Comparing and Personalizing Human Following Behaviors for Mobile Ground Robots

Vergleich und Personalisierung des menschlichen Folgeverhaltens für mobile Bodenroboter
Bachelor thesis by Nathalie Woortman
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Abstract

The fundamental goal of robot development is to simplify tasks in everyday human life. These include various activities, such as assisting in the care of the elderly or the (partial) automation of manufacturing processes. An important component of many such systems, in which humans and robots collaborate on a task, is the functionality of the robot to autonomously follow a human. The human following must function robustly, but at the same time also take the social components of the human-robot interaction into account. In this thesis, we implement and evaluate three approaches to human following, which are based on the body tracking of the "Azure Kinect" camera on the robot "Turtlebot". In addition, user-configurable speed and distance limits are implemented to determine their impact on the user experience. The evaluation of the presented methods is first done in a simulation and then extended by a study with human test subjects, collecting data on their interaction with the robot. The experimental evaluation with 15 human subjects showed that the participants prefer following from behind rather than following from the side. The ability to adapt the following behavior by configuring parameters has improved the user experience.

Zusammenfassung

Grundsätzliches Ziel der Roboterentwicklung ist die Vereinfachung von Aufgaben im menschlichen Alltag. Zu diesen gehören diverse Tätigkeiten, zum Beispiel die Unterstützung bei der Betreuung von Senioren oder die (Teil-) Automatisierung von Fertigungsprozessen. Ein wichtiger Baustein vieler solcher Systeme, bei denen Mensch und Roboter gemeinsam an einer Aufgabe arbeiten, ist die Funktionalität des Roboters, autonom einem Menschen zu folgen. Das Folgen (engl. „Human Following“) muss dabei robust funktionieren, aber im gleichen Zug auch die sozialen Komponenten der Mensch-Roboter-Interaktion berücksichtigen. In dieser Arbeit implementieren und evaluieren wir drei Varianten des Human Followings, welche auf das„Body Tracking“ der Azure Kinect Kamera auf dem Roboter „Turtlebot“ basieren. Außerdem werden anwender- konfigurierbare Geschwindigkeits- und Abstandslimits implementiert, um deren Auswirkung auf die Benutzererfahrung zu ermitteln. Die Evaluation der vorgestellten Methoden geschieht zunächst in einer Simulation und wird dann auf eine Studie mit menschlichen Testpersonen ausgeweitet, bei denen Daten, über deren Interaktion mit dem Roboter erfasst werden. Die Experimente mit 15 Teilnehmenden zeigen, dass diese das Folgen von hinten einem seitlichen Folgeverhalten vorziehen. Die Möglichkeit zur Anpassung des Folgeverhaltens durch Konfiguration von Parametern hat die Nutzererfahrung verbessert.

Acknowlegements

The pandemic situation has challenged all of us. Therefore I am even more thankful for the support I got from the wonderful people I came along with. First of all, I would like to thank Dr.-ing. Dorothea Koert, who made this thesis as head of the research group IKIDA possible and who supervised my thesis. I am grateful for the encouraging support and the valuable feedback, I got from her. Furthermore, I would like to thank Lisa Scherf M.Sc., my co-supervisor, who was available throughout the time, for helpful discussions and for introducing me to the interdisciplinary research in psychology and computer science. I would like to thank Prof. Jan Peters for giving me the opportunity to work at the IKIDA group which is part of the Intelligent Autonomous System (IAS) group. Additionally, I thank the participants who attended the performed study. Finally, I would like to thank my family and friends, who motivated me during this time.

Contents

1. Introduction

1.1. Motivation

The incorporation of technical systems in human life is becoming more important in our everyday lives. Especially the development of robotics is an ongoing topic [1][2]. The greatest advantage of robots is their application in diverse areas ranging from manufacturing robots in the industry to service robots in elderly care [3].

In particular, *human following* of service robots is widely discussed [1][3][4][5][6]. Human following describes the behavior of a robot, which aim is to track a person and then autonomously follow the user.

The abstract idea of following a person is researched by considering different scenarios (see Figure 1.1). Underwater, robots mostly autonomously swim after a person and complete tasks [7]. A common example of aerial application is drones, which follow humans to support hands-free filming [8]. The application of ground mobile robots can be divided into indoor and outdoor. A typical usage of robots outdoors is to carry heavy loads. Service robots such as in elderly care can be found indoors [9]. Outdoor person following comes with special requirements for sensors considering e.g. changing lights, weather, and proper obstacle avoidance.

Figure 1.1.: Application scenarios a) Underwater b) Aerial c) Outdoor Ground d) Indoor Ground [10]

Considering indoor ground robots following humans, it is important to address *human-robot interaction (HRI)*. Successful interaction between robots and humans is characterized by socially aware behavior patterns, which are compatible with the user's perception [11][4]. An example of a social aware feature is the *proxemic awareness* by robots also known as *proxemics*.
Although proxemics is defined by Hall as the spatial behavior of people, it is also described as non-verbal and implicit communication[12][4]. The studies on proxemics are mostly on the human preferred space around them and its influence on behavior and interaction [11][13]. By firstly identifying the appropriate distance between humans and robots and then adapting it to navigation, the user's comfort can be improved [1].

Especially HRI has its advantage in the application of service robots. They can range from offering companionship and entertainment, assisting with the completion of daily tasks, and providing physical, mental, and social support (see Figure 1.2) [9].

Particularly, users who do not have much experience with robots and technical systems in general, rely on approaches that make it as easy as possible to adapt to the new tool [14]. In HRI elderly people are a special group of interest. They need more feedback and even an explanation for some behaviors [15].

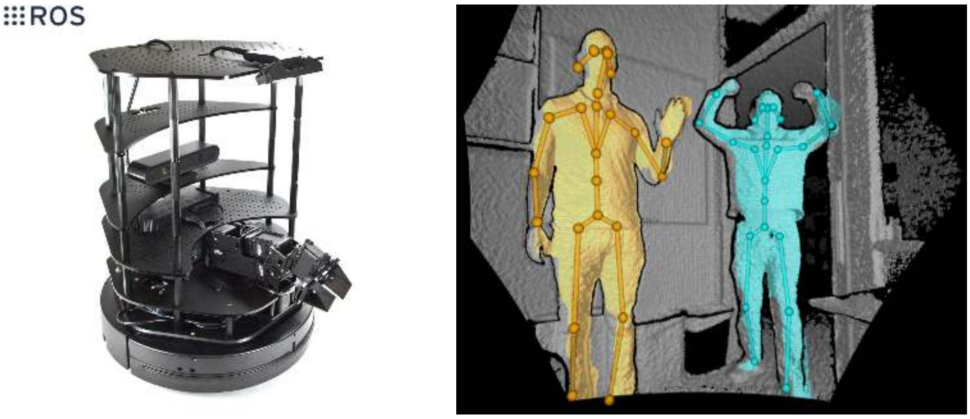
Figure 1.2.: Pictures taken during interactions between: an elderly and Nao (on the left), an elderly and Pepper (on the right) [16]

This work addresses personalizing human following behaviors using mobile ground robots indoors. The robot operates in a straight, flat, and controlled workspace including no incline or unevenness. Generally, the focus is to implement a human following scheme that provides a functioning following itself and goes additionally hand in hand with a pleasant perception of the robot by the user. Firstly, several human following schemes are fundamentally implemented. Then these behaviors are extended to use parameters, which take the velocity of the robot and the distance between the robot and human into consideration.

The aim is to improve by that the social awareness of the implementation and therefore the user experience. Eventually, these approaches are evaluated in simulation first and after that in a study with human subjects.

In this work, we use the robot *TurtleBot 2i* [1], pictured in Figure 1.3a). It is equipped with several sensors such as *Intel RealSense 3D Camera SR300-Series*[2], *Orbbec Astra Cam*[3], an *Azure Kinect DK*[4], and a *RICOH THETA V*[5].

The Azure Kinect camera is a golden standard regarding people tracking. The AI sensor provides an interface for solid body tracking as in Figure 1.3b.



(a) Picture of Turtlebot2i [17]

(b) Example of body tracking [18]

Figure 1.3.: TurtleBot and its usage of Azure Kinect

This thesis tries to use the mentioned body tracking to follow humans in a socially accepted way. The evaluation emphasizes the perception of users and how codetermination improves the following experience.

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[1] `https://www.trossenrobotics.com/interbotix-turtlebot-2i-mobile-ros-platform.aspx`

[2] `https://www.intel.com/content/www/us/en/products/sku/92329/intel-realsense-camera-sr300/specifications.html`

[3] `https://orbbec3d.com/`

[4] `https://azure.microsoft.com/en-us/services/kinect-dk/`

[5] `https://theta360.com/de/about/theta/v.html`

1.2. Structure of this Thesis

This thesis is structured in the following chapters:

Chapter 2 provides an overview of the related work to the current research state of human following. Especially human-robot-interaction in human following is addressed.

Chapter 3 defines a problem statement and gives an introduction on different following methods and how to personalize them.

Chapter 4 presents the implementation of the human following framework.

Chapter 5 presents the evaluation of the behavior and the human's perception. It shows the experimental results of the three implemented approaches

Chapter 6 resumes the outcome and discusses future work in the field of human following

The **Appendix** contains the questionnaires and the results of the performed study on the perception of human following.

2. Related Work

This chapter briefly summarizes the related work on human following behaviors. Furthermore, research is presented, which draws attention to different methods to incorporate social awareness in human-robot interaction.

2.1. Human Following Strategies

Researching on human following, Honig et al. compare several approaches and present a systemic approach for designing robotic person-following behavior [1].

Gockley et al. investigate the natural person following behavior [19]. After a person is tracked with a laser-based approach, either a direction following or a path following is run. In direction following, the robot drives towards the current position of the tracked person. This is combined with a local obstacle avoidance called the *Curvature-Velocity-Method*. This method defines the problem as a constrained optimization in velocity space considering physical limitations and the environment [20]. In contrast, the path following is archived by using the *Pure Pursuit Path-Following Algorithm*. It is calculating the curvature moving the vehicle from its current position to a goal position. The goal position is a distance ahead of the vehicle on the path selected [21]. The evaluation showed that the direction following was perceived as more human-like.

The work by Doisy et al. presents an adaptive person following which dynamically generates the path of the robot in a pre-mapped environment. The comparison in Figure 2.1 shows that the adaptive person following takes shorter paths than the regular path following algorithm. The adaptive person following is following the human with less distance than the path following [22].

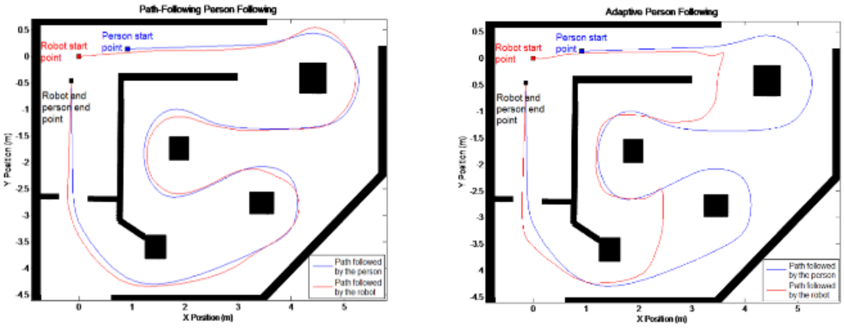


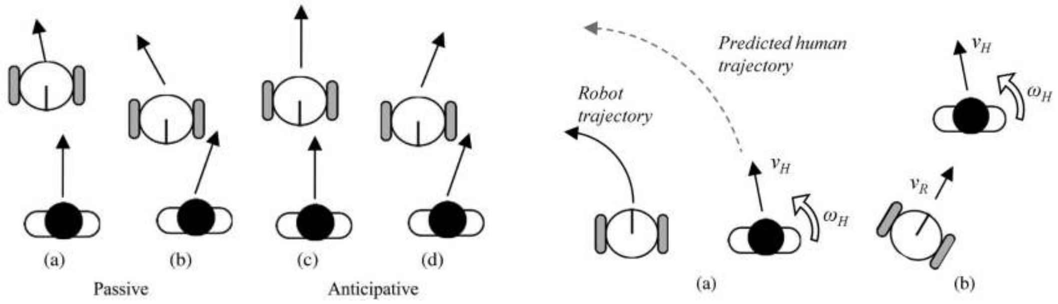
Figure 2.1.: Comparison of path following (left) and adaptive person following (right) [22]

Jevtić et al. compare three natural interaction modalities for the guidance of a mobile robot. By pushing the robot, users apply *direct physical interaction (DPI)* to displace the robot. Using 3-D vision-based human-skeleton-tracking, also walking in front of the robot is possible. The robot follows the user at a safe distance. Pointing towards a desired location on the floor with the right hand is as third interaction modality discussed. After the user raises his or her left hand above the level of the left elbow, the robot stops. If the hand is put down (see Figure 2.2), the robot continues driving.

The evaluation contains two scenarios. Firstly, the user had to guide the robot through three different areas in an apartment, which were marked on the floor. The second task included following three exact waypoints. The evaluation showed that DPI was the fastest, then follows the human following and pointing is the slowest considering the completion time. Also, the study showed, that DPI was more accurate, the participants stated it was connected with less mental demand, less effort, less frustration, and had the feeling to perform better [3].

Figure 2.2.: Interaction modalities: person following (left); pointing control (center); direct physical interaction (right) [3]

A presentation of an anticipative human-following behavior including human tracking, a human walk model, and a control strategy is given by Hu et al. They evaluated following from behind, following on the side, and following in front. Evaluation showed an improvement of the following algorithms when using a combination of anticipative and passive behaviors. Whereas the robot cannot follow the human walking direction with behavior if it is not aligned with the human as in Figure 2.3a, with the anticipative behavior it is possible. The behavior is switched if the distance between user and robot is below a predefined interaction distance as in Figure 2.3b. [23].



(a) Comparison of alignment [23]

(b) Comparison in a curve [23]

Figure 2.3.: Comparison between passive and anticipatory behaviors

An overview of other techniques for human following, which are described in papers, is given in Table 2.1

Table 2.1.: An overview of the research on human following

Ref	**Sensor**	**Tracking Type**	**Path Planning**	**Relative Position**	**Variable Velocity**	**Variable Distance**	**Social Aspects**
[3]	Kinect	Skeleton	Direction	Not mentioned	No	No	Workload
[24]	Kinect	Skeleton	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
[25]	Kinect	Skeleton	Direction	Behind	No	Yes	Comfort
[26]	Kinect	OpenPTrack	Direction	Behind, angle	No	No	Not mentioned
[27]	Kinect	Skeleton	Direction	Not mentioned	No	Not mentioned	Interaction
[22]	Kinect	Skeleton	Path Adaptive	Behind	No	No	Not mentioned
[14]	Kinect	Skeleton	Direction	Behind	No	No	Elderly
[28]	Kinect	Skeleton	Direction	Not mentioned	No	No	Comfort
[29]	Laser scan	SLAM, conceptual mapping	Not mentioned	Behind	Yes	Yes	Distance, context knowledge
[30]	Laser scan	Particle filters, statistical data association	Not mentioned	Not mentioned	No	No	Not mentioned
[31]	2 CCD cameras	ApriAttenda^{TM}	Not mentioned	Not mentioned	Not mentioned	No	Not mentioned
[32]	Laser scan	Map-based	Direction	Side, behind	No	No	Distance
[33]	Laser scan	HumPos	Direction	Side, behind	No	Yes	Distance
[34]	Kinect	Skeleton, walking gait	Not mentioned	Not mentioned	Not mentioned	Not mentioned	Not mentioned
[35]	Kinect Laser scan	Not mentioned	Direction	Behind	Yes	No	Trust, comfort
[36]	Stereo cameras	Binocular sparce feature segmentation	Direction	Behind	Yes	No	Not mentioned

2.1.1. Human Tracking

The realization of tracking humans is discussed in several papers [2][3],[37] and see Table 2.1. Generally, either an *Azure Kinect* [1] or a *Time of Flight (ToF)*[2] is used. One of the advantages of using the Kinect is the real-time object segmentation of depth images at the rate of 30 fps, which is based on distance gradient and insensitive to variable lighting conditions [3]. The Kinect also provides a skeleton tracking algorithm, which is capable of tracking multiple human bodies at once. A skeleton is annotated with an ID and is subdivided into 32 joints [38].

Schwarz et al. propose in [2] a method for full-body pose tracking of a human so that it fits gesture-based interaction. They test their approach with both cameras whereas, on one hand, the Kinect had a better resolution and less noise than ToF. On the other hand, they showed that ToF was less computational exhausting.

To optimize human tracking Luber et al. presented an approach to predict human movements with a place-dependent motion model for specific places. They extended the tracker with spatial priors so that possible paths can be predicted, which leads to a more accurate human following [5].

Doisy et al. address the problem of autonomous person tracking. While in other approaches the user has to make sure to be perceived by the robot, this method makes use of external sensors helping the robot to autonomously ensure to perceive the user. They use different following behaviors and gestures to start and stop the behavior [6].

2.2. Personalization of Following Behavior

Combining human following with social aware features is not in every approach discussed. The overview in Table 2.1 shows that most of the research is centered around the spatial behavior of humans and robots.
The improvement of comfort in human following is investigated by Sun et al. focusing on varying the distance between humans and robots [25]. They showed that users experience more comfort with models taking a variable distance into account than in traditional. The proposed *Human Comfort Following Behavior* is based on human factors which are used in the human following.

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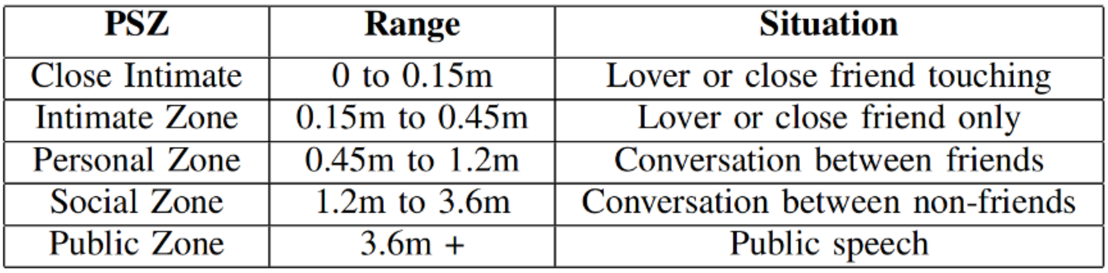
[1] `https://azure.microsoft.com/en-us/services/kinect-dk/`
[2] `https://pmdtec.com/en/technology/time-of-flight/`

2.2.1. Proxemics in HRI

The proxemic behavior of robots is stated as important due to working in environments with little distance between the robot and human [4].

The work of Lehmann et al. focuses on the role of personal spatial zones in context of human-robot interaction. Humans have different zones at different distances which are used in specific situations (see 2.4). In the study, the participant approached the robot and entered its personal space of the robot (See Figure 2.5. Then the robot started gazing at the person. If the participant intruded of its intimate space, it leaned back.



PSZ	Range	Situation
Close Intimate	0 to 0.15m	Lover or close friend touching
Intimate Zone	0.15m to 0.45m	Lover or close friend only
Personal Zone	0.45m to 1.2m	Conversation between friends
Social Zone	1.2m to 3.6m	Conversation between non-friends
Public Zone	3.6m +	Public speech

Figure 2.4.: Human personal spatial zones (PSZ) for northern Europeans [11]

(a) Experiment setup (b) Spatial zones of human and robot (c) Participant gazes at robot

Figure 2.5.: The experimental setup by Lehmann et al. [11]

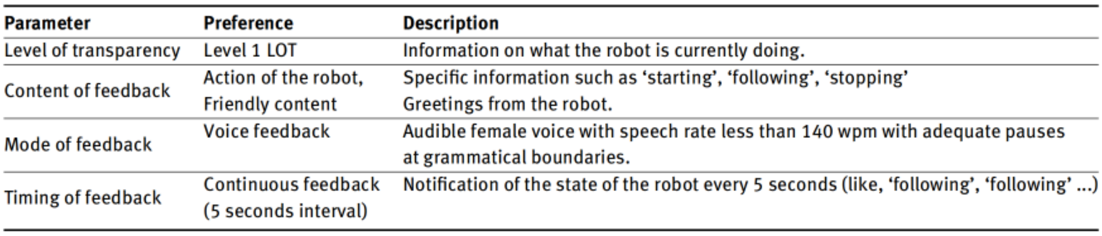
The result showed that the average approach distance to the robot was 48cm which represents the inner limit of the human-size personal zone. This means that the participants did not scale down the zones to the size of the robot, which should have been between 16 and 42cm (representing the human-robot personal zone). Also, the action of leaning back was received correctly as an intrusion of the robot's personal space [11].

Siebert et al. study the user experience concerning the proximal behavior of robots, which have the task to follow humans. Their study included an investigation of the influence on the participant's perception of distance and lateral offset of humans following robots. They conduct that users prefer robots being in the social space without a lateral offset. They also showcased that a high technological affinity leads to preferring closer following distances of robots [4].

The following work of Siebert et al. ties in with the human-robot interaction. It states that human-robot interaction cannot be one-to-one transformed on human-human interaction. Studies show that participants keep a larger distance from robots than humans, even if both of them are carrying a valuable personal item [13].

Petrak et al. assume that a robot provides an improved user experience if they make a good first impression. Additionally, robots could improve this perception by acting in a proxemic aware manner. They used a virtual reality setup and simulated scenarios with a proxemic-ware robot and a non-proxemic-aware one. Evaluation shows that an appropriate proxemic-aware following has caused a perception of anthropomorphism and trustworthiness by users [39].

The interaction modalities for elderly are inspected in the work of Olatunji et al. They studied feedback parameters for socially assistive human following such as feedback time and mode. Figure 2.6) shows the parameters which were chosen to adapt the system to be more comfortable for elderly.
Results showed that elderly people favored continuous minimal information feedback and not rare feedback providing only important information. Additionally, voice feedback was preferred over tone. Also, older people wanted to know what the robot is doing but they do not need the system to be completely transparent. They prefer minimal information at short intervals [35].



Parameter	Preference	Description
Level of transparency	Level 1 LOT	Information on what the robot is currently doing.
Content of feedback	Action of the robot, Friendly content	Specific information such as 'starting', 'following', 'stopping' Greetings from the robot.
Mode of feedback	Voice feedback	Audible female voice with speech rate less than 140 wpm with adequate pauses at grammatical boundaries.
Timing of feedback	Continuous feedback (5 seconds interval)	Notification of the state of the robot every 5 seconds (like, 'following', 'following' ...)

Figure 2.6.: Feedback design parameters [35]

3. Approach

This chapter presents the definition of the problem statement of human following. After that methods for improving social awareness are described.

3.1. Problem Statement

In this thesis, we consider a mobile ground robot, namely the TurtleBot2i, that should follow a single person. The following behavior takes into account the position of the robot $p_r = (x_r, y_r, z_r)^T$, orientation $q_r = (a_r, b_r, c_r, w_r)^T$, velocity $v = (v_x, v_y, v_z)^T = (v_{\text{lin}}, v_{\text{ang}})$ as well as the humans position $p_h = (x_h, y_h, z_h)^T$, orientation $q_h = (a_h, b_h, c_h, w_h)^T$ and velocity $u = (u_x, u_y, u_z)^T$.

In this thesis, the goal is to compare different approaches to human following, which is depicted in Figure 3.1. The robot should approach the human and plan a path toward the human's position. In the meantime, the human could move so the position would change, leading the robot to start a new calculation of the path. While approaching the human the minimum distance x_{min} should be considered.

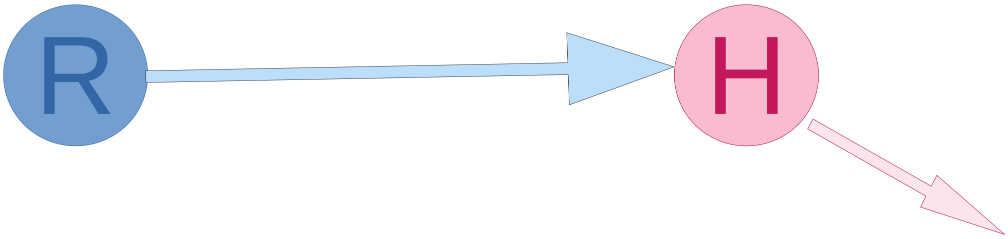
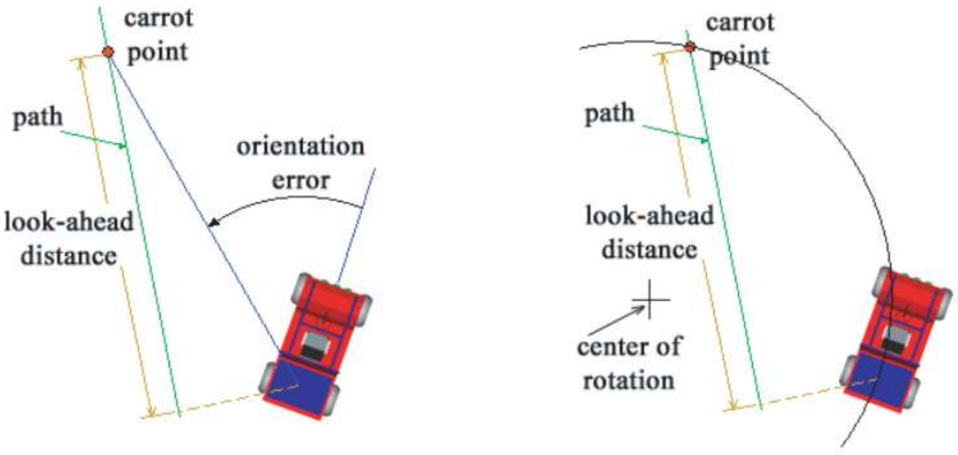


Figure 3.1.: An example for human following. The human H is followed by the robot R. The positions p_r and p_h are marked as a circle with the according letter R or H

3.2. Path Tracking Approaches

To archive this, a control has to be used. In literature, a common technique of using a control in path tracking approaches is the *Follow-the-carrot* approach [40]. The robot aims directly toward a goal, also known as a carrot point, by minimizing the orientation error e (see Figure 3.2a). This is tied up with two major drawbacks: First, the robot could oscillate about the path, for example if the speed is too high. Second, when immediately turning to another carrot point, this approach leads to cutting corners instead of driving around them [40].

An improvement of this approach is the *Pure pursuit* approach [41]. It is based on follow-the-carrot but additionally a circle is fit between the current pose of the robot and the position of the carrot point. Therefore, the robot tracks the resulting circular arc, which is depicted in Figure 3.2b. The *Screw theory*-based control ensures that the robot arrives with the correct orientation and curvature at the carrot point. This is done by minimizing simultaneously the position and orientation errors, mostly as an objective function that is a weighted sum of the errors [40].



(a) Follow the carrot

(b) Pure Pursuit

Figure 3.2.: Control approaches for path tracking al. [40]

However, the performance of the follow-the-carrot approach could be readily improved by using a PID controller as control law for this algorithm [40].

In this work, we implement a follow-the-carrot approach with a PI control. In testing the control has been performing efficiently enough, so that the derivative term has not been required to use.

The definition of the PI control is now given. The proportional term of the control can be defined as

$$y_P(t) = k_p \cdot e(t) = k_p \cdot (v - u)$$

and the integral term as

$$y_I(t) = k_I \cdot \int_0^t e(\tau)d\tau = k_I \cdot [p_h - p_r]_0^t$$

So the controller will be defined as

$$y = y_P + y_I = k_p \cdot e(t) + k_I \cdot \int_0^t e(\tau)d\tau = k_p \cdot (u - v) = k_I \cdot [p_h - p_r]_0^t$$

In this thesis, we reference the result from the control calculation as $c = (c_x, c_y)$.

3.3. Considered Following Behaviors

This section gives an overview of the considered human following behaviors.

3.3.1. Direction Following

Direction following takes the current position of the human into account. First, the robot registers the user's position. Then the robot starts to drive directly towards the registered human position [1]. If the user's position changes, because, the participant moves, for example, the robot incorporates the new position and drives towards it. The robot stops only, if the human waits at a waypoint or terminates the behavior by intervention.

Direction Following from Behind

Direction following from behind is pictured in Figure 3.3. The robot approaches the user form behind. Its implementation is pictured in Figure 3.4. Here, it is not necessary to differentiate between the robot following a human facing only from the front or from the back.

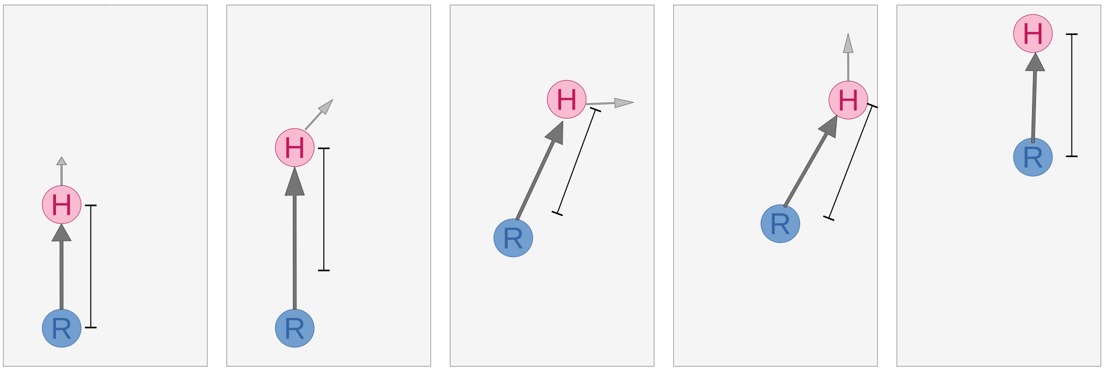


Figure 3.3.: Illustration of direction following from behind. The dark line shows the minimum distance that is considered.

By starting the following, the robot waits until it receives information about the position of the human.
If the distance between the human and the robot exceeds the predefined maximum distance, the robot stops. Otherwise, there is a check if the distance is smaller than the predefined minimum. If not, the robot drives forward towards the received human position. The linear and angular velocities $v_{\text{lin}}, v_{\text{ang}}$ for driving forward are computed as followed:

$$\begin{aligned} v_{\text{lin}} &= c_x \\ v_{\text{ang}} &= c_y \end{aligned} \tag{3.1}$$

The distance being fallen below the minimum distance, there is a test if the distance is below a share p of the minimum distance. The share can be adapted. We have used $p = 0.9$ as share. If this case happens, the robot stops immediately, or else the robot drives backwards to ensure the minimum distance between robot and human. The velocities are computed as in Equation 3.2.

$$\begin{aligned} v_{\text{lin}} &= -(x_h/(x_{\min})) \cdot abs(c\_x) \\ v_{\text{ang}} &= c\_y \end{aligned} \tag{3.2}$$

There has been the need to introduce an additional term to the output of the control because the robot has to drive backwards and for this reason command velocities have to be negative. Also the nearer the person gets to the robot, the faster the robot has to drive to maintain the minimum distance.

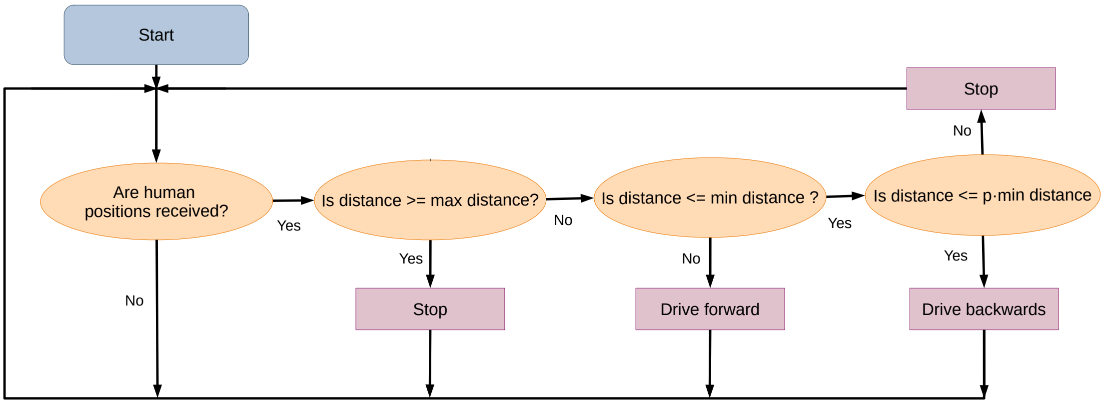


Figure 3.4.: Algorithm scheme of direction following from behind

Direction Following Side

The lateral direction following simulates the walking of two persons or a human and a dog side by side [1]. An example is shown in Figure 3.5.
Additionally, the approach shown in Figure 3.6 firstly checks if the robot is positioned laterally to the person. Possibly the robot has to drive to a position so that it stands side by side with the human. After checking the distances, the robot drives either backwards and forwards taking an offset to the human into account.
If the robot loses the user, it starts a recovery behavior explained in subsection 4.4.6.

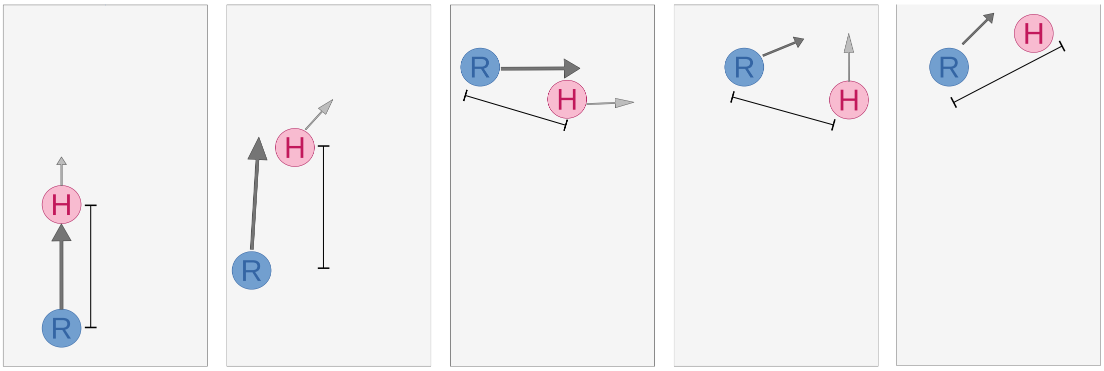


Figure 3.5.: Illustration of direction following from side.

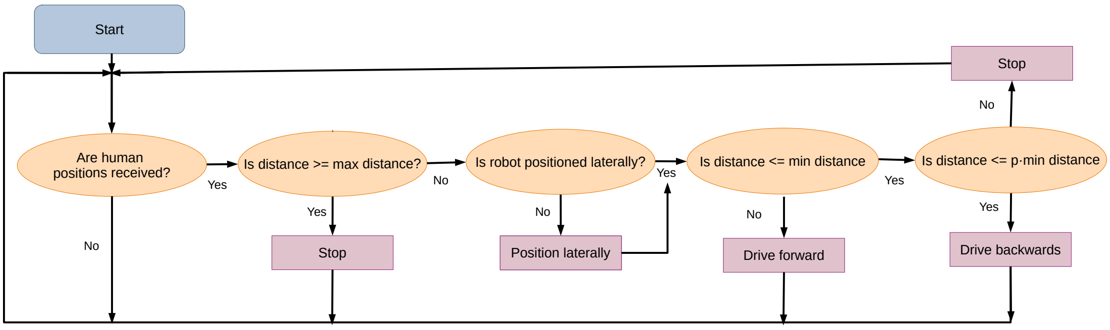


Figure 3.6.: Algorithm scheme of lateral direction.The dark line shows the minimum distance that is considered.

3.3.2. Path Following

If path following is used, the robot follows exactly the registered user's path [1]. This kind of human following makes our setup only following from behind reasonable. While the robot registers human positions, the robot drives from one saved position to another as pictured in Figure 3.7.

In contrast to all before mentioned approaches, this algorithm implements path following instead of direction following. The registered human positioned are firstly saved and secondly filtered. Firstly the amount of positions which are to similar to each another one are removed. We use euclidean distance [42] as our similarity measurement. A

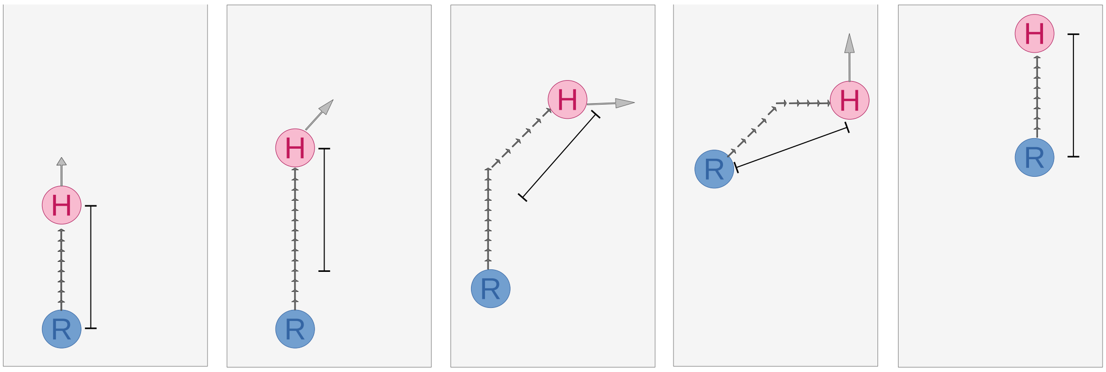


Figure 3.7.: Illustration of path following. The dark line shows the minimum distance that is considered.

new position is only registered if the similarity between the last registered position and the actual one is beneath a given threshold. After that, a *Savitzky-Golay filter* is applied to the buffered position list. The continuous trend within the data points leads to a smoother following. The Savitzky-Golay filter smooths data by fitting low-degree polynomial functions with the method of linear least squares [43].

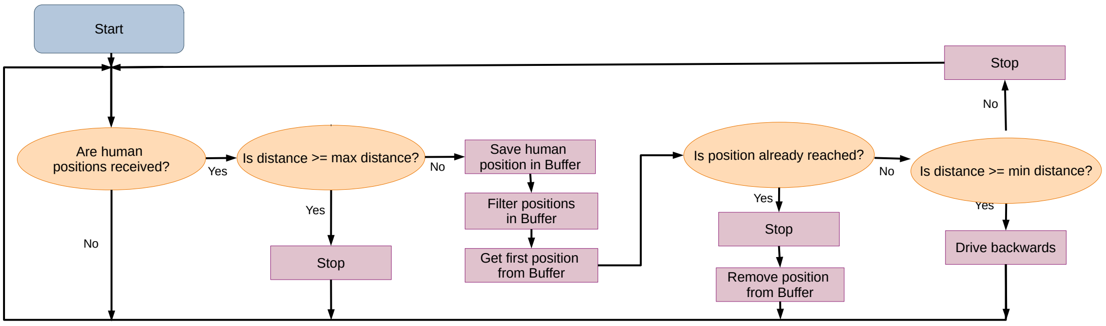


Figure 3.8.: Algorithm scheme of path following

Only if the distance between the robot and the human match accordingly the predefined maximum and minimum variables, the robot starts to drive towards a buffered position. The algorithm, which implements driving to a position from the buffer, is depicted in Algorithm 1.

When driving towards human poses, the robot takes the angle between itself and the position into consideration.

Algorithm 1 Drive towards a desired Position

```
$x_r \leftarrow robot.position.x$
$y_r \leftarrow robot.position.y$
$x_h \leftarrow buffer.human.position.x$
$y_h \leftarrow buffer.human.position.y$
$\theta \leftarrow convert(robot.orientation)$
$\alpha \leftarrow rotation\_angle$
$d \leftarrow min\_distance$
while not $r.reached(h)$ do
    $d_x \leftarrow x_h - x_r$
    $d_y \leftarrow y_h - y_r$
    $\alpha \leftarrow atan2(d_x, d_y)$
    if $abs(\alpha - \theta) > \alpha$ then
        if $d_x >= d$ or $d_y >= d$ then
            $v_{\text{lin}} \leftarrow 0.5$
        else
            $v_{\text{lin}} \leftarrow 0.0$
        end if
        $v_{\text{ang}} \leftarrow \alpha - \theta$
    else
        $v_{\text{lin}} \leftarrow 1.0$
        $v_{\text{ang}} \leftarrow 0.0$
    end if
end while
```

If the robot loses the user, a recovery starts to ensure that a human is being observed again (see subsection 4.4.6).

3.4. Personalization

This section describes how the following behaviors are extended to improve the social awareness.

3.4.1. Proxemics

To ensure that the robot is moving in a socially aware manner, proxemics are taken into account while implementing the behaviors [4]. This means, that the approaches make sure that the robot does not decrease the distance to the participant below the minimum distance. In direction following the robot moves backwards, if the user walks towards it.

3.4.2. Adapting Parameters

In this work, we have considered providing an option to adapt the velocity of the robot and the distance between the robot and the user. The implementation can be looked up in subsection 4.4.1.

4. Setup and Implementation

This chapter firstly describes the setup in simulation and secondly on the real robot. Then, the fundamental parts of the implementation are introduced. The previously presented algorithms are implemented using *Robot Operation System (ROS)*[1]. Most of the code is written in *Python*[2] with some exceptions in *C* ++[3], *JavaScript*[4] , and *HTML*[5].

4.1. Simulation-based Setup

We used *Gazebo*[6] as simulator for the simulation of the Turtlebot and the human. Besides the representation of the Turtlebot and one of a human pose, the simulation itself does not require a specific setup. The robot starts at the starting position $s = (x, y) = (0, 0)$. The pose of the human and its movement are modeled as a marker with a pose and a form of visualization in *RViz*[7]. These positions are published by a `human_pose_publisher` (See subsection 4.4.2). The published data is used in the human following to calculate a goal position. In the end, the robot follows a red human marker as in Figure 4.1.

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[1] `https://www.ros.org/`
[2] `https://www.python.org/`
[3] `https://cplusplus.com/`
[4] `https://developer.mozilla.org/en-US/docs/Web/JavaScript`
[5] `https://developer.mozilla.org/en-US/docs/Web/HTML`
[6] `https://gazebosim.org/`
[7] `http://wiki.ros.org/rviz`

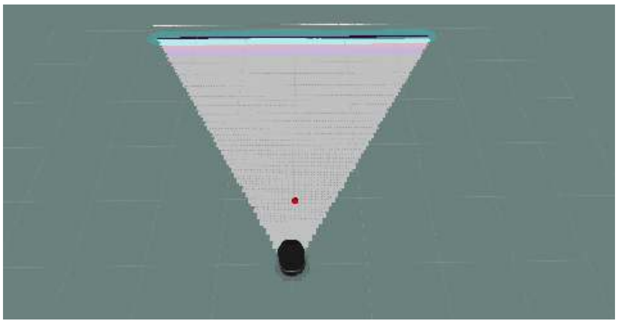

Figure 4.1.: The marker (in red) is followed by the Turtlebot (in black)

4.2. Robot Setup

The goal was to test our approach with a robot and humans. Therefore we used a Turtlebot, which is mainly equipped with computing units, an Azure Kinect, a RICOH THETA V and a speaker. To estimate the human positions, we utilized the Azure Kinect with its pre-build body tacking. It is capable to track multiple bodies at the same time. A body is defined as a skeleton with 32 joints. The position and orientation of every joint is designed as an own right-handed coordinate system. These joints are connected and follow a joint hierarchy with the pelvis being the origin [38]. Figure 4.2 displays exactly the dependencies of those connections between each joints. The distances between the coordinates and especially between the camera and the skeleton ist calculated by the use ot the integrated depth camera. By transforming the frames into the `base_link` frame of the robot, the positions between human an robot can be estimated.

If the Azure Kinect is not geared towards a human , the approach switches to use the RICOH THETA V. The 360°camera, combined with the *MediaPipe Pose*[8] software, can also provide a pose tracking of humans. Similarly to the software of the Kinect, MediaPipe also divides a tracked body into joints, 33 so-called "landmarks". Within a frame, MediaPipe detects a person or a pose region-of-interest (ROI) and then predicts the pose of the landmarks in the ROI using the cropped ROI frame as input. The pose detection model consists of "detecting the midpoint of a person's hips, the radius of a circle circumscribing the whole person, and the incline angle of the line connecting the shoulder and hip midpoints". [44] The tracking is limited to track only one person. If the human is not

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[8] `https://google.github.io/mediapipe/solutions/pose`

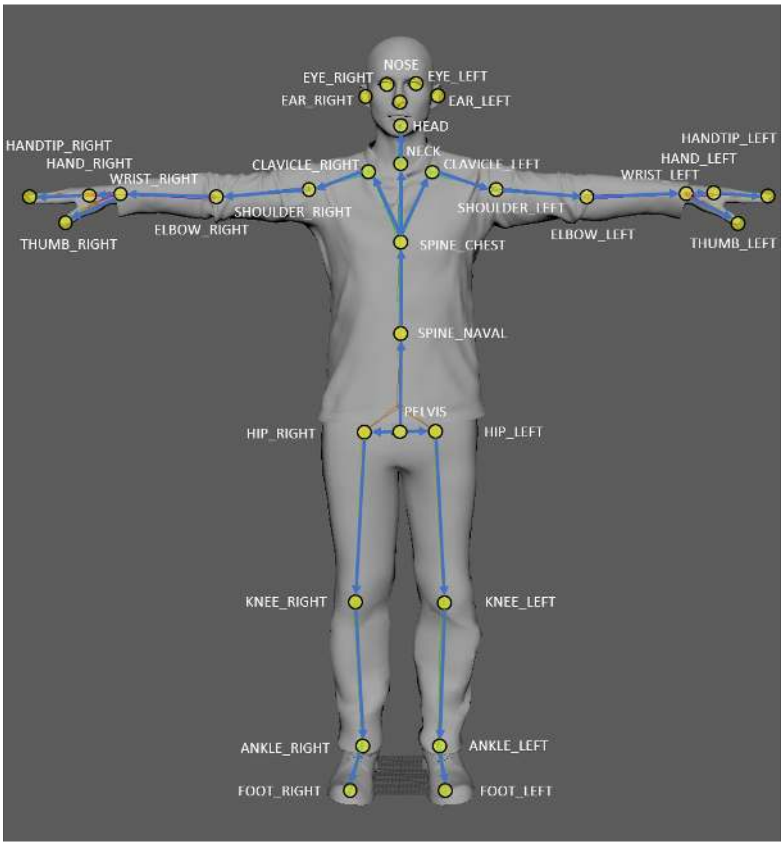

Figure 4.2.: An overview of the joints which are tracked by the Azure Kinect [38]

aligned with the Azure Kinect, the Theta V is used to detect a human. With the calculated pose, the robot is able to turn in a correct way to be aligned with the human again.

The speaker is used to give an audible signal if the Kinect is not directed towards the user. We used the text-to-speech service *tts*[9], which provides a ROS node enabling robots to speak.

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[9] `http://wiki.ros.org/tts`

4.3. OptiTrack Setup

To evaluate this work, there was the need to track the positions of human and robot from an external source. So we used the motion capture system OptiTrack[10] to estimate the positions of the human and robot precisely. The system consists of multiple calibrated cameras. Both the human and the robot are equipped with a marker, which is tracked by the system. Using the `natnet_bridge` [11] the captured and streamed positions of the marker can be used in ROS software. These poses are saved into a csv file to use them in the future.

4.4. Implementation of Human Following

These sections will explain the separate parts of the human following framework.

4.4.1. Web GUI

The web GUI has been implemented using the CSS framework *Bootstrap*[12]. The interface itself is build with a HTML file which implements the buttons like in Figure 5.12. If the start button is pressed, the method `stopButtonPressed` is invoked, so that a boolean is set on true and published on `start_stop_human_following`. If Increase Velocity button is pushed, then the current value is increased by 0.5 and then published to `adjusted_velocity`. If decrease, then its other way round. Distance is implemented analogously only on the `adjusted_distance` topic.

4.4.2. Registering Human Positions with Azure Kinect

In this work, the tracking of humans is realized by utilizing the Azure Kinect camera. This camera performs a body tracking which gives us the ability to get the position of every joint in the camera due to a depth camera. These frames are published on the `/azure_skeleton3D_data` topic. If a message is received on that topic, the callback

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[10] `https://optitrack.com/`

[11] `https://im-kitsch.github.io/natnet_doc/`

[12] `https://getbootstrap.com/`

function firstly looks up the id of the nearest person by calculating the distance with the euclidean distance. After that the position and orientation of the person's pelvis is estimated and transformed to `/base_link`. The transformed poses are then published every 0.01 second as `PoseStamped` on `/human_sim/human_pose`. To visualize this pose it is also published as `Marker` on `/human_sim/human_vis`.

4.4.3. Computing Velocity

We used the PI Control defined in 3.2 to calculate the velocity of the robot in order to achieve the desired goal position. It is calculated every time a new position of the user is registered.
An experienced issue has been the abrupt steering of the robot. Therefore we smoothed the velocity commands by calculating the mean of the two last velocities and the current as $v = \frac{(v_i + v_{i-1} + v_{i-2})}{3}$. The parameter k_I is defined as $k_I = k_P/T$.

4.4.4. Direction Following

With every registered position on `/human_sim/human_pose` the before selected following behavior is started. With the human pose being transformed into `base_link`, the coordinates $p_h = (x_h, y_h)$ of the human's pose are read out. After that, the velocity is calculated. The calculation follows the rules of a PI control. If x_h is greater that the minimal value for x, then the robot uses the calculated velocity and drives forwards towards the current position. If x_h is smaller than the minimum distance in x direction, there exists a check if the position in x_h is below $p \cdot x_{min}$. If yes, then the robot drives backwards to reestablish the distance. Therefore the velocity command is negative. If not, then the robot will wait at that position. If the side following is chosen, a threshold to the side is added to the angular velocity. To address the problem of quick changes in the velocity, we implemented to use the mean of the last 4 velocity commands. This velocity is published on the `/cmd_vel` topic. This does not apply if the stop button in the GUI is pressed, then the behavior stops immediately.

4.4.5. Path Following

The path following approach is similar to the direction following explained in subsection 4.4.4. The difference is in the handling of new poses. While in direction following every pose is discarded, if a new one is registered, in path following each pose is saved in a buffer. Before buffering, a pose is transformed into the `/map` frame, as global frame and then saved. We cannot let them in `base_link` because the robot is moving and the positions would not make any sense to consider. To eliminate the problem of multiple positions at one place only because the person is not moving or minimal moving, the positions are filtered. If the euclidean distance between the last buffered pose and the current measured one is too similar, the position is not considered to be saved. As similarity measure we used the euclidean distance. The list of buffered positions is smoothed every second with the `savgol_filter` from the `scipy` package which implements a *Savitzki-Golay* Filter.

The actual following uses the first position in the buffer and sets it as goal position. Then the approach from the direction following from behind is adapted. Firstly the velocity is calculated and then it is estimated how to drive forward.The robot does not drive backwards in this behavior. So he only waits of the minimum distance to the current measured position to the robot would be below the threshold.

In the last step before publishing, there is a check if the position from the buffer is reached. If yes, then the position is removed from the buffer if not, then he stays there. After that the velocity command is published on the `/cmd_vel` topic.

4.4.6. Human Lost Behavior

The Kinect provides a new position of the skeleton every 0.1 second. But sometimes, if for example the human moves too fast, the human is out of view of the camera. Therefore no skeleton information can be received. Consequently, the robot has to orientate itself so that the Kinect faces towards a human. If for the period of one second no new information can be registered, a *human lost approach* is started. The topic `/human_tracking_info` sends a `True` message. If a message on that topic is true, then the Ricoh Theta V is used to rotate the robot in a correct way to align it again with the human.

The approach in `pose_detection.py` starts, if the message on the mentioned topic is true. Then, the MediaPipe library is combined with the use of the Theta V. The position of the detected skeleton is published as ROS message on `/theta_tracking/human_pose`.

With that information, it can be calculated if the robot has to turn to the right side or to the left and by how much. If the azure kinect is able to detect a skeleton again, the rotation stops.

In order to feedback the user about the current situation we use `mary_tts` to inform the user with" I am looking for you "that the robot does not see the person in that situation and has to position itself new. Initially, it was implemented that the user has only to wait until the robot approach him or her again but sometimes the participants were going to the robot again.

5. Experimental Evaluation

In this chapter, we present the evaluation of the implementation both in simulation and in a study with human subjects interacting with a Turtlebot. In a simulation setup, tests on the accuracy of the path which has been calculated by the human following are performed. Additionally, a study with human subjects provides results on the perception of the personalization of the human-robot interaction in the human following.

5.1. Evaluation in Simulation

The evaluation will show the results of the comparison between the following behaviors on the path taken by the robot. We use the accuracy of the paths as our metric.
In this simulation-based setup, a marker is used as a reference for simulating the user's path including the positions and orientations (See Figure 4.1).The robot drives directly towards the pose of the marker if *direction following from behind* is selected. The *lateral direction following* takes an offset to the side into account, so that the robot approaches the human from the side. Following every single waypoint, the *path following* leads to an exact following of the route.

After registering the marker's position, the robot starts to follow the moving marker. The route consists of a right turn, a straight section, a left turn and finally another straight section. The added yellow arrows show exemplarily how the waypoints are being considered. The robot drives directly towards the current position of the marker and updates its velocity commands at every incoming marker position if *direction following from behind* is selected (Figure 5.1). *Lateral direction following* differs only in the definition of the goal which is driven towards. Figure 5.2 shows that the goal is defined with an offset to the side. Contrarily, the *path following* algorithm defines not only one goal position, but a set of goal positions, which can be noted in Figure 5.3).

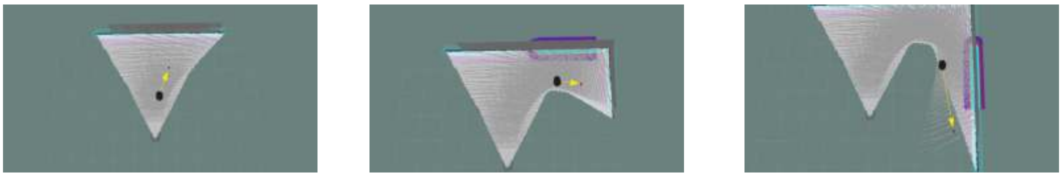


Figure 5.1.: Snippets from direction following from behind

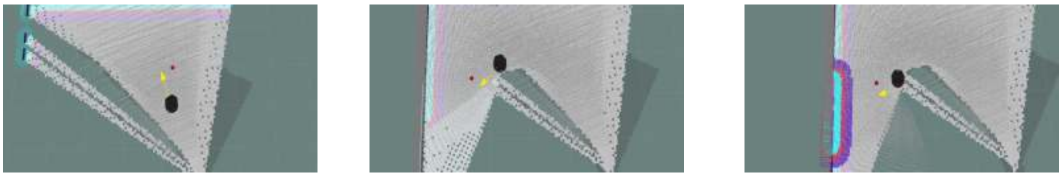


Figure 5.2.: Snippets from lateral direction following

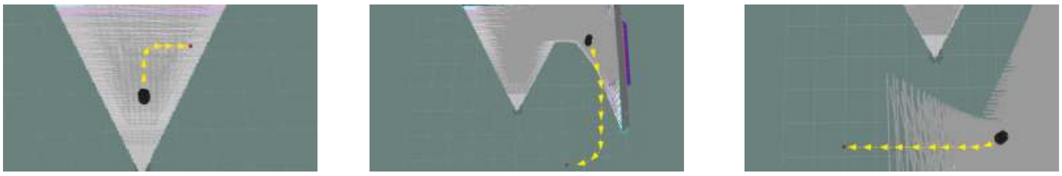
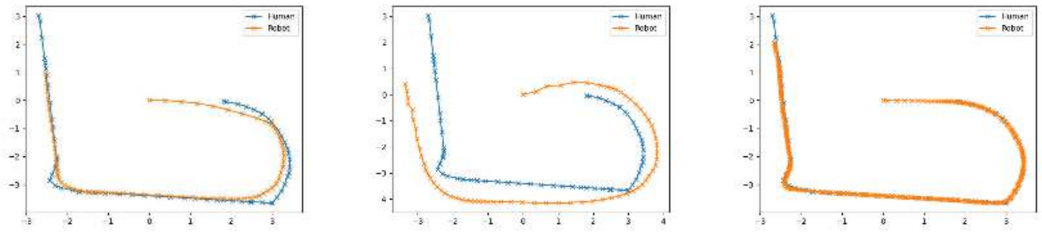


Figure 5.3.: Snippets from path following

This route is initially created, recorded, and then saved into a csv file. The file is played and the path of the marker is repeated for every behavior, resulting in the same setup for each following scheme (Figure 5.4). With the path being built, the robot follows the human marker considering its positions according to the chosen behavior. Those robot poses are also registered and used for illustrating the path and calculating the accuracy.

5.1.1. Results

To compare all behaviors, we used the same parameters for each velocity of the robot and the distance between the human marker and the robot. Figure 5.4 shows the resulting paths of the robot using the prerecorded path of the marker. The robot starts at the coordinates (0,0) and ends at the last coordinate of the marker.
It can be noted that the *direction following from behind* results in a similar path to the path of the marker. Only driving around corners seems to lead to a little deviation. The *lateral following* is approaching the marker from the side but only around corners, the distance



(a) Direction Following from Behind (b) Lateral Direction Following (c) Path Following

Figure 5.4.: Paths which have been taken

to the side is smaller than on the rest of the route. Overall, the *path following* covers the human marker path, even while driving around corners.

In order to classify if the human following functions as intended and to compare these behaviors, the accuracy is taken into account. The accuracy a is a measure to specify the quality of the selected waypoints by the chosen behavior. It is calculated in this work as the number of correctly selected waypoints n of the total number of points p.

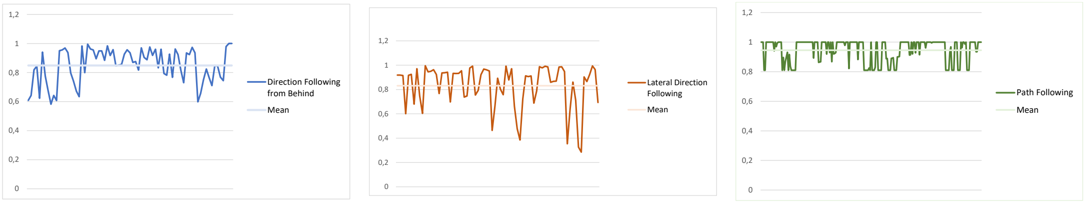
$$a = \frac{n}{p}$$

A waypoint w is defined as correctly chosen if the coordinate of the waypoint is in the range $w \in A$. The set is defined for the coordinates of the robot x, y, the human's coordinates x_h, y_h and the minimum distance x_{min}, y_{min} as

$$A := \{(x, y) : ((x < x_h + x_{min}) \vee (x < x_h - x_{min}) \wedge ((y < y_h + y_{min}) \vee (y < y_h - y_{min})\ \}$$

A look at Figure 5.5 shows the measured accuracy in simulation. While both direction following behaviors have similar average accuracy of 0.85959431 (behind) and 0.8309632 (side) with a standard deviation of 0.11932212(back) and 0.17 (side), path following has an better accuracy with a mean of 0.94523612 and a low deviation of 0.07719528.

All in all, only small differences between the behaviors in simulation could be measured. The reason for the lower rate for the direction behaviors could be the design of the following itself. Whereas in path following every position is registered, processed, and then approached if the distance to the current human position matches. For direction



(a) Direction Following from Behind

(b) Lateral Direction Following

(c) Path Following

Figure 5.5.: An Overview of the measured accuracies

following, the position is only registered at one moment and then discarded if the distance does not match. In this time the position of the marker changes again so that the direction following scheme skips a position if it has been too near. The control is calculated for the next position which is far enough to be considered.

5.2. Study about Personalization of Human Following Behaviors on Turtlebot

To get feedback on the personalization of the human following, we performed a study on a Turtlebot. We evaluated the direction following from behind and the direction following from the side in a study including 15 participants. They were in a range from 18 to 25 years old. The users were 47% female, 53% male and 0% diverse. Most of the participants rated their competence in handling a robot as "fair" or "good". Rating the experience of them ended in a rating of "average" and "fair". This information can be obtained from Figure 5.6.

5.2.1. Study Setup

The goal of the study was to examine if the personalization of the human following has an impact on the perception of the user. In our evaluation, we used the Turtlebot with both cameras: Azure Kinect and a Ricoh Theta 360 (see Figure 5.7a and Figure 5.7b). To measure a potential improvement, we used the questionnaire "Trust in automation (TiA)" by Körber et al. [45]. It provides items with scales on the reliability, competence, understanding, predictability, and familiarity of a system but includes also the intention of the developers, propensity to trust and trust in automation.

Generally, the participant's task was to walk a route that was marked by a line on the ground as depicted in Figure 5.7c. They started at the starting position and while following the line on the ground, they were followed by the Turtlebot.

As a metric for the comparison, we want to track the positions and execute calculations. Therefore, the positions of the human and the robot are tracked using the motion capture system OptiTrack[1]. The OptiTrack markers were placed on a cap and the Turtlebot as shown in Figure 5.8. With a bridge, we were able to transfer the positions from the motion capture system to the ROS setup of the implementation.

The procedure of the evaluation can be divided into eleven parts (see Figure 5.9). Firstly the introductory questionnaire is completed. Secondly, the first direction following (DF) approach is started with default parameters, which are the mean of parameters chosen in a small testing study before the actual study. After completing the route, a TiA questionnaire is handed out. After that, the same repeats for the second direction following approach. Then, the participants were asked to adapt the parameters for the first direction following for velocity of the robot and the distance between herself or himself and the robot while walking the route as often as they feel comfortable. With the parameters set, the participant followed this line again evaluating the first following behavior and replied to the TiA questionnaire again. Finally, the second behavior is analogously adapted to the parameters, then run and assessed in the last questionnaire.

The order in which direction following was tested first, has been alternated to reduce a bias in the data due to habituation to the system. So some participants tested direction following from behind and then lateral direction following, whereas others had been evaluating the other way around. Figure 5.10 and Figure 5.11 give an insight into the performance of the human following approaches in the study.

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[1] `https://optitrack.com/`

The configuration of the parameters was done by using a smartphone and a dedicated web graphical user interface (GUI) (Figure 5.12). The first two runs provided the GUI from Figure 5.12a with the possibility to start and stop the following at any time. After two runs the GUI was updated to the GUI portrayed in Figure 5.12b.

5.2.2. Results

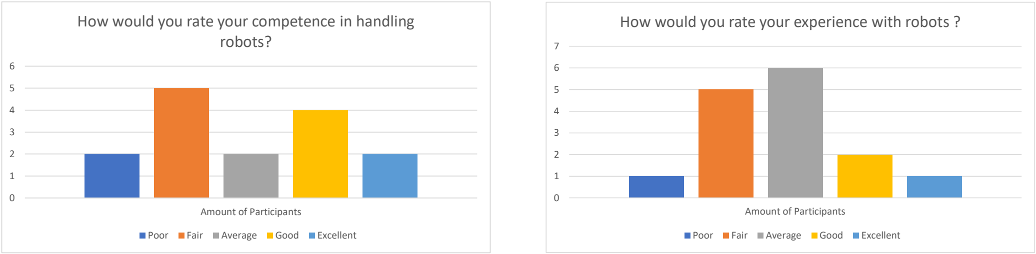
We examined the data from the GUI, the OptiTrack system and the answers of the questionnaires. In Figure 5.13 are plots shown from the study. There is evidently much more noise in the data than in the simulated data.

The results of the questionnaires on the facing pages (Figure 5.14, Figure 5.15. Figure 5.16, and Figure 5.17) show that in *direction following from behind* and *direction following from the side*, the trust has increased after the adaption of the parameter. Especially the tabular overview in Figure 5.18 compares the items scale-wise. Therefore the *reliability and competence* is more present for the user in the *following from behind* than from the side. The adaption of the parameter shows no greater difference in the user's assessment. The same holds for the scale *understanding and predictability*. Whereby both, *familiarity* and the *intention of developers*, stayed nearly unchanged with every behavior. The *propensity of trust* is measured in *direction following from behind* slightly higher than in the *lateral following*. There is no remarkable difference after the adjustments of the parameters given. Notable is the perception of *trust in automation*. Using the *lateral direction* without the adaption of parameters it is strikingly low perceived. The other behaviors and the adapted *lateral following* show a similar vote for trust.

We also evaluated the parameters, which had been finally chosen by the participants to run the adapted behavior. The average velocity has been 0.626667 cm/s with a standard deviation of 0.118134 cm/s. The mean of the distance has been 0.58 m with a standard variance of 0.1833 m. In contrast, the robot using the *lateral following* should drive with only an average of 0.526567 cm/s and deviates by 0.13275. The mean distance is 0.626667 m with a standard deviation of 0.118134 m.

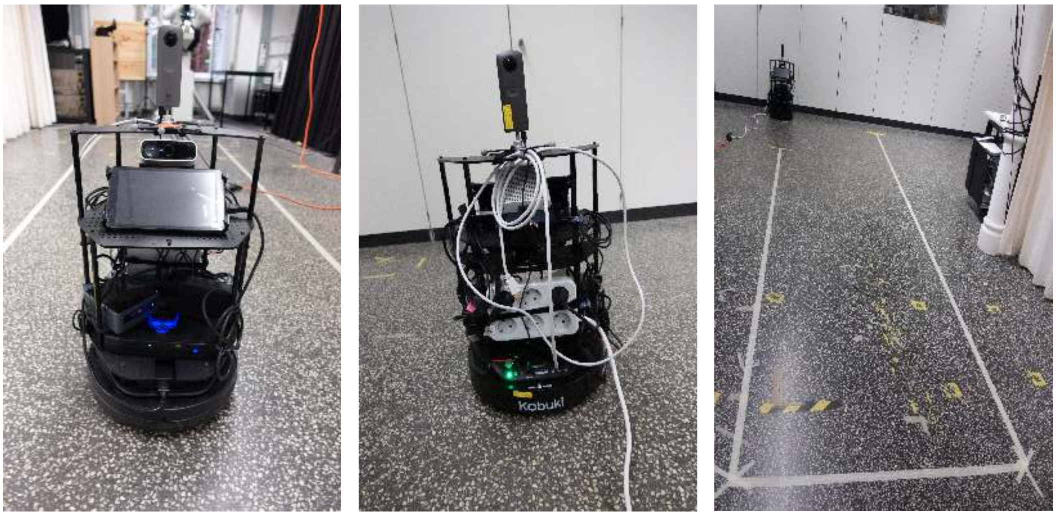
The number of adjustment of the parameters seems not to be linked to the selected behavior. Rather the order of the presented behavior and which parameter is firstly adapted, leads to a significant amount of adjustments. The plot in Figure 5.21 shows no regularities with regard to the number of adaptions.

(a) Age (b) Gender



(c) Competence (d) Experience

Figure 5.6.: Results of the questionnaire, which had been handed before the experiment



(a) Turtlebot from front

(b) Turtlebot from behind

(c) The route is marked with a white tape on the ground. The robot is positioned at the starting position.

Figure 5.7.: An overview about the setup of the robot and the testing environment

(a) The cap with the marker

(b) The marker on Turtlebot

Figure 5.8.: The marker pair

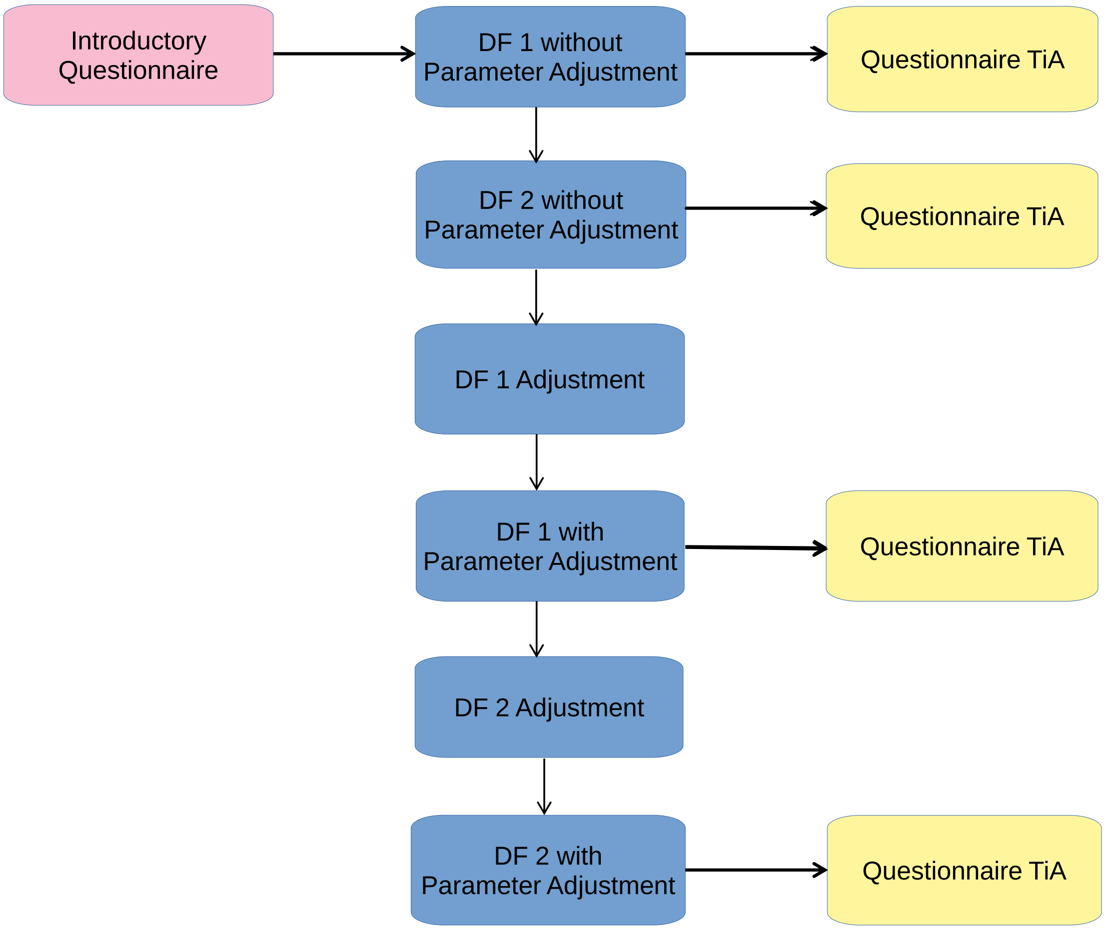


Figure 5.9.: The procedure of the study

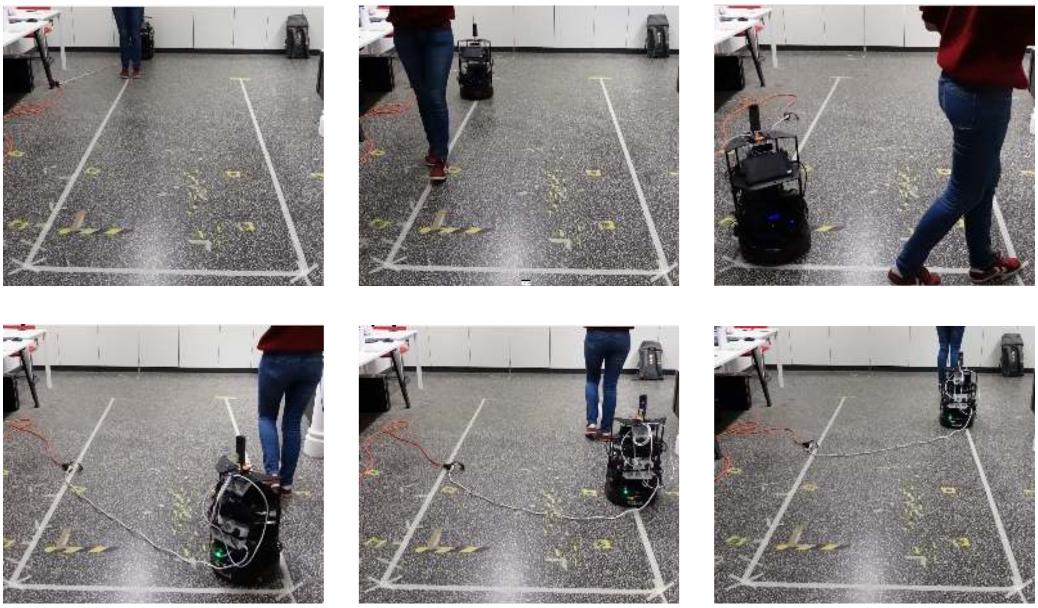


Figure 5.10.: Direction following from behind performed in the study

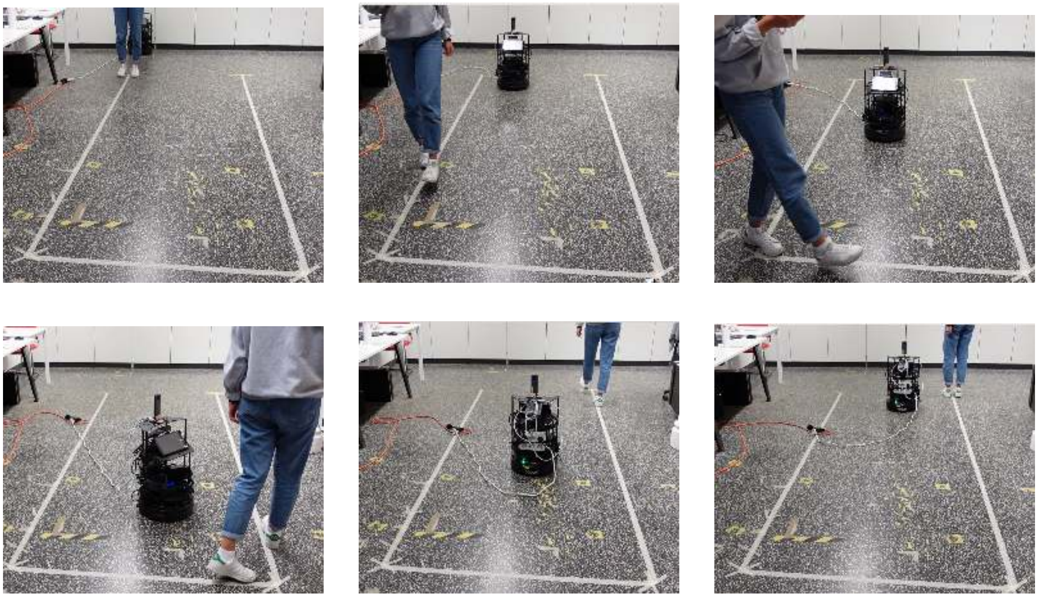
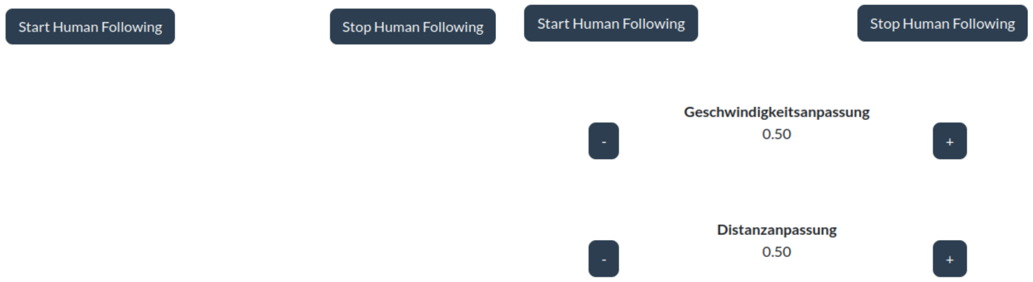


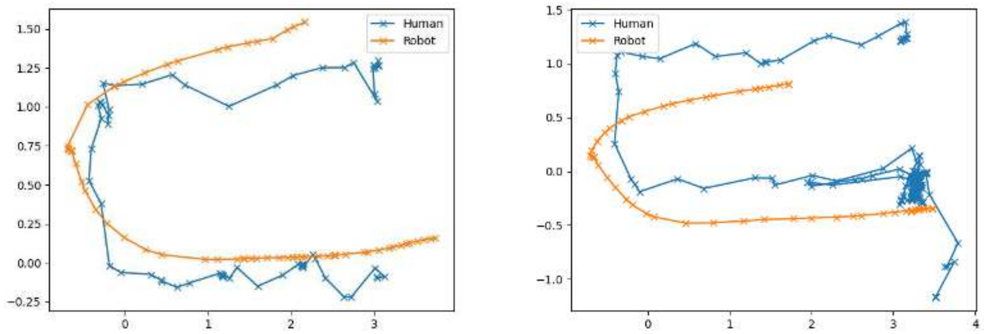
Figure 5.11.: Lateral direction following performed in the study



(a) The GUI without the option to adapt parameters

(b) The GUI with the option to adapt velocity and distance

Figure 5.12.: The used web GUI



(a) Direction Following from Behind

(b) Lateral Direction Following

Figure 5.13.: Plots from the positions tracked at the conducted study

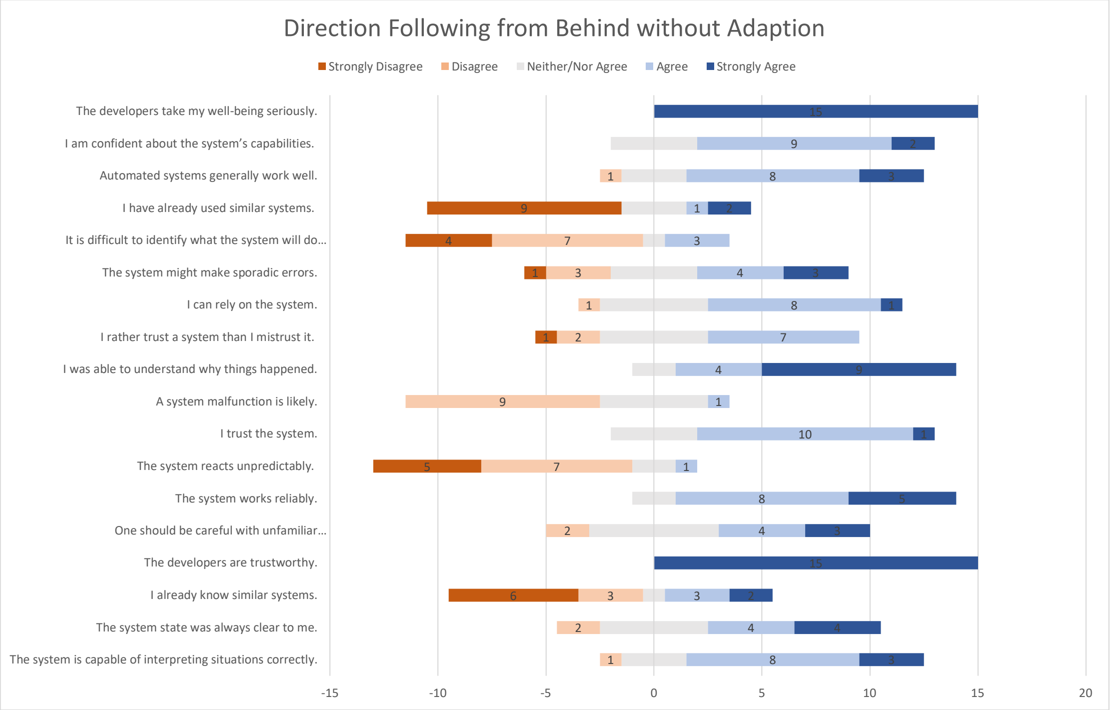


Figure 5.14.: Results of the questionnaire after running direction following from behind without the adaption of velocity and distance

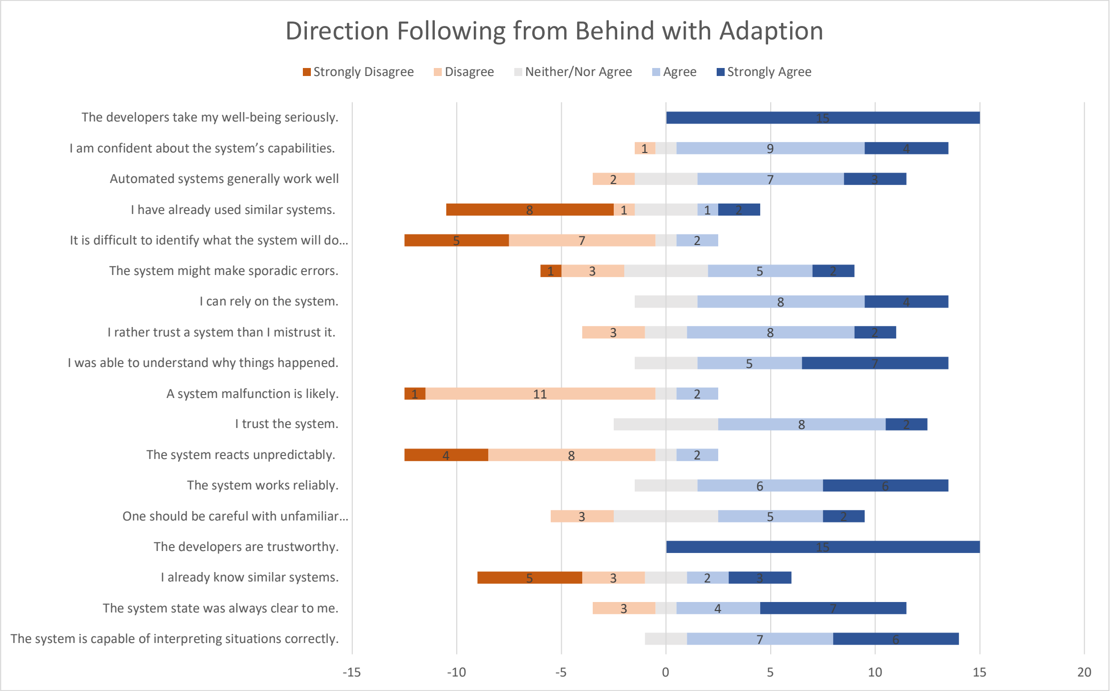


Figure 5.15.: Results of the questionnaire after running direction following from behind with the adaption of velocity and distance

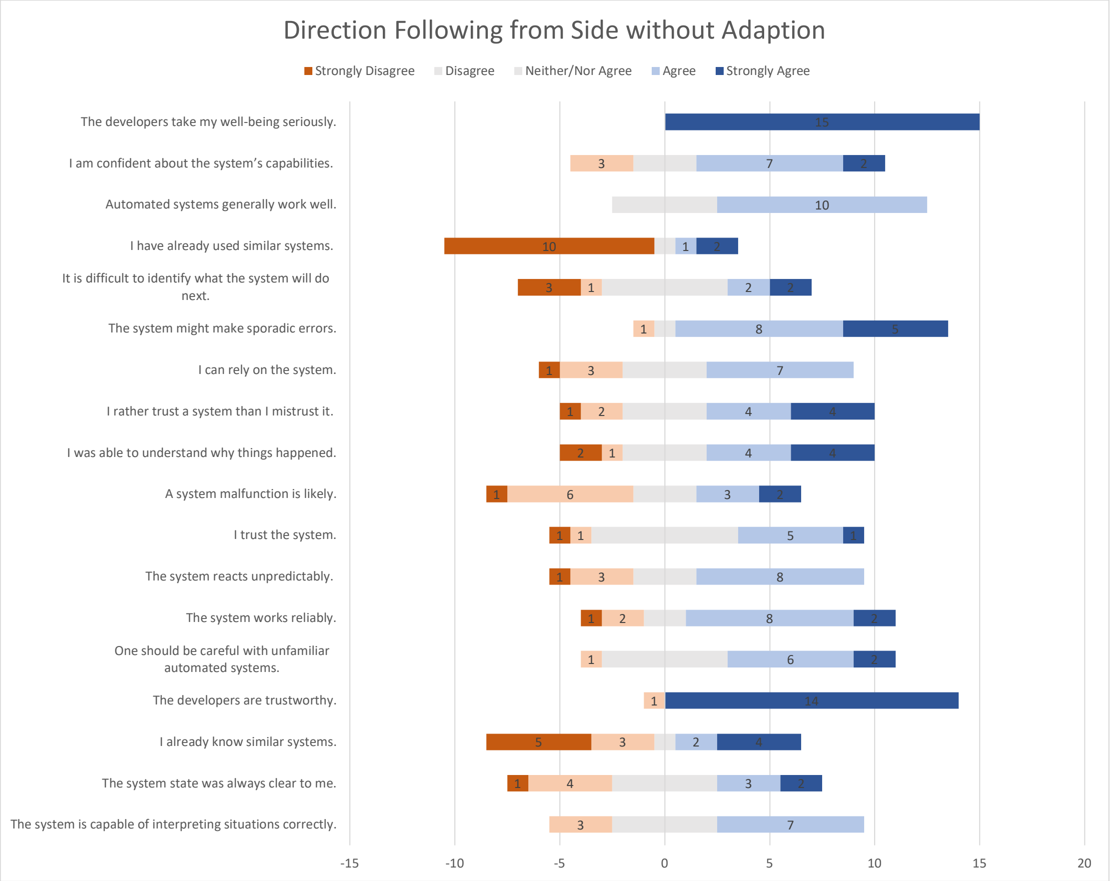


Figure 5.16.: Results of the questionnaire after running lateral direction following with the adaption of velocity and distance

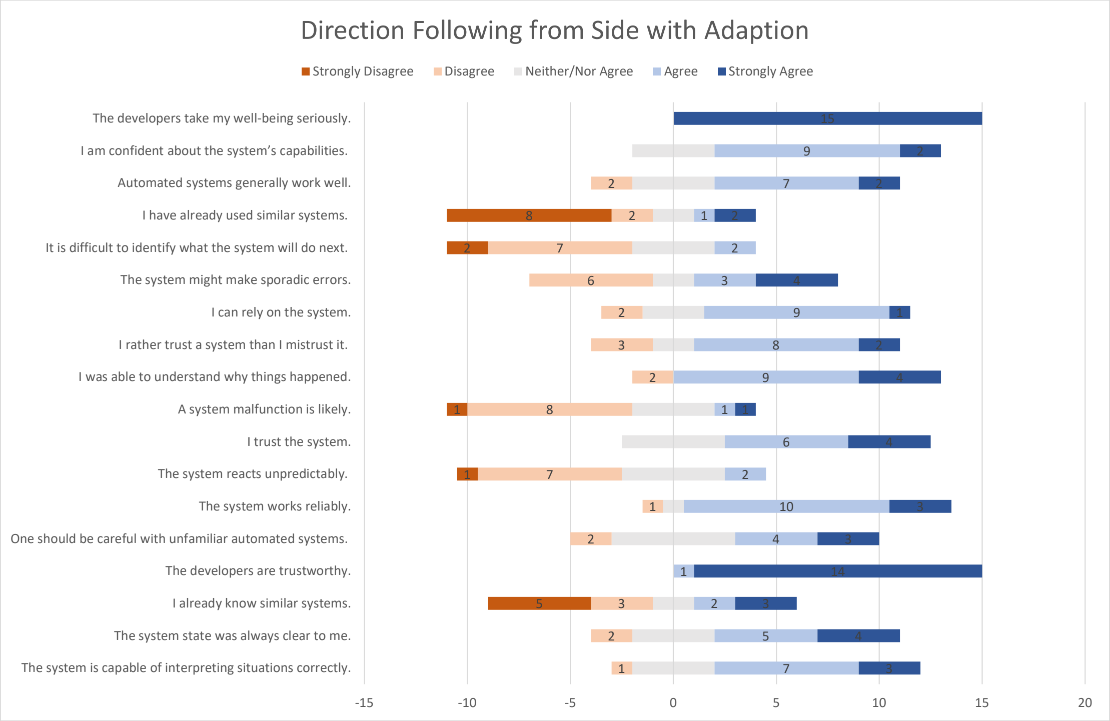


Figure 5.17.: Results of the questionnaire after running lateral direction following

Reliability/ Competence	**DP**	**DoP**	**Sp**	**SoP**
The system is capable of interpreting situations correctly.	19	13	12	4
The system works reliably.	18	18	15	8
A system malfunction is likely*	-11	-8	-7	-1
The system might make sporadic errors.*	4	5	5	17
I am confident about the system's capabilities	16	13	13	8
Sum	53	44	40	20
Inverse Elements Sum	-7	-3	-2	16
Sum - Inverse Elements Sum	60	47	42	4

Understanding/Predictability	**DP**	**DoP**	**Sp**	**SoP**
The system state was always clear to me.	15	10	11	1
The system reacts unpredictably.*	-14	-16	-7	3
I was able to understand why things happened.	19	22	15	7
It's difficult to identify what the system will do next.*	-15	-12	-9	-1
Sum	34	32	26	8
Inverse Elements Sum	-29	-28	-16	2
Sum - Inverse Elements Sum	63	60	42	6

Familiarity	**DP**	**DoP**	**Sp**	**SoP**
I already know similar systems.	-5	-8	-5	-3
I have already used similar systems.	-12	-13	-13	-15
Sum	-17	-21	-18	-18
Inverse Elements Sum	0	0	0	0
Sum - Inverse Elements Sum	-17	-21	-18	-18

Intention of Developers	**DP**	**DoP**	**Sp**	**SoP**
The developers are trustworthy.	30	30	29	27
The developers take my well-being seriously.	30	30	30	30
Sum	60	60	59	57
Inverse Elements Sum	0	0	0	0
Sum - Inverse Elements Sum	60	60	59	57

Propensity to Trust	**DP**	**DoP**	**Sp**	**SoP**
One should be careful with unfamiliar automated systems.*	6	8	8	9
I rather trust a system than I mistrust it.	9	3	9	8
Automated systems generally work well.	11	13	9	10
Sum	20	16	18	18
Inverse Elements Sum	6	8	8	9
Sum - Inverse Elements Sum	14	8	10	9

Trust in Automation	**DP**	**DoP**	**Sp**	**SoP**
I trust the system.	12	12	14	4
I can rely on the system.	16	9	9	2
Sum	28	21	23	6
Inverse Elements Sum	0	0	0	0
Sum - Inverse Elements Sum	28	21	23	6

Overall Score:	208	175	158	64

Figure 5.18.: A summarized overview of the results shown in the previous figures. The listing provides also the inverse elements. DP stand for direction following from behind and SD for the direction following from Side. oP shows that the parameter has not been adapted and only the letter P states an adaption of the parameters.

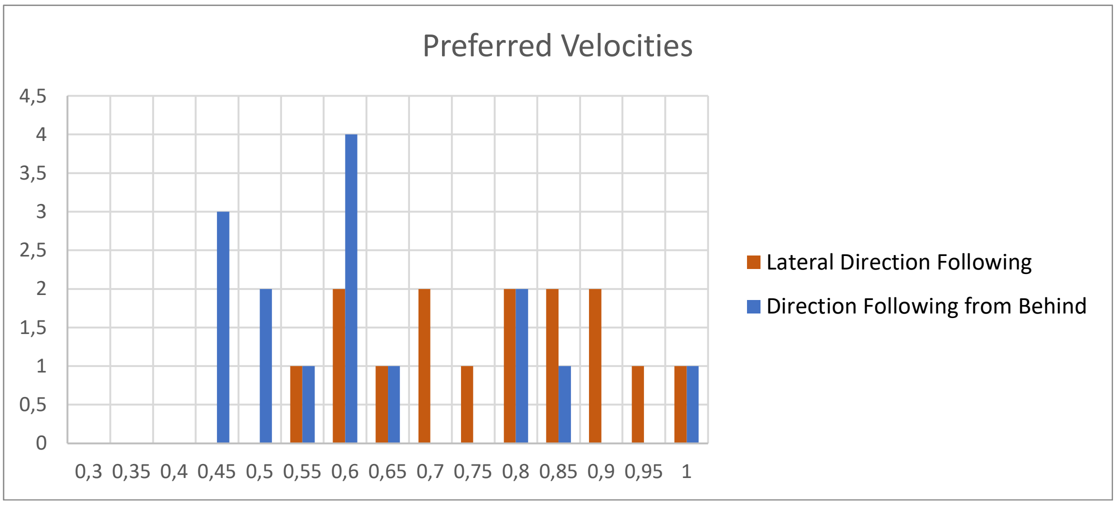


Figure 5.19.: The preferred velocities, which had been chosen by the users.

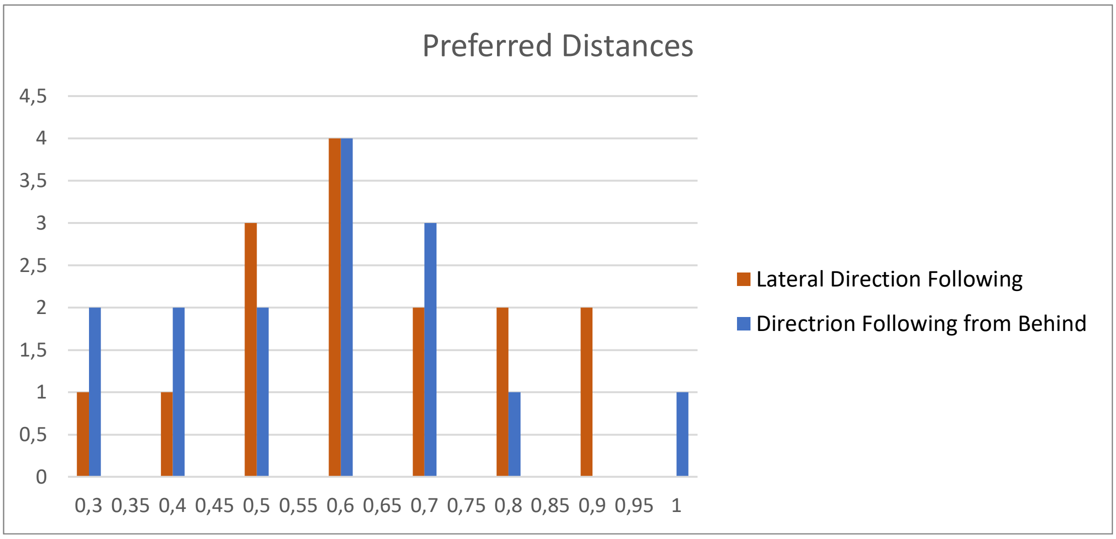


Figure 5.20.: The preferred distances, selected by the participants.

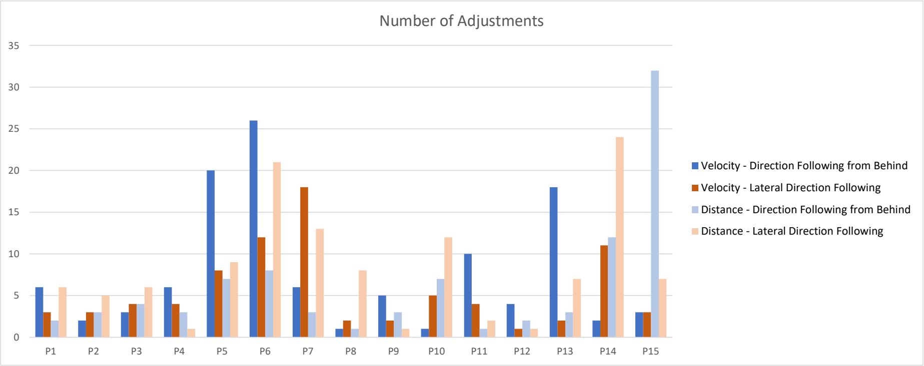


Figure 5.21.: Amount of the adjustments of the parameters.

6. Discussion

Summarizing, we have implemented three different human following behaviors and extended them an adaption for velocity and distance. The following and personalization have shown that the approaches are working. The results of the evaluation present differences between these behaviors and also if parameters had been adapted or not. The evaluation contained a number of further results which are discussed hereafter.

The paths in Figure 5.4 show that tight cornering leads to cutting corners in the path while selecting direction following. This also has been experienced in the work of Gockley et al. [19]. The reason for cutting corners is having the goal position a certain distance in front of the vehicle [41]. By combining the follow-the-carrot algorithm with a control, the chances could be decreased to face that problem. Another cause could be keeping the minimum distance between user and robot. In these behaviors, the current goal is discarded after a new goal position is registered. Therefore the change of the calculated path can be noisy. However, path following covers in simulation the whole path and does not cut corners.

The accuracy in Figure 5.5c of the path following has a lower bound of 0.8. This might be caused by the design of the approach. The robot waits until the user moves forward and saves concurrently the human poses. If the minimum distance between human and robot is exceeded, the robot starts to drive towards the buffered positions until the distance to the current human position is below the minimum distance. The goal position is reached if it is similar enough to the current robot pose. By setting this parameter lower, the accuracy could be increased. By eliminating the cutting corners issue, the accuracy of the direction following approaches could be increased.

In the conducted study, direction following from side has performed poorer than direction following from behind. Lateral direction following needs more space than the approach from behind. But the space, where the experiments took place, was limited. Also, the limited speed of the TurtleBot poses a challenge. While turning, a longer distance has to be traveled, so that a higher velocity of the robot is required. Due to hardware restrictions, the speed cannot be infinitely raised. The limit is lower than the participants' average speed of walking, so the robot is much slower than the user and falls behind. The robot is only able to keep up with the user if the position is not changing significantly because of waiting or if the human slows down. Another drawback in the lateral following has been the position of the Azure Kinect. It was positioned to the front, the same way as for following from behind. But the camera could not track skeletons that have been positioned to the side.

The participant's path in Figure 5.13 is depicted with the measurement noise, whereas the path of the robot is smoothed. The marker for the participant has been on a cap on the head. While working the head could have been moving and causing the angular plot.

6.1. Discussion on the Personalization

Generally, the adjustment of parameters has led to an improvement in trust in the system. "Now after a few runs with different speeds and distance adjustments, which one was allowed to try out oneself, the "being followed" already feels safer and more secure." The participant's statement shows that not only the adaption of distance and speed made the difference, but also the impression of understanding the system.

The participants of the study outlined that they did not see the robot all the time, so one participant stated that "Many questions difficult to answer, because the robot was behind me while running the track, and since it was the first run was not yet clear what to expect.". This could lead to assuming side following would be preferred, which did not happen. Side direction following with parameter adjustment is nearly as good as the direction following without parameter adjustment.

The side following without the adjustment of parameters has been preferred the least. Here two aspects are combined: First, the poorer working following, and second, the lack of adjustment to the system. The statement has not been perceived as reliable. "When moving quickly, I crashed into the robot in the tight curve." The problem of too small space was recognized. But all in all the system has been less predictable, particularly when not adapting parameters, than direction following from behind. The propensity to trust and the trust in automation were measured as significantly lower than the other behaviors.

However, participants interacted with the robot-like a dog, especially when laterally following. During the evaluation, they sometimes talked with the robot as if it was a dog. Also, one participant wrote that "The indicated distance of the following robot corresponded for me approx. to that of a dog when walking, e.g. when approaching roads. And I had the feeling the farther he keeps distance, the more inaccurate was the tracking". The idea of an object following from the side has been known but did not improve the trust compared to the direction following from behind.

Direction following from behind with the adaption of parameters has been the most preferred behavior. It was perceived as the most reliable and predictable system. Especially the parameter adaption caused that the more participants think that a malfunction is less likely than without an adaption.

According to Honig et al. in [1] the level of performance and reliability are likely to influence the spatial preference. In our evaluation, this has not been the case.

All in all, the distance from the user to the robot is categorized into the personal zone of northern Europeans according to Figure 2.4. This is the distance that is measured in a conversation between friends.

7. Conclusion and Outlook

7.1. Conclusion

In this thesis, we compared different human following behaviors and extended them for personalization. Firstly, we defined the problem of human following and defined a PI-control to control the position of the robot according to the human pose. Then, we introduced three human following behaviors. Direction following implements a method that moves the robot directly towards the human's position. We presented two versions of direction following. The first one describes a following, in which a robot is behind the user. The side following implements a method that uses an offset so that the robot approaches the human laterally. The third human following behavior is path following. Instead of discarding every position after registering, the positions are buffered. If a new position is too similar to the last buffered position it gets discarded. Additionally, regularly a Savitzky-Golay filter is used to smooth the remaining data. After researching the following approaches, we investigated parameters that aim to improve the social awareness of the human following. We adapted the velocity selection so that it is smoother than before. Furthermore, we made sure that the distance between humans and robots is rarely below the minimum distance. We added to this approach the ability for the user to adapt the maximum speed and the distance via a GUI on a smartphone. In a simulation setup, we calculated the accuracy of the paths and the behaviors calculated and compared them. The best accuracy was given by the path following approach, followed by the direction following behind and then the lateral side following. A study with 15 participants showed that the direction following with a parameter adaption from behind compared in matters of trust the best. The direction following from behind without the adjustment follows as second best and then side with parameter adjustment and the side without parameters was the least preferred one. The distance between can be categorized as the personal zone of northern Europeans.

7.2. Outlook

The presented implementation has been used successfully to evaluate the personalization of human following through adaption of speed and distance. There are some aspects that could be researched to improve the existing approach. First of all, it has been challenging to make sure that the robot registers the human position while following laterally. If the user was positioned to the side of the robot, the human has been out of view. So the lateral following could be improved by mounting the Kinect to the side instead of to the front. Another idea is to mount the camera on a platform on the robot that can be rotated so that the camera is aligned with the human most of the time. Potentially, updating the robot base, which is capable to drive faster, could make the following more social-aware. Then, the robot would not make loud noises while driving and the user has to worry less about slowing down. To evaluate the behavior an experiment environment with more space would be necessary to ensure that every behavior is tested equally.

Currently, the presented following approach does only consider the nearest person. If the camera captures multiple bodies, the human following does not work robustly and switches between these skeletons. Therefore only one human can be in the field of view of the Kinect. An extension could be to incorporate a method to distinguish between different tracked skeletons. This could be done by e.g. using a physical marker or a software approach. The method should prevent switching too fast between the considered skeleton and evaluate if a switch is necessary.

Calculating the path, there is no obstacle avoidance yet considered. In [19] Gockley et al. present a method based on the curvature-velocity method for local obstacle avoidance [20]. The concept of pose prediction could increase improve the calculation of the path. The robot could move according to the pose prediction of the human poses and would not be that dependent on the received positions. Including place-dependent people tracking with spatial priors on human behaviors as introduced by Luber et al. in [5] could be beneficial to improve the social awareness of the following in specific situations.

There are also use cases that could apply a combination of all implemented behaviors. For instance, when traversing narrow corridors a switch to direction following behind or path following would be necessary.

The approach currently uses only following to move a robot according to the user's goal. In future work, an investigation on pointing, direct physical interaction as in the work of Jevtić et al. in [11] and gesture control would be advantageous to compare all types of interaction in this field.

We evaluated this work only with participants ranging from 18 to 25 years old. In the end, a study with participants whose ages are ranging in a greater area could give additional input according to the human-robot interaction. According to Olatunji et al., especially the interaction between older adults and robots has to be investigated separately [35].

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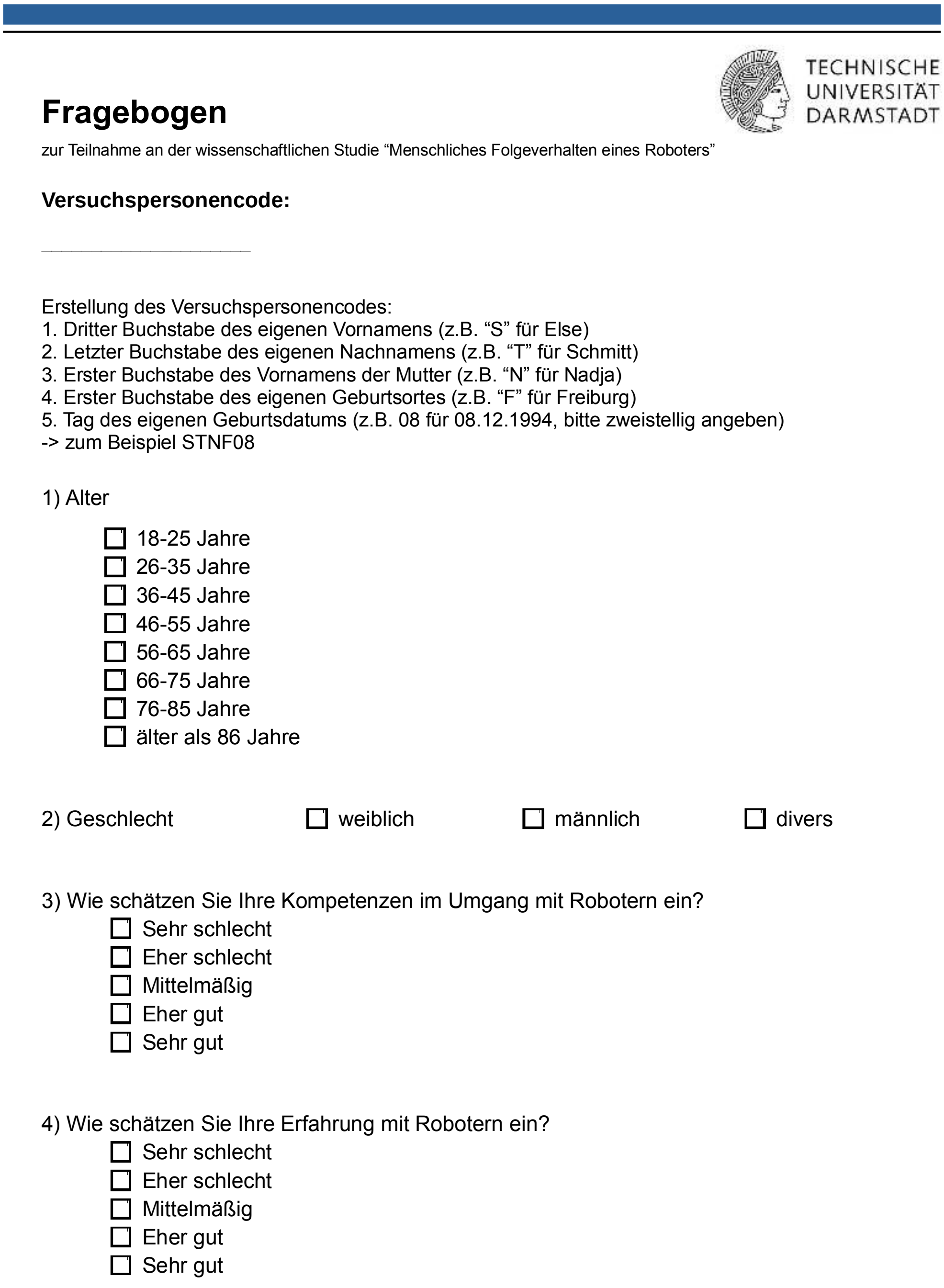
A. Appendix

A.1. Questionnaire for the evaluation with human subjects

The study, which is presented in this work, was done with 15 people in a range from 18 to 25 years old. Firstly the participants were asked to complete the first questionnaire shown in Figure A.1. After every completed route a questionnaire, based on *TiA* questionnaire, is handed to the participant Figure A.2. In the end the participants needed to complete the first questionnaire once and the other one four times.
The Table A.1 presents the further remarks, which were given by some participants.

Participant	**Following Behavior**	**Remarks**
NRUW30	SoP	Tracking war kurz inakurat. In der engen Kurve bei schneller Bewegung raste ich in den Roboter rein.
NRUW30	DoP	Verhalten von letzten Durchgang (SoP) war reproduzierbar.
NRUW30	SP	Die UI war etwas anstrengend wenn man + oder – drücken wollte, ist das webframe rein/rausgezoomed.
NRUW30	DP	Es war weird als der Roboter eine lange Pause gemacht hat.
LHBW21	DoP	Viele Fragen schwer zu beantworten, da Roboter beim Laufen der Strecke hinter mir war und, da es der erste Durchgang war, noch nicht klar was zu erwarten war.
LHBW21	SoP	Bei manchen Fragen hätte ich mir die Antwortmöglichkeit „keine Angabe“ oder ähnliches gewünscht.
LHBW21	DP	Jetzt nach ein paar Durchgängen mit verschiedenen Geschwindigkeiten und Distanzanpassungen, die man selbst ausprobieren durfte, fühlt sich das „verfolgt“ werden schon sicherer an.
LHBW21	SP	Der angegebene Abstand des folgenden Roboters entsprach für mich ca. dem eines Hundes beim Gassi gehen, z.B. anstraßen. Und ich hatte das Gefühl umso weiter er Distanz hält, umso ungenauer ist das „verfolgen“. Nur so so einige Überlegungen und Empfindungen, die mir während des Versuchs durch den Kopf gingen.
RRER14	DoP	Den Roboter einzuschätzen , den ich die ganze Zeit nicht gesehen habe und mit mir interagiert fühlt sich nicht komplett nach einer meiner Kompetenzen an.
BFFH02	SP	Ich habe unterdurchschnittlich gute Raumwahrnehmung (Propriopzeption), wenn ich den Roboter nicht sehe oder er nah genug ist, kann ich seine Position nicht zuverlässig schätzen.

Table A.1.: This questionnaire has been handed to the participant before starting the actual following.



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Fragebogen

zur Teilnahme an der wissenschaftlichen Studie “Menschliches Folgeverhalten eines Roboters”

Versuchspersonencode:

____

Erstellung des Versuchspersonencodes:
1. Dritter Buchstabe des eigenen Vornamens (z.B. “S” für Else)
2. Letzter Buchstabe des eigenen Nachnamens (z.B. “T” für Schmitt)
3. Erster Buchstabe des Vornamens der Mutter (z.B. “N” für Nadja)
4. Erster Buchstabe des eigenen Geburtsortes (z.B. “F” für Freiburg)
5. Tag des eigenen Geburtsdatums (z.B. 08 für 08.12.1994, bitte zweistellig angeben)
-> zum Beispiel STNF08

1) Alter

- ☐ 18-25 Jahre
- ☐ 26-35 Jahre
- ☐ 36-45 Jahre
- ☐ 46-55 Jahre
- ☐ 56-65 Jahre
- ☐ 66-75 Jahre
- ☐ 76-85 Jahre
- ☐ älter als 86 Jahre

2) Geschlecht ☐ weiblich ☐ männlich ☐ divers

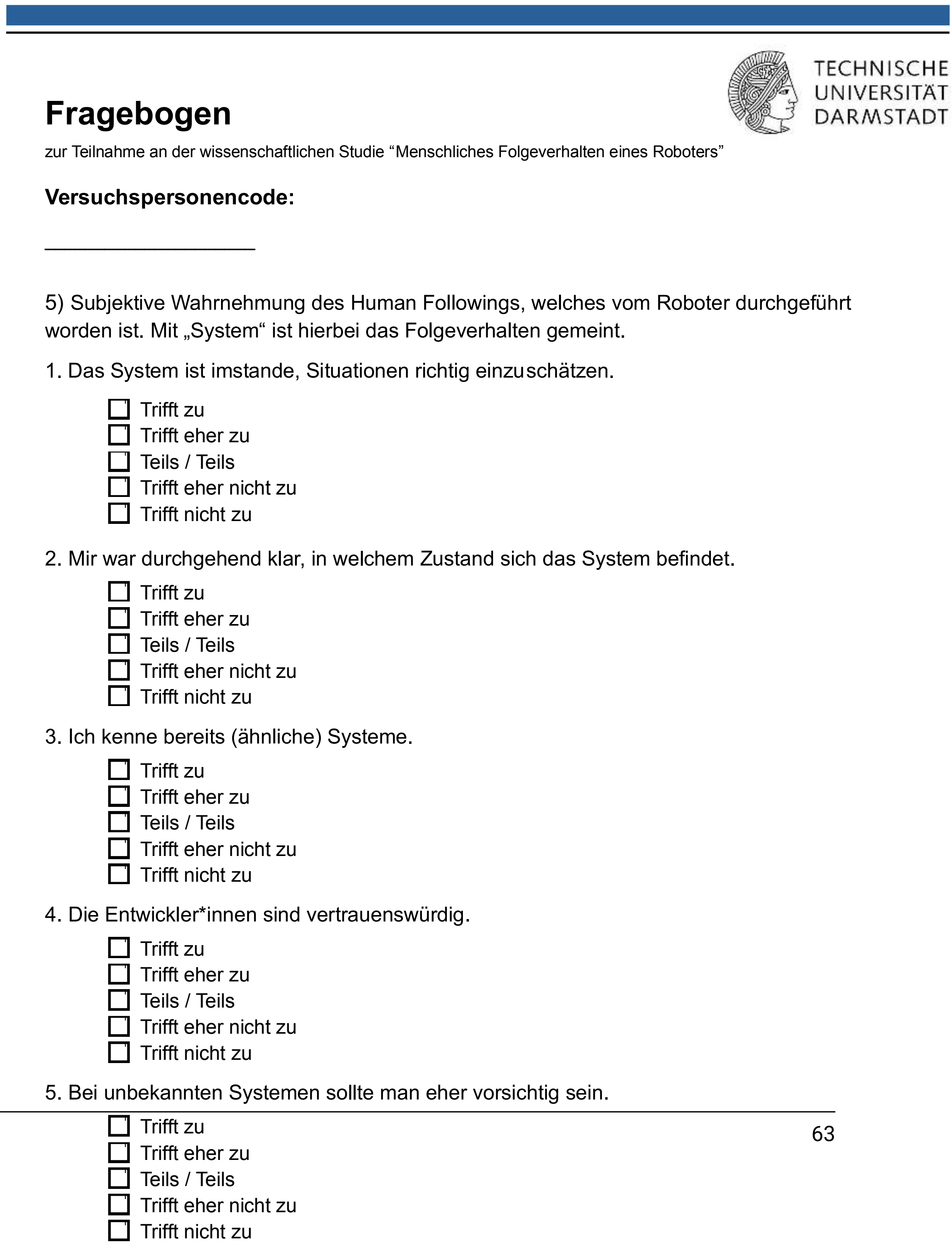
3) Wie schätzen Sie Ihre Kompetenzen im Umgang mit Robotern ein?

- ☐ Sehr schlecht
- ☐ Eher schlecht
- ☐ Mittelmäßig
- ☐ Eher gut
- ☐ Sehr gut

4) Wie schätzen Sie Ihre Erfahrung mit Robotern ein?

- ☐ Sehr schlecht
- ☐ Eher schlecht
- ☐ Mittelmäßig
- ☐ Eher gut
- ☐ Sehr gut

Figure A.1.: This questionnaire has been handed to the participant before starting the actual following.



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Fragebogen

zur Teilnahme an der wissenschaftlichen Studie “Menschliches Folgeverhalten eines Roboters”

Versuchspersonencode:

____

5) Subjektive Wahrnehmung des Human Followings, welches vom Roboter durchgeführt worden ist. Mit „System“ ist hierbei das Folgeverhalten gemeint.

1. Das System ist imstande, Situationen richtig einzuschätzen.

☐ Trifft zu
☐ Trifft eher zu
☐ Teils / Teils
☐ Trifft eher nicht zu
☐ Trifft nicht zu

2. Mir war durchgehend klar, in welchem Zustand sich das System befindet.

☐ Trifft zu
☐ Trifft eher zu
☐ Teils / Teils
☐ Trifft eher nicht zu
☐ Trifft nicht zu

3. Ich kenne bereits (ähnliche) Systeme.

☐ Trifft zu
☐ Trifft eher zu
☐ Teils / Teils
☐ Trifft eher nicht zu
☐ Trifft nicht zu

4. Die Entwickler*innen sind vertrauenswürdig.

☐ Trifft zu
☐ Trifft eher zu
☐ Teils / Teils
☐ Trifft eher nicht zu
☐ Trifft nicht zu

5. Bei unbekannten Systemen sollte man eher vorsichtig sein.

☐ Trifft zu
☐ Trifft eher zu
☐ Teils / Teils
☐ Trifft eher nicht zu
☐ Trifft nicht zu

6. Das System arbeitet zuverlässig.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

7. Das System reagiert unvorhersehbar.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

8. Ich vertraue dem System.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

9. Ein Ausfall des Systems ist wahrscheinlich.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

10. Ich konnte nachvollziehen, wieso bestimmte Dinge passiert sind.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

11. Ich vertraue einem System eher, als dass ich ihm misstraue.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

12. Ich kann mich auf das System verlassen.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

13. Das System kann gelegentlich Fehler machen.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

14. Es ist schwer zu erkennen, was das System als nächstes macht.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

15. Ich habe mit (ähnlichen) Systemen bereits gearbeitet.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

16. Automatisierte Systeme funktionieren im Allgemeinen gut.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

17. Ich bin überzeugt von den Fähigkeiten des Systems.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

18. Die Entwickler*innen nehmen mein Wohlergehen ernst.

- ☐ Trifft zu
- ☐ Trifft eher zu
- ☐ Teils / Teils
- ☐ Trifft eher nicht zu
- ☐ Trifft nicht zu

Zusätzliche Anmerkungen

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