in the engine's environment and displays them accordingly. Lastly, the image tracking problem would have had to be solved again. The used image tracking library (Voforia engine, see section 4.4.1) supports the Unity Engine, iOS, Android and UWP platforms. In principle, any library could be used.

For example, the Unreal Engine 4 [42] allows C# DLLs to be imported, and can thus work easily with the PARRHI libraries.

6.3.3 Replacing AR Device

Transitioning to another AR device is probably the easiest of all technology transitions. Unity itself supports building for multiple devices including mobile phones, desktop apps, HoloLens, consoles and more [43]. Basically, the new device only has to possess an accessible camera, which can be used for AR applications, and there has to be a 3D engine, which supports the device.

6.4 Future Work - A generalised Concept

Although the PARRHI system seems to be an interesting and promising approach, it is by all means not a perfect implementation. As the evaluation showed, there are some problems that exist in an academic environment. These problems are only expected to scale, when the system is brought into the industry.

As I mentioned in section 6.2, there are two major issues with the PARRHI system as of now. One being a lack of overview in the development environment, and the second being the lack of possibilities to easily extend and customise the PARRHI system, with other machines and functionalities.

As proposed, the first problem could be solved by some simple restructuring of the Parametrised Program, and by a graphical editor, which generates the XML code. With a graphical editor, the developer would not have to care about some syntax specific features and could focus on the application's workflow.

The second problem, which was the lack of extendability and customisability of hardware and functionalities, could be solved by increasing the modularity of the PARRHI system in three ways. The first adaption would have to be, to loosen the tight implementation of the Robot Library and generalising the concept to some kind of *generalised target*. Next, the PARRHI library would have to be adapted to allow the registration of multiple *target libraries*, which would communicate with different these targets. Lastly, these new targets will most probably have functionalities, which an industrial robot does not have. This requires the parametrised program to be customisable with new triggers, actions, points and even holograms. Fig. 6.1 shows an adapted architecture image from chapter 3.

This generalised concept of the current PARRHI concept would event allow multiple users to join one AR application, since a user could simply be represented by one of the real world

targets. Another interesting idea for such an endpoint target would be another computer to perform monitoring or archiving tasks.

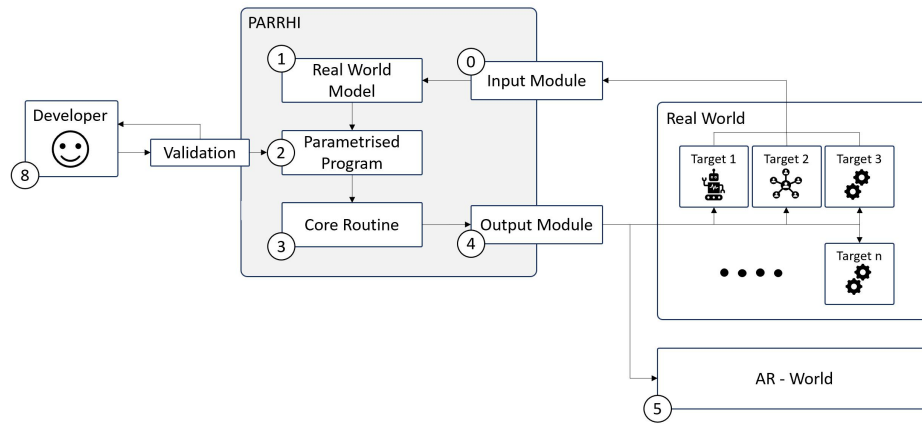


Figure 6.1

7 Bibliography

- [1] G. Klein, P. J. Feltovich, J. M. Bradshaw, and D. D. Woods, “Common ground and coordination in joint activity”, *Organizational simulation*, vol. 53, pp. 139–184, 2005.
- [2] C. Laschi, B. Mazzolai, and M. Cianchetti, “Soft robotics: Technologies and systems pushing the boundaries of robot abilities”, *Sci. Robot.*, vol. 1, no. 1, eaah3690, 2016.
- [3] M. Billinghurst, “Augmented reality in education”, *New horizons for learning*, vol. 12, no. 5, pp. 1–5, 2002.
- [4] U. D. o. L. Bureau of Labor Statistics. (2018). Occupational outlook handbook, software developers, [Online]. Available: <https://www.bls.gov/ooh/computer-and-information-technology/software-developers.htm> (visited on 03/28/2019).
- [5] H. J. Baker. (2017). 2018’s software engineering talent shortage — it’s quality, not just quantity, [Online]. Available: <https://hackernoon.com/2018s-software-engineering-talent-shortage-its-quality-not-just-quantity-6bdfa366b899> (visited on 04/25/2019).
- [6] R. T. Azuma, “A survey of augmented reality”, *Presence: Teleoperators & Virtual Environments*, vol. 6, no. 4, pp. 355–385, 1997.
- [7] A. Minds. (2019). Endgeräte für ar mr, [Online]. Available: <https://www.augmented-minds.com/de/erweiterte-realitaet/augmented-reality-hardware-endgeraete/> (visited on 04/25/2019).
- [8] C. Perey, T. Engelke, and C. Reed, “Current status of standards for augmented reality”, in *Recent Trends of Mobile Collaborative Augmented Reality Systems*, Springer, 2011, pp. 21–38.
- [9] P. Figueroa, R. Dachsel, and I. Lindt, “A conceptual model and specification language for mixed reality interface components”, in *VR 2006, In Proc. of the Workshop “Specification of Mixed Reality User Interfaces: Approaches, Languages, Standardization*, 2006, pp. 4–11.
- [10] W. Hoenig, C. Milanes, L. Scaria, T. Phan, M. Bolas, and N. Ayanian, “Mixed reality for robotics”, in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, IEEE, 2015, pp. 5382–5387.

- [11] I. Y.-H. Chen, B. MacDonald, and B. Wunsche, “Mixed reality simulation for mobile robots”, in *2009 IEEE International Conference on Robotics and Automation*, IEEE, 2009, pp. 232–237.
- [12] R. S. Magazine. (2018). The grand challenges of science robotics, [Online]. Available: <https://robotics.sciencemag.org/content/3/14/eaar7650> (visited on 04/25/2019).
- [13] P. Milgram, S. Zhai, D. Drascic, and J. Grodski, “Applications of augmented reality for human-robot communication”, in *Proceedings of 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS’93)*, IEEE, vol. 3, 1993, pp. 1467–1472.
- [14] M. Walker, H. Hedayati, J. Lee, and D. Szafr, “Communicating robot motion intent with augmented reality”, in *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, ACM, 2018, pp. 316–324.
- [15] V. Grozdanov, D. Pukneva, and M Hristov, “Development of parameterized cell of spiral inductor using skill language”, Apr. 2019.
- [16] M. Stavric and O. Marina, “Parametric modeling for advanced architecture”, *International journal of applied mathematics and informatics*, vol. 5, no. 1, pp. 9–16, 2011.
- [17] H. Seichter and M. A. Schnabel, “Digital and tangible sensation: An augmented reality urban design studio”, 2005.
- [18] F. D. Salim, H. Mulder, and J. Burry, “A system for form fostering: Parametric modeling of responsive forms in mixed reality”, 2010.
- [19] X. Wang, P. E. Love, M. J. Kim, C.-S. Park, C.-P. Sing, and L. Hou, “A conceptual framework for integrating building information modeling with augmented reality”, *Automation in Construction*, vol. 34, pp. 37–44, 2013.
- [20] B. A. R. Association. (2018). Robot programming methods, [Online]. Available: <http://www.bara.org.uk/robots/robot-programming-methods.html> (visited on 04/07/2019).
- [21] P. Diegmann, M. Schmidt-Kraepelin, S. Eynden, and D. Basten, “Benefits of augmented reality in educational environments-a systematic literature review”, *Benefits*, vol. 3, no. 6, pp. 1542–1556, 2015.
- [22] P. Salamin, D. Thalmann, and F. Vexo, “The benefits of third-person perspective in virtual and augmented reality?”, in *Proceedings of the ACM symposium on Virtual reality software and technology*, ACM, 2006, pp. 27–30.
- [23] S. Henderson and S. Feiner, “Exploring the benefits of augmented reality documentation for maintenance and repair”, *IEEE transactions on visualization and computer graphics*, vol. 17, no. 10, pp. 1355–1368, 2011.

- [24] T. J. McCabe, “A complexity measure”, *IEEE Transactions on software Engineering*, no. 4, pp. 308–320, 1976.
- [25] M. Corporation. (2019). Microsoft hololens, [Online]. Available: <https://www.microsoft.com/en-us/hololens> (visited on 05/15/2019).
- [26] F. Ltd. (2019). Fanuc, [Online]. Available: <https://www.fanuc.eu/uk/en> (visited on 05/15/2019).
- [27] —, (2019). Fanuc cr-7ia/l, [Online]. Available: <https://www.fanuc.eu/de/en/robots/robot-filter-page/collaborative-robots/collaborative-cr7ial> (visited on 05/15/2019).
- [28] —, (2019). Fanuc r-30ib, [Online]. Available: <https://www.fanuc.eu/de/en/robots/accessories/robot-controller-and-connectivity> (visited on 05/15/2019).
- [29] Schunk. (2019). Schunk gripper co-act egp-c, [Online]. Available: https://schunk.com/shop/de/de/Greifsysteme/SCHUNK-Greifer/Parallelgreifer/Co-act-EGP-C/c/PGR_3995 (visited on 05/15/2019).
- [30] M. Corporation. (2019). Microsoft .net framework, [Online]. Available: <https://docs.microsoft.com/en-us/dotnet/framework/> (visited on 05/15/2019).
- [31] —, (2019). Microsoft c-sharp, [Online]. Available: <https://docs.microsoft.com/en-us/dotnet/csharp/> (visited on 05/15/2019).
- [32] —, (2019). Microsoft .net class library, [Online]. Available: <https://docs.microsoft.com/en-us/dotnet/core/tutorials/library-with-visual-studio> (visited on 05/15/2019).
- [33] W3C. (2008). Xml specification, [Online]. Available: <https://www.w3.org/TR/xml/> (visited on 05/15/2019).
- [34] —, (2009). Xsd specification, [Online]. Available: <https://www.immagic.com/eLibrary/ARCHIVES/TECH/W3C/W090430S.pdf> (visited on 05/15/2019).
- [35] R. M. Murray, *A mathematical introduction to robotic manipulation*. CRC press, 2017.
- [36] U. 3D. (2019). Unity game engine, [Online]. Available: <https://unity3d.com/unity> (visited on 05/18/2019).
- [37] Vuforia. (2019). Vuforia ar engine, [Online]. Available: <https://developer.vuforia.com/> (visited on 05/19/2019).
- [38] M. Corporation. (2019). Microsoft mixed reality toolkit, [Online]. Available: <https://github.com/microsoft/MixedRealityToolkit-Unity> (visited on 05/19/2019).
- [39] Fanuc. (2019). Fanuc karel programming language, [Online]. Available: <https://www.fanucamerica.com/support-services/robotics-training/CourseDetails.aspx?CourseNumber=KAREL-OP> (visited on 05/19/2019).

- [40] M. Corporation. (2019). Xml scheme document tool, [Online]. Available: <https://docs.microsoft.com/en-us/dotnet/standard/serialization/xml-schema-definition-tool-xsd-exe> (visited on 05/20/2019).
- [41] P. organisation. (2019). Perl programming language, [Online]. Available: <https://www.perl.org/> (visited on 05/20/2019).
- [42] Epic. (2019). Unreal engine 4, [Online]. Available: <https://www.unrealengine.com/en-US/> (visited on 06/27/2019).
- [43] U. Technologies. (2019). Unity multiplatform support, [Online]. Available: <https://unity3d.com/de/unity/features/multiplatform> (visited on 06/27/2019).

Declaration

The submitted thesis was supervised by Prof. Dr.-Ing. Birgit Vogel-Heuser.

Affirmation

Hereby, I affirm that I am the sole author of this thesis. To the best of my knowledge, I affirm that this thesis does not infringe upon anyone's copyright nor violate any proprietary rights. I affirm that any ideas, techniques, quotations, or any other material, are in accordance with standard referencing practices.

Moreover, I affirm that, so far, the thesis is not forwarded to a third party nor is it published. I obeyed all study regulations of the Technical University of Munich.

Remarks about the internet

Throughout the work, the internet was used for research and verification. Many of the keywords provided herein, references and other information can be verified on the internet. However, no sources are given, because all statements made in this work are fully covered by the cited literature sources.

Munich, December 1, 2016

YOUR NAME