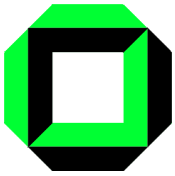

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ROYAL INSTITUTE
OF TECHNOLOGY

An Interactive Interface for a Service Robot – Design and Experimental Implementation

Diplomarbeit

Elin Anna Topp

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Hiermit erkläre ich, die vorliegende Diplomarbeit selbständig angefertigt zu haben. Die verwendeten Quellen sind im Text gekennzeichnet und im Literaturverzeichnis aufgeführt.

Karlsruhe/Stockholm, 31. Oktober 2003,

Elin Anna Topp

Preface

This master thesis presents the work done between May, 1st and October, 31st 2003. It was conducted within the group of Professor Henrik I. Christensen at the Centre for Autonomous Systems (CAS) of the Department of Numerical Analysis and Computing Science (NADA) at the Royal Institute of Technology (KTH) in Stockholm. I would like to thank first of all my supervisor in Stockholm, Professor Christensen, as well as Dr. Danica Kragic and Dr. Patric Jensfelt for their help during the work. Thanks to Professor Rüdiger Dillmann at the Institute for Computer design and Fault Tolerance at the University of Karlsruhe, who made it possible for me to work on this thesis in Stockholm. Further, I would like to thank Ludwig Seitz for repeated proof reading of the thesis, which kept changing permanently. The thesis is written in English, but contains a German summary in the appendix. It will be turned in as "Diplomarbeit" at the University of Karlsruhe.

Vorwort

Die vorliegende Diplomarbeit ist im Zeitraum vom 01.05. bis 31.10.2003 in der Arbeitsgruppe von Professor Henrik I. Christensen am Zentrum für autonome Systeme (Centre for Autonomous Systems, CAS) an der informationstechnologischen Fakultät (Institutionen för Numerisk Analys och Datalogi, NADA) der Königlichen Technischen Hochschule (Kungliga Tekniska Högskolan, KTH) in Stockholm entstanden. Ich möchte an dieser Stelle meinem Betreuer in Stockholm, Professor Christensen, sowie Dr. Danica Kragic und Dr. Patric Jensfelt sehr herzlich für Ihre Hilfe und Aufgeschlossenheit danken. Weiterer Dank gebührt Professor Rüdiger Dillmann am Institut für Rechnerentwurf und Fehlertoleranz an der Universität Karlsruhe, der es mir möglich gemacht hat, diese Arbeit in Stockholm durchzuführen. Ein zusẗzliches Dankeschön geht an Ludwig Seitz, der es bewältigt hat, die sich laufend verändernde Arbeit zur Korrektur zu lesen. Die Ausarbeitung ist vollständig in englischer Sprache geschrieben, mit Ausnahme einer deutschsprachigen Zusammenfassung im Anhang.

Förord

Den här avhandlingen sammanfattar arbete som gjorts mellan 1.Mai och 31.Oktober 2003 i Professor Henrik I. Christensens grupp vid Centrum för Autonoma System,

(CAS) på KTH, Stockholm. Jag skulle vilja tacka min handledare, Professor Christensen, liksom Dr. Danica Kragic och Dr. Patric Jensfelt för deras hjälp med arbetet. Dessutom tackar jag Professor Rüdiger Dillmann, som skapade möjligheten att genomföra arbetet här i Stockholm. Ett extra tack går till Ludwig Seitz, som orkade läsa och korrigera avhandlingen under alla förändringar som gjorts. Avhandlingen är skriven på engelska, men en sammanfattning på tyska finns bland bilagorna. Avhandlingen kommer att lämnas in som "Diplomarbeit" vid Karlsruhes Universitet.

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1 Introduction

The idea of the service robot that moves around autonomously and cleans or tidies the apartment while the owner can spend her free time doing something more interesting and relaxing is tempting. Considering our aging society and therefore upcoming problems for care systems, the housekeeping robot might even not be only tempting but become really useful and even necessary.

This thesis discusses an approach to an interactive interface for a service robot. The introductory chapter will give an example for a scenario in which an interactive interface indeed can be of great use.

1.1 Motivation

Mobile robots are already capable of many actions like moving around autonomously in known or even unknown environments, fulfilling tasks like grasping objects or delivering objects from position A to position B. A lot of interfaces are built and tested to instruct such a robot to grasp an object or move to a certain position, ranging from input like typed commands to natural language. If the service robot's task is not only to grasp one single object but, for example, to learn that "this is the coffee table that should be cleaned only using the special cleaning product" a lot more interaction between the user and the service robot is involved. The robot in this scenario would have to solve the following problems:

- Realise that it should pay attention
- Detect the person that it should pay attention to
- Distinguish this person from other people possibly being around
- Understand that it should follow this person
- Follow the specified person without bumping into obstacles, may they be moving (other people) or not
- Recognise a pointing gesture towards the mentioned coffee-table
- Recognise the object pointed to as "coffee-table", store a model of the table and maybe the current position

- Interpret and understand the explanation about the table
- Remember the instructions when the command "clean the coffee-table" is given, find the table again and clean it

At this point it becomes obvious, why carefully designed interaction systems for service robots are needed. It is not only necessary to equip a service robot with means of communication, it is also important to make them usable for unskilled users. In psychological studies ([PR97]) it became clear, that individuals have different attitudes towards automated systems, which are often related to system performance and the feedback. Those attitudes should be considered, when an interaction system is build as an interface between humans and robots, otherwise the robot is of no use for the people it is designed for.

Another important fact about interaction in general is the appropriateness of communicational means. An interaction system for service robots should be capable of dealing with different types of in- and output, because especially when thinking of a system for elder or disabled people it is not self-evident that the user has all abilities to communicate. For example, users could be blind, hear badly or even be not able to speak.

Most of the existing systems concentrate either on the supported modalities or on behaviours provided by the robot, but it is interesting to look into the possibilities of providing some general approaches, independent from situations, scenarios and technical solutions.

1.2 Problem specification

The general idea behind the described work is to design an interactive interface for service robots. Some examples of existing human robot interfaces will be considered to reason about decisions during the design process. The underlying questions are "Why does a user want to communicate with a service robot?" and "How does a user want a service robot to communicate?" To answer those questions really satisfactorily would involve lots of user studies, which would have been far beyond the time scope of this work. Nevertheless, it is possible to consider a fair amount of examples by taking into account reports on users' attitudes to automated systems.

The thesis presents the design of an interactive interface for service robots and the experimental implementation for parts of such a system using different types of sensory input and modalities. In order to understand the abilities a system that can handle the example scenario in section 1.1 should have, the requirements are pointed out in the following.

- **People detection:** Based on sensory input, the system must be able to detect people being around. Once they are detected they have to be tracked, or at least the one person that is determined as being the current user of the system has to be kept in the focus of attention.

- **Dialogue:** Some form of dialogue has to be established. This does not necessarily have to be a spoken dialogue, but some interface must be provided, so that the user can communicate her intentions. Dialogue is also needed for feedback, so that the system can inform the user about its state.

- **Command representation:** A representation for utterances and commands from the user is needed. This representation has to be generated from the dialogue interpretation and has to attach to each command an internal representation of the actions needed to handle this command.

- **Deictic information:** Usually a person would not refer to objects as "the green cup on the big table left to me" but as "this cup on that table over there". The deictic words "this","that" and "there" would be accompanied by pointing gestures. In general, a deictic word is a word referring to an identity or spacial or temporal location within the context of communication. Thus, an interactive interface should have the ability to understand deictic information.

- **World knowledge:** For the example scenario given above a world knowledge base would have to be available that makes it possible to store new objects or attach information to objects already known. Thus, a form of knowledge representation is needed.

Considering these needs, a basic set of sensory data and modalities is proposed. This basic set consists of a combination of laser range data and vision for tracking and spoken input combined with vision based gesture recognition for the communication. The implementation is based on those types of data and modalities. Adequate ways of giving feedback seem to be the use of a camera that focuses on the user and a text to speech system.

Some of the components for the implementation are already present, others have to be implemented, in order to make a test of the proposed integration idea possible. The thesis will discuss these components and point out problems and advantages of used approaches.

Due to time constraints not all aspects of the system are designed to implementation level. The general approach maintains nevertheless some principles for interaction that might have to be considered in some future work.

1.3 Outline

The thesis consists of six chapters and two appendices. Chapter 2 gives an overview of related work, chapter 3 explains the approach to a design of an interactive interface, chapter 4 presents the experimental implementation for an interactive interface using laser range data, image processing and spoken input. Some experimentation results are given in chapter 5. A conclusion is drawn and ideas for future work are expressed in chapter 6. Appendix A describes the technical environment that was used for the implementation and appendix B gives a German summary of the thesis.

2 Background and related work

This chapter gives an overview of different approaches to human robot interaction and separates those in three levels of complexity. The first section deals with interaction on a high, relatively abstract level. The second section describes approaches to interaction on a middle level, considering different modalities for interaction. Most of the referenced work is related to this second level of interaction. The third and last section describes an important but basic part of interaction, the tracking of users.

2.1 Human robot interaction

The field of human robot interaction is quite broad and many different approaches are presented in so far publications. Therefore, it is useful to distinguish between different views on human robot interaction. One is interaction from a social point of view. The second is to see human robot interaction as goal oriented. This type of interaction is more pragmatic and a question could be if this is still interaction. As the principle of interaction – reacting on actions – is maintained, this is still the fact.

2.1.1 Interaction from the social point of view

In [Bre98] a motivational system for the regulation of human-robot interaction is presented. Motivational in this context means based on the psychological grounded term of motivation. The system is implemented on the robot "Kismet", which has the ability to express emotions. Figure 2.1[1] on shows the robot that has movable "ears",

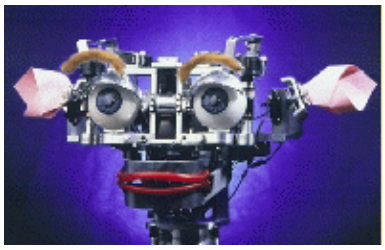


Figure 2.1: *The robot Kismet at MIT's AI group. It can express emotions with the help of its movable eyes, ears, eyebrows and its mouth.*

"eyeballs", "eyelids" and a "mouth". The system is developed referring to ethology and psychology, especially emotions and motivations. Based on the motivational regulating system "Kismet" is able to interact with a person in a caretaker-infant scenario, where the caretaker role is taken by the person. According to its *drives* (like for instance *fatigue* or *social*), the robot reacts to the caretaker's input (interaction, like for example "play") by expressing its resulting *emotions*. If the *drive fatigue* has gone beyond a certain level, for example, the robot is "exhausted" after a long playing period, but the caretaker keeps it in the behaviour *play* with continuous interaction - although now the system itself would switch into the *sleep* behaviour - the robot becomes "cranky" which is shown by a moderate anger expression. In this case the resulting emotion is *anger*, which shows, that something within the interaction is wrong and the robot does not feel "happy". Thus, the input has to be changed - which could involve to stop the interaction completely to allow "sleeping" or just change a bit in the way to interact. Interaction is seen here in its basic meaning of acting and reacting.

2.1.2 Goal oriented interaction

The other view on interaction is more pragmatic. Here, a user wants to interact with a machine (a robot) to make it perform a certain action. Interaction is used to communicate and disambiguate interests and commands, if possible in a natural way. So the idea in this case is not to build a human-like reacting system that reflects feelings and social skills, but a system that communicates as human-like as possible. It seems appropriate to call such a system "interactive interface" rather than "interaction system", because its purpose is not the interaction itself. Even if the approach is different than in the social interaction idea, psychology and studies of human behaviour when working with automated systems can not be ignored. In [PR97] this aspect is exposed very clearly as a result of some broad studies of various human attitudes towards automated systems in general.

A number of user studies, conducted within robotics had similar results. In [HSE02], for example, the experiences in a long-term study with a fetch-and-carry robot (CERO) are described. CERO is a mobile robot at the IPLab of KTH[2] that is equipped with a life-like character ([Gre01]) and provides, among others, a spoken dialogue interface. It is used for different user studies concerning human attitudes and behaviour towards robots and interfaces. One result of the study is, that an important part of interaction with a robot lies in feedback and the possibility to show possible users (or in this case, bystanders), how they can communicate with it. The robot was during the study regarded as a personal assistant for one user and

[1]Picture taken from http://www.ai.mit.edu/projects/sociable/videos.html
[2]http://www.nada.kth.se/iplab/

Figure 2.2: *The fetch–and–carry robot CERO at the IPLab at KTH, Stockholm. It is equipped with a life–like character that suggests people that some form of communication with the robot is possible.*

could only be instructed by this user who was equipped with the devices[3] required to control it. The character sitting on the robot (see figure 2.2[4]) indicates that it is possible to communicate with the robot. During the study people passing the robot would stop to "chat" with it, but at that time it was not meant for it to communicate with others than the responsible user. This is one of the common problems in the field of human robot interaction. In this thesis a careful approach to a solution is considered.

As the work presented here concentrates on goal oriented interaction, the following section concentrates on approaches to this type of interaction.

2.2 Modalities for (goal oriented) interaction

Interaction systems and approaches can be classified based on the types and the number of modalities they use. Many systems are based on spoken input, as language (speech) is the primary modality in human communication, but also gestures, and even emotional cues as a modulator for communication are part of current research. Another, maybe not that natural, subject is the use of graphical user interfaces for task specification. The following subsections present some approaches to different modalities and their integration to interactive interfaces.

2.2.1 Multi-modal approaches: Integration of modalities

A general overview of different coordination or integration approaches is given by MacKenzie and Arkin in [MAC97]. In the special case of this publication the coor-

[3]For the user study the robot was controlled by a graphical interface that was installed on one locally fixed computer and – in a reduced version – on a handheld PDA

[4]Picture taken from http://www.nada.kth.se/iplab/hri/robots/index.html

dination of a multi-agent system, i.e. a group of mobile scout robots, was regarded. However, the principles of coordination hold for coordination and integration of different modalities as well. The authors group coordination into *continuous* or *state based* approaches, and refine this classification for the *state based* idea into *competitive* or *temporal sequencing*. Continuous approaches are only considered being cooperative as a refinement. An example for a state based temporal sequential system is a finite state automaton. A system with, for example, various behaviours running in parallel where output of one could block the others is state based and competitive. Continuous cooperation is achieved by for example computing the weighted sum of different modules' output as an overall result.

This section gives an overview of recent systems and projects that already integrate different modalities so that an interactive interface is achieved. The used control architectures are described and divided into continuous or state based-sequential.

MOBSY, Erlangen, Germany

One example for an integrated interactive service robot system is MOBSY, shown in figure 2.3[5] on page 8. As described in [ZDH+03], MOBSY is currently used as a mobile robot receptionist to welcome visitors at the institute. The system integrates

Figure 2.3: *The receptionist robot MOBSY, equipped with a stereo camera vision system for people detection and active face tracking.*

different modules in a state based control loop. The components for interaction are dialogue and vision based face tracking. The loop itself is started out of a WAIT state by a detection of a certain event, that indicates the presence of a visitor. This event sets the system to an *approach* state, in which different basic behaviours like obstacle avoidance and navigation abilities are combined, and the robot approaches the visitor.

[5]Picture from http://www5.informatik.uni-erlangen.de/~mobsy

When the desired position is reached, a dialogue is started in the *dialogue* state to give the visitor information about the location. During the dialogue the face of the visitor is tracked with an active stereo camera system, so that the visitor gets the feeling of being in the centre of interest of the robot. When the dialogue is finished, the robot moves back to its home position and the system is set back into the wait state, until the next visitor appears.

The authors of [ZDH+03] claim that they could build a very robust and fully integrated system by using a rather simple approach. Modules and system components are integrated on a high level of abstraction so that it is possible to improve the single components without changing the whole system. On the most abstract coordination level, the system works sequentially. Within each state the required modules are running in parallel, which makes the system a partly sequential and partly continuous system. However, in the continuous phase, when vision and dialogue run in parallel, the results are not really integrated, as results from image processing do not affect the dialogue itself.

ALBERT, Karlsruhe, Germany

Figure 2.4 shows the robot ALBERT [DZER02], a service robot at the IAIM[6] group at Karlsruhe University. Interaction is used to program the robot in a natural way.

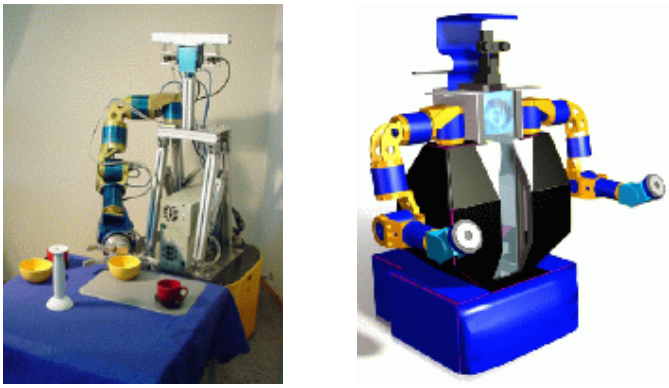


Figure 2.4: *Left: The service robot ALBERT, engaged in setting a table. ALBERT provides and interactive interface for natural programming. Right: A new (actual) design for ALBERT*

The integration of different modalities like speech and gesture is based on handling everything that happens (in the relevant environment) as an event. Those events are buffered in a so called *event plug* from where they are taken and processed by a set of automatons (transformers). Those transformers are sequentially asked if they can handle the particular event; if not, the event is passed on to the next transformer, beginning with the one that can handle the most likely event or group of events.

[6] http://wwwiaim.ira.uka.de/

The ruling, what type of event is most likely and therefore which transformer has to be the most important, is given by a priority module. Transformers are in general independent and can be exchanged, added and removed as required. The incoming event is processed by the responsible transformer, which can also mean that two or more transformers provide a fusion of two or more related events, and an action is generated. This action can then be sent to the hardware components as a command. Events are continuously interpreted and processed. Here, the input of all perceptual modalities can be responsible to trigger processing.

Nursebot, USA and Germany

The Nursebot project[7] is a large project involving different universities in the US and Germany that was established to design personal service robots for the elderly [BFG+00, MPR+02]. The current Nursebot robot PEARL, shown in figure 2.5 on page 10, provides two of the main functionalities the project aims at: 1) It reminds people not to forget certain actions, like taking medicine (cognitive prosthesis), and 2) it guides people from location A to location B, adjusting its velocity to that of the guided person. In order to be able to remind people of certain things, the system

Figure 2.5: *The Nursebot robot PEARL at a nursing home.*

must constantly keep track of what the particular person is doing or not doing. The initiative for the actual interaction with the person has to be taken by the system, not by the person. Modalities used in this case are speech, typed output and vision, the latter basically for keeping track of the user. The robot provides a touch sensitive display which was used only to additionally present the spoken output as text. The study does not refer to any particular purpose of this feature in the conducted user tests, but it is mentioned that the display should be used to point out certain locations on a map. At this point it is not clear how this information integration should be done.

PEARL's control architecture used to organise different functionalities and make

[7] http://www-2.cs.cmu.edu/~nursebot/

Figure 2.6: *The robot at NRL, equipped with laser light emitter and tuned camera for gesture recognition*

decisions for the interaction with the user is a hierarchical variant of a partially observable Markov decision process (POMDP). Hierarchy is needed to reduce the state space to a reasonable number of possible states, as pointed out in [MPR+02]. The action hierarchy for the test scenarios is based on the three action states *remind* (cognitive prosthesis), *assist* (guiding user to certain location) and *rest* (no interaction, recharging battery). The authors state that, apart from some initial problems with poorly adjusted audio systems, all scenarios (visiting users and take them to a certain location, explaining reasons of the visit, etc.) worked well and users were able to understand the functionality of the robot after about five minutes of introduction.

Navy Center for Applied Research in AI, NRL, USA

In [PASM00] a system that integrates spoken commands, natural gestures and a graphical interface on a handheld personal digital assistant (PDA) is presented. These can be used both to give commands and for pointing gestures to control a robot. Figure 2.6[8] shows the robot used in the experiments reported. Gestures are in both cases used only for deictic elements in commands. An example would be a "grab this"–command. "This" refers to something in the field of view of both communication partners and usually is accompanied by a pointing gesture.

In order to be able to interpret pointing gestures from the PDA, the environment is presented as a map on the PDA. In this multi-modal interface, gesture and speech processing are run in parallel, so this system could be seen as a continuously working system with two input cues. Input from the PDA is separated into either a gesture or a command and fed into the respective queue on the appropriate level of processing. The (spoken) command interpretation is done with the help of the group's system "Nautilus", presented in [PSA98]

[8]Picture from http://www.aic.nrl.navy.mil/

Both processing queues provide a representation of "their" input, which are then checked for appropriateness in a filter. This filter creates a logical representation of the command combined with the interpretation of the most recent gesture. Gestures are queued until the filter requests a gesture to complete command input that was processed recently. If no appropriate match of gesture and command can be conducted, the system produces an error message.

Interact Project, CMU Pittsburgh, US and Karlsruhe, Germany

The Interact Project of the Interactive Systems Lab[9] (ISL), located at the University of Karlsruhe and at the Carnegie Mellon University Pittsburgh, aims to combine multiple communication modalities to enhance human computer interaction. The project consists by now of different sub-projects that cover eye gaze tracking, face tracking, integration of gesture and speech, focus-of-attention modelling, multi-modal interactive error correction, lipreading and speaker identification. The integration of speech and gesture is itself a project that integrates two different modalities. Here, gestures are assumed to be handwriting or pen-pointing gestures on a touch sensitive display combined with spoken comments. The original purpose of this integration is to provide a time schedule (re)organising facility. Entries in a calendar can be picked and with a spoken command, e.g. "Reschedule this tomorrow", be moved to another date.

Discussion

The following paragraphs compare the systems presented previously to each other and to the ideas and principles underlying the work of this thesis.

MOBSY The idea of modularity and exchangeability is one of the most important principles used for the implementation work this thesis refers to. However, in terms of user centred interaction, MOBSY has some drawbacks that the work presented in this thesis tries to avoid. MOBSY detects people with a support vector machine based categorisation that decides, whether an elevator door is open or closed. An open door implies the presence of a visitor, so that the whole loop (approaching, starting a dialogue, etc.) would even be started, if a *leaving* person opens the elevator's door to enter it. In contrast to this, the implementation in this work makes sure that a person is detected, *before* she is addressed and drawn into some communication. Second, MOBSY approaches the visitor by moving to a fixed position, assuming that the person stops right in front of the elevator after being asked not to go away. In the work presented, the robot should only approach the user, when this is necessary in the context of the communication, or to fulfil a task the user asks for. The robot moves to an appropriate position relative to the user and not to a, maybe intimidating, fixed

[9] http://isl.ira.uka.de/js/ or http://www.is.cs.cmu.edu/js/

position. Yet, the strategy of integration of different modules that will be presented in chapters 3 and 4 is quite similar to the one used for MOBSY.

ALBERT Compared to a system like MOBSY, the control architecture for ALBERT is based directly on the actio-reactio principle and not on the idea of a certain scenario, involving some communication. As the authors of [DZER02] point out as an example, a user's greeting "Hello Albert" is considered a speech event of a particular type and some appropriate response is generated. When thinking of a scenario based approach this is still a special type of speech event (greeting) but it could also be considered a necessary input to start the control loop for interaction. The design approach in chapter 3 interprets interaction with service robots more scenario based. This makes it possible to keep track of a communication state. Events can be interpreted within the context of the whole communication process between user and robot which makes it possible to consider certain events more likely than others depending on the context.

PEARL PEARL's control architecture is - compared to the one used for MOBSY - rather complicated and it is nots obvious, how the system would scale, when more functionalities are introduced into the control hierarchy. States of dialogue and system states of interaction (or actions) seem to be considered the same, so a change in the dialogue itself would cause changes in the whole control structure. Such drawbacks are possible to avoid if the integration of components is done on a high level of abstraction. Only actual required modules can be combined at the respective state of interaction. Therefore, the work this thesis is based on concentrates more on the high level integration than this is done for PEARL.

NRL The authors of [PASM00] point out that the system allows the user to decide spontaneously, which modality she wants to use. This makes it possible to cope with situations in which the one or the other input type can not be processed satisfactorily. For example, in a very noisy environment it is easier to use the graphical PDA-interface instead of using speech.

In order to achieve this liberty for the user, the interpretation of input coming from speech recognition, image processing or from the PDA is kept independent from the representation of commands including interpreted deictic elements. This idea of keeping the interpretation separated from the coordination and action decision will be found again in the design proposed in chapter 3.

Summary

This section presented various approaches to interactive interfaces and tried to point out their advantages, disadvantages, connections and delimitation to the author's approach presented in chapter 3. The presented systems were classified depending

on the type of integration (state based or continuous) that are used to combine different modalities.

2.2.2 Graphical interfaces and usability

The idea of using graphical interfaces in (natural) human robot interaction seems to be a step back, but experiences with this modality show, that it is not that unfounded. Considering users with certain impairments or environments where for example speech recognition is difficult, such interfaces can even be a helpful enhancement of other modalities. If a graphical display is used to show maps of the environment which can be helpful to point to a certain location, this is not even far away from human-tos-human communication when one person shows the other a location on a (paper) map. Some examples of graphical interfaces that are used in human robot communication will be given in the following.

MissionLab, USA

An example of a graphical interface used to assist users in specifying robot missions is presented in [EMA02] and [MAC97]. The authors also refer to a very carefully designed user study which had as a result, that with increasing complexity of the test task also the utility of the interface increased. A relatively easy test task could be solved as reliable with the textual input system that was used before. The study was designed for two groups; one was using the graphical interface, the other worked with the textual input only. Two test tasks had to be solved, one rather easy, the second more complicated. For the first task the time required to solve it was not significantly different and results about the same in both groups. With the complicated task the group with the graphical user interface was significantly faster and better. This shows some interesting results and produces new questions for human robot interaction. First, it does not seem to be important if an interface is based on so called "natural" means of communication, it seems to be sufficient to build it "natural" for the task environment. Second, costly designed user interfaces are only helpful, when the costs of learning how to use them are in adequate relation to their use.

The presented robot mission specification system MissionLab is equipped with this graphical user interface. The whole system concentrates on actions a robot or, as described in [MAC97], a multi-agent system should perform. MissionLab itself provides a generic interface to a robots' control systems so that it is completely independent from the basic robot behaviours. The graphical user interface provides tools to specify for example sensory abilities of the robot used currently, which leads to the use of the appropriate interface type.

CERO, IPLab KTH, Stockholm

When the IPLab conducted their user study with the fetch-and-carry robot CERO mentioned in section 2.1.2, a graphical user interface was used. The interface was running on a regular PC at a fixed location. A reduced version of this it was additionally installed on a handheld PDA. The idea was, to control the robot basically from the fixed PC. The PDA was meant as a tool for irregular situations if it became necessary to control the robot directly where it was. The program running on the PDA could disable certain basic security behaviours like obstacle avoidance or environment checks. This made it technically possible to navigate the robot in situations, where it self would have stopped, if it would have been running autonomously.

The handheld PDA was – according to the user – a bit uncomfortable to carry around. The disadvantage of the fixed user interface at only one certain place is obvious: A user would have to go to the control computer to communicate with the robot, even if both, user and robot, are in the same location. For this user study the robot was only controllable with the two graphical devices because the usability of a service robot in an office environment was to be tested, not the means of communication.

Navy Center for Applied Research in AI, NRL, USA

As mentioned before, [PASM00] presents a system that integrates a graphical interface on a handheld PDA in addition to spoken commands and natural gestures. The PDA provides a map of the environment, used for pointing gestures for deictic elements and a number of buttons that represent basic commands like for example “Go to”. As the graphical interface provides the same information as speech and gesture interpretation, it can be used deliberately, or not at all. Unfortunately, no user study is reported about the attitude of users towards the different means of communication in this case and there are no reports of how often the graphical interface is used in addition or as a substitute to the other modalities.

Summary

This section presented three different cases in which a graphical interface was used to control mobile robots. The graphical interfaces where implemented on different platforms, on a fixed computer, on a mobile handheld PDA and both, in one case. In general, the results show that graphical interfaces indeed can be considered helpful in human robot interaction, but the question of where the interface should be implemented is still far from being answered. The implementation presented in chapter 4 does not use any graphical interface or hand held device, but it could be an interesting enhancement for interactive interfaces and should not be forgotten.

2.2.3 Speech and dialogue systems

Speech is often considered the primary modality for interaction. Some current approaches to speech and dialogue processing are presented in this section. In general, speech processing can be classified in three different levels: a) the recognition of words and phrases, b) the context based interpretation of the recognised words and phrases and c) dialogue management. The following sections give examples for systems that deal with the respective levels of speech processing.

Speech recognition: ESMERALDA, Bielefeld, Germany

The speech recognition system ESMERALDA was developed by the Applied Computer Science group at the Faculty of Technology, University of Bielefeld, Germany. A detailed view of its Hidden Markov Model (HMM) based recognition process is given in [Fin99]. The system was used for speech recognition in the implementation presented later.

ESMERALDA works speaker-independently and it is rather uncomplicated to add new words and sentences to the system. Newly added words have to be set in some context sentences so that the likelihood for a particular word in the context recognised previously can be estimated. To add special domain dependent words only some specific files have to be changed. General lexical word lists come with the system. After adding new words the sentences are used for training. When testing the system for the rather small set of sentences required for the implementation's purpose (see chapter 4 for details) it was possible to get sufficient results with low training effort.

Speech recognition: JANUS, Karlsruhe, Germany

More research in speech recognition and processing is done at the Interactive Systems Lab (ISL) at Karlsruhe University (TH), Germany[10], and CMU, Pittsburgh, USA[11]. To build the speech-to-speech language translation system "JANUS" [WJM+91], speech recognition was based on time delayed neural networks (TDNN) [WHH+89]. By now, as stated on the project's web page, the system still has problems with ill pronounced natural language, but works – with a vocabulary of 3000 to 5000 words (depending on the language) – rather sufficiently. Parts of JANUS, in particular the speech recognition and parsing, is used in other projects of the lab, for example for the "LingWear" project, which aims to build wearable assistant tools.

Grammar based interpretation: KaSpER, Karlsruhe, Germany

In terms of interaction not only speech recognition, but also the interpretation and disambiguation of recognised input is important. [Rößß02] describes the grammar and

[10] http://isl.ira.uka.de/
[11] http://www.is.cs.cmu.edu/js/

linguistic theory based system KaSpER that syntactically and semantically interprets (German) spoken input to generate symbolic descriptions of it. These can then be used to build commands or information for a service robot. Such a system is particularly useful when the dialogue has to be mapped to some prior knowledge about the environment the robot has to work in. [Röß02] refers to some other speech interpretation approaches, some of which are grammar based.

Pattern search based interpretation: MOBSY, Erlangen, Germany

A second method for the interpretation of spoken input is keyword spotting or pattern searching, as for instance done for MOBSY, the mobile receptionist robot presented in section 2.2.1 with respect to [ZDH+03]. The system searches for relevant words or phrases in the hypotheses coming from speech recognition. When such a phrase appears, it is used for further processing. If no relevant phrase can be found, the utterance is ignored. This can in some cases be a positive factor for robustness, because the "obviously wrong" input does not mislead the system into unexpected states. Therefore, it is easy to detect an utterance that the system can not process correctly, which makes it possible to react with an error message and question for repetition. The speech interpretation for the implementation presented in chapter 4 is based on the word spotting principle.

Managing dialogues: ariadne, CMU, Pittsburgh, US

One problem when processing speech and language is disambiguation. [DW97] proposes an idea to guide users to their communicative goals by giving appropriate feedback. Here, typed feature structures are used with respect to [Car92] to detect a lack of information or an ambiguity. Based on this detection the user can be asked for clarification. On this base a generic (domain independent) dialogue management system ("ariadne", [Den02]) was developed that can be used to design domain specific dialogue systems, as for example described in [Top02]. In this case the dialogue system handles all the communication until the goal of this particular communicational event is clearly specified. A connected system gets the appropriate command to perform the desired action. All responsibilities for feedback, error messages etc. are located in the performing system, but the knowledge base used for the dialogue is not accessible directly. If something goes wrong during execution, a new dialogue would have to be initiated to solve the problem. Thus, it seems to be more useful, to connect both, the dialogue and the executing system, to some world knowledge.

Summary

In this section speech processing was classified in three basic steps, a) recognition, b) interpretation and c) dialogue management. A number of different approaches to each of those classes were presented. Some of the underlying principles can be found

in the design in chapter 3 and in chapter 4, where the work this thesis refers to is described.

2.2.4 Gesture recognition for interaction

Another modality for interaction, that is often referred to, is gesture recognitions. Many of the current systems try a combination of gestures and spoken input, but nevertheless some of the single modality systems are presented. A way to distinguish between gesture recognising systems is if they are designed for static (e.g. pointing) or dynamic gestures (e.g. waving). Both types of systems are named in the following.

HMM based (dynamic) gesture recognition, KTH, Stockholm

The gesture recognition system described in [San99] uses the results of a skin colour detection based tracking algorithm (see section 2.3.3) and is based on Hidden Markov Models (HMM). The system is built for recognition of dynamic gestures and was tested on graffiti sign language gestures and some controlling gestures for a robot. These could be interpreted as commands like “move left” or “stop” with quite high recognition rates. Within this thesis it should be tested, if the tracking approach of this recognition system could be used in the context of other cues as a recognition system for static (pointing) gestures. This idea is based on the fact that pointing to something involves moving the hand into the particular pointing position.

2 1/2D position based trajectory matching, NRL, USA

This approach to gesture recognition is presented in [PSA98] and is used in the integrated interface at the Navy research center ([PASM00]) mentioned previously. Gestures are recognised by matching observed trajectories of hand movements to known example trajectories. The trajectories are generated from sequential calculated positions of the hand(s). To get the positions a laser range finder is combined with a camera which is tuned to the laser light frequency with the help of a filter. Both devices are mounted on the robot used for the experiments. The laser light is sent out in a horizontal plane at a height of approximately 75cm and the tuned camera makes intersections of objects and the laser light visible. Intersection points are clustered and the cluster(s) closest to the camera are considered representing a hand. The respective positions are calculated in coordinates relative to the camera, i.e. the robot. Pointing (deictic) gestures are not considered being a static gesture that would involve recognising a finger pose, therefore this approach could be seen rather as a system for recognition of dynamic gestures than static ones. An obvious disadvantage of this approach to gesture recognition is, that gestures would have to be made at a certain height.

Self organising maps for 3D pose reconstruction, Bielefeld

In [NR99] and [NR00] a method for the reconstruction of the hand pose with parametrised self organising maps (PSOMS) is proposed. From the position of certain points in the 2D-image, which represent the fingertips, the hand pose can be reconstructed. This is possible, as the hand configuration space can be reduced drastically when the interdependence between certain finger postures is considered. With the help of this observation the feature set resulting from the fingertip detection, that is fed into the PSOMS, can be kept rather small, which allows a relatively fast reconstruction and thereupon recognition of different hand postures. Such an approach would make the recognition of a static pointing gesture possible, but would require that the camera is focused on the respective part of the image, so that fingertips and -postures can be extracted. With a system that has to be used for different purposes like person detection and gesture recognition this can not be guaranteed.

Template based 3D gesture recognition

Another approach for gesture recognition is used in [Vac02] with respect to [GBMB00]. Here, 3D hand postures are matched to a respective template. The authors of [GBMB00] state that they reached a recognition rate of 96% under changing light conditions for six different gestures. In [Vac02] the recognition of pointing and grasping gestures is based on this approach. Here, it had to be stated, that the false alarm rate is rather high. Arbitrary hand postures where recognised as gestures as the system does not have any context information to estimate the likelihood that in fact a gesture was observed. This leads to the question if it is useful to have a gesture recognition running continously. The design described in chapter 3 considers gestures only within a certain context as likely, which reduces false alarm rates.

Summary

This section presented some different approaches to gesture recognition, based on different types of data. Due to the given hardware and the availability of one of those systems, the implementation concentrates on the approach used in [San99] and the idea of recognising gestures only in the appropriate context.

2.3 Tracking for interaction

Keeping track of the person to interact with, is a very important part of any kind of interaction system. Among others, tracking can be used to generate feedback, for instance by moving a camera towards the user, which indicates “attention”. In fact, keeping track of the communication partner is the base for most actions within communication. If the robot does not know, who it should communicate with, it is not able to follow particular actions, gestures for example. Therefore, this section

describes the general problem of tracking and gives some examples for tracking based on different sensory input types.

2.3.1 Tracking in general

Tracking in general means estimating the state of a moving target over a certain time period, using measurements generated from data sequences. Such sequences can for example be video streams or consecutive laser scans. The state of the target could then be

- the centre point position of a face as a pair of coordinates x and y with respect to image data represented as a pixel matrix or
- a position of a person in a room, given in coordinates with respect to the coordinate system of the laser range finder the data originates from.

These examples can be represented by the following general tracking problem for one target:

Let x_k denote the state of the target at time step t. Given a data sample sequence $z_0, z_1, z_2, \ldots z_k$ taken at the time steps $t = 0, \ldots, k$ and knowing the initial state x_0 corresponding to the data sample z_0, the problem is now to extract the state x_k at any time step k from the corresponding data sample z_t.

The tracking problem can be extended to multiple targets by assuming a set of targets $X = x_0, x_1, \ldots, x_n$. A very important part of tracking, especially when multiple targets should be tracked, is data association. That means answering the question, which feature belongs to which target and vice versa. Data association can even be difficult when only one target is involved, for the features the target generates in the data sample are not necessarily unique. This ambiguity problem can occur both in laser or image data, therefore the respective sections will refer to it more detailed.

A tracking process can be separated in two main parts, initialisation and tracking itself. Initialisation means finding the initial position of the person or object to be tracked. Each of the following sections refers separately to these distinct parts of the tracking process. Figure 2.7 shows the basic steps of a tracking algorithm. After initialisation the tracking process is a loop consisting of four steps. First new features are generated (*detect*) and *matched* with the predictions (coming from initialisation or the last step in the loop); this result is used as base for an *estimation* step that is needed to *predict* the new state.

Initialisation

The initialisation step for tracking depends on the type of data and the type of target to track. In general it means detecting a feature in the data that matches a

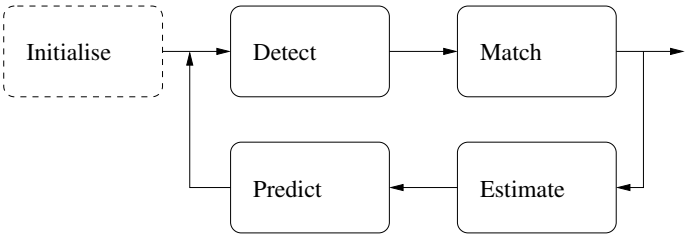


Figure 2.7: *The tracking process. First the tracker has to be initialised, then the predict and match loop is entered*

representation of the target. This step is described more detailed for the different types of data used for tracking.

Estimation and Prediction

The loop of estimating, predicting and updating (matching) can be in general based on Bayes theorem. [AMGC02] presents an overview of different filter techniques that are based on this basic idea. The goal is, to give an estimation for the probability of the target state x_k at step k based on the known measurements $z_i, i = 1, .., k$ or shorter $z_{1:k}$. This is achieved with the two steps prediction and update. The prediction computes the prior probability density function (pdf) $p(x_k|z_{1:k-1})$ via the Chapman-Kolmogorov equation:

$$p(x_k|z_{1:k-1}) = \int p(x_k|x_{k-1})p(x_{k-1}|z_{1:k-1})dx_{k-1}, \tag{2.1}$$

the update from prior to posterior pdf is done with Bayes' rule

$$p(x_k|z_{1:k}) = \frac{p(z_k|x_k)p(x_k|z_{1:k-1})}{p(z_k|z_{1:k-1})} \tag{2.2}$$

with the normalising constant

$$p(z_k|z_{1:k-1}) = \int p(z_k|x_k)p(x_k|z_{1:k-1})dx_k. \tag{2.3}$$

The state sequence itself is assumed to be given by $x_k = f_k(x_{k-1}, v_k k - 1)$ where f_k is a possibly non-linear function of x_{k-1} and v_{k-1} is a noise sequence. The measurement sequence can be described respectively as $z_k = h_k(x_k, n_k)$ where h_k is a possibly non–linear function and n_k a measurement noise sequence.

Kalman filter One classic filter is the Kalman filter which assumes that the posterior density is Gaussian at every step k. This invokes some more assumptions about parameters and functions:

- $vk - 1$ and n_k are from Gaussian distributions of known parameters
- $f_k(x_{k-1}, v_{k-1})$ is known and linear

- $h_k(x_k, n_k)$ is known and linear.

In other words, the movement of the target must be predictable as a linear process and a missing measurement due to occlusion causes problems for the tracking process.

Monte Carlo filters – Particle filter A Monte Carlo filter is a filter based on the Sequential Importance Sampling (SIS) algorithm. Various approaches to Monte Carlo filters are known as bootstrap filtering, condensation algorithm, particle filtering, interacting particle approximations and survival of the fittest. The basic idea is to generate a set of N weighted samples that all represent a more or less likely state of the tracking target. These samples can be written as $(x_k^i, w_k^i), i = 1, ...N$ where $x_{0:k}^i$ is the state of the ith sample at time step k and has the weight w_k^i. $\{x_{0:k}^i, w_k^i\}$ is then a random measure for the posterior pdf $p(x_{0:k}|z_{1:k})$, where $x_{0:k}$ is the set of all states of the target up to step k. With the weights normalised to $\sum_i w_k^i = 1$ the pdf at step k can be estimated as

$$p(x_{0:k}|z_{1:k}) \approx \sum_{i=1}^{N} w_k^i \delta(x_{0:k} - x_{0:k}^i). \tag{2.4}$$

The weights are computed using the principle of Importance Sampling, which is explained in [AMGC02] with reference to [Dou98]. With a proposal, a so called importance density $q(\cdot)$ samples $x_{0:k}^i \sim q(x_{0:k}|z_{1:k})$ can be obtained by augmenting each existing sample $x_{0:k-1}^i \sim q(x_{0:k-1}|z_{1:k-1})$ with $x_k^i \sim q(x_k|x_{0:k-1}, z_{1:k})$. Thus, in each step the samples (particles) are assigned a new estimation of the target state and a new weight, according to the more detailed description in [AMGC02].

The advantage of these filters is, that constraints for the functions that describe the state and measurement sequences are more relaxed than for Kalman filtering. A particle filter as for example used in [SBFC01] is much more robust to occlusions and measurements missing temporarily.

Data Association

Two approaches to solving the data association problem will be presented within the respective examples of tracking methods in the following sections. One of these approaches is based on a statistic Bayesian method, the other is a more heuristic anchoring technique.

Summary

In this section the tracking process in general was explained. Tracking is one very important task for any interactive interface for a service robot, as it might be used to detect the user and focus on her. Another purpose is tracking for gesture recognition which can also be part of an interactive interface. The next section will give some examples of recent work of person tracking using laser range data.

2.3.2 Tracking with laser range data

A typical laser range scan contains a set of $n + 1$ distance values, covering a certain angle in a planar scan. The distance values are achieved by measuring the reflecting time for each laser light beam when it comes back after it reached the next object in its particular direction. Laser range data is easy to interpret, but the only information it provides is in fact the front position of an object at a certain height. Laser range finders are often used for a robot's self-localisation or to track people and other moving objects that do not leave the scanning plane by moving up or down (like hands, for example). All examples consider person tracking, as localisation is not in the main interest of this thesis.

Detecting persons in laser data

Two main cues can be considered, when a person should be detected with the help of laser data. The first one is shape, the second movement.

Shape There are quite a lot of systems that are based on shape and even those can be separated as the following paragraphs suggest. The decision, which approach to use is in this case mainly driven by the used hardware, as the two approaches require the laser range finder at a certain height respectively.

Body shape The shape of a person's body can be a cue, as presented in [Klu02]. The author of this publication points out that a person causes a convex pattern in the scan. Such patterns are relatively easy to find by using the convex hull of the poly-line the data points describe. If a convex feature is detected, it can be checked for appropriate size, which can be estimated from minimal and maximal assumed person width and the distance. However, even with this size constraint an algorithm that only uses body shape would find lots of "people" that turn out to be furniture, screens and other static objects that happen to have the width of an average person.

Shape of legs A rather popular approach is to look for legs, i.e. look for a pattern in the scan that represents two leg-wide convex minima in suitable distance. This approach is used for example in [KLF+02] and [FZ00]. The presented approaches work quite well, but a problem referred to in [FZ00] are long skirts or other clothes that make the legs invisible. In this case the system would in fact fail to detect the person at all, whereas the search for body shaped features produces rather false alarms than failures. A method to reduce the false alarm rate for the body shape detection is to use a second cue, for example motion.

Motion One approach to get a first guess, which of all detected person-like objects is actually a person, is to take motion into account. If the "person" does not move at all (or could even be found as a static object in some a priori known world map) it

is not longer considered a person. In [SBFC01] this is done with a grid representing positions in the world map of a mobile robot. First, the probability for legs being detected at grid position (x,y) relative to the robot, $P(legs^k_{x,y})$, is computed. The next step is to distinguish between static and moving objects (or persons) by looking for changes in consecutive scans. Therefore, local occupancy grid maps, with respect to [ME85] are used. Based on those, the probability $P(new^k_{x,y})$ that an object (or person) has moved to a new position (x,y) can be computed. As the movement of the robot has to be considered, too, the built occupancy grid maps have to be matched first, which is done by a scan matching technique as presented in [LM94].

As the used laser range finder was mounted too high for the leg detection approach (see appendix A for technical details), the implementation presented in chapter 4 uses a combination of body shape and movement to detect possible users.

Estimating current positions of persons

After a person is detected and the initial position is known, the next step is to find the person again in the succeeding laser scan, based on estimation, prediction and update (matching) as described before.

[SBFC01] presents for example the use of a special particle filter version (see above) which also solves the association problem for multiple targets. This particular filter is called a Sample Based Joint Probabilistic Data Association Filter (SJPDAF). The idea here is to do the data association with the help of a Joint Probabilistic Data Association Filter (JPDAF), a technique that computes the posterior probability β_{ji} that a feature j was caused by person i at a time step k:

$$\beta_{ji} = \sum_{\theta \in \Theta_{ji}} P(\theta | z_{1:k}) \tag{2.5}$$

where Θ_{ji} denotes the set of all valid joint association events θ. Such a joint association event is a pair (j, i) and determines which feature is assigned to which person. $P(\theta|z_{1:k})$ is the probability to get the association θ if the sequence of measurements $z_{1:k}$ is observed. $P(\theta|z_{1:k})$ can be computed using Bayes' rule and the assumption that the whole estimation problem is Markov to

$$P(\theta | z_{1:k}) = \alpha p(z_k | \theta, X^k) P(\theta X^k) \tag{2.6}$$

where α is a normaliser and X^k represents the state of all persons at step k. This computation can further be based on the general idea of Bayesian tracking (see above). The last step is then to use the so derived prediction and update rules for a set of samples which invokes a particle filtering process. Details are described in [SBFC01] where also the use of such a combined approach is pointed out clearly. The authors state, that, besides the advantage of particle filters compared to a Kalman filter, the combined method with data association makes the association even more

robust to occlusions. A particle filter used for multiple moving persons would in case of occlusions tend to set the samples on the remaining "visible" persons and loose the occluded one. The SJPDAF is – according to the authors – capable of handling this problem, too.

When the person tracking for the implementation within the work of this thesis had to be done, the first idea was to base it on a method related to the presented one. But during first tests it turned out that under particular assumptions (see chapter 4 for details) a much simpler approach worked sufficiently well.

Summary

This section presented some particular approaches to detecting and tracking persons with the use of a laser range finder and explained the relations to the implementation conducted for this thesis.

2.3.3 Tracking using computer vision

Tracking based on computer vision can be used for different purposes. One is the tracking of a person, another is tracking of a person's actions, movements and poses. Of course, this differentiation is a bit artificial, as both types of tracking have to handle basically the same problems, but for the presentation of different approaches it seems to be adequate to distinguish between those purposes at least for the detection, i.e. initialisation. Some of the presented approaches handle 2D-data, others are based on 3D-data from a stereo camera system. Only approaches to the detection of the targets are used, as the tracking process can be described basically similar to the approaches presented before.

Detecting persons in images

Two cues are used rather often to detect persons or person related targets like hands and faces in images. These are skin colour and shape. [San99] describes an approach for the detection and tracking of a user's face and hands, which is based exclusively on skin colour. The author had to assure certain constraints for the user's position relative to the used camera to make sure that this approach was successive. Such constraints can not always be met in a flexible environment.

In [BBB+98] a combination of four cues for user detection is proposed. The authors use skin colour detection, shape template matching, facial structure and a motion cue to determine a user's position from an image sequence. In this case the whole person is detected, but the general idea of using a shape cue in addition to colour could also be helpful for hand posture tracking and recognition.

2.3.4 Combining laser data and vision for tracking

As this thesis presents an approach of combining laser range data, vision and speech, the following tracking idea based on those types of sensory data is one of the most inspiring ones. In [KLF+02] an approach to tracking for interaction based on laser range data and image processing is presented. The results are integrated with the help of an anchoring method, proposed in [CS00], that allows to solve the data association problem for different types of data. Th initialisation is achieved from laser range data by looking for legs. If the parallel run face detection also succeeds for this position, the user is tracked. Both cues, position information from laser data and face position information from the image processing a used continuously to track the user and her face. In delimitation to this approach the system presented in chapters 3 and 4 uses the face detection only for verification, the tracking itself is based on laser range data exclusively.

2.3.5 Summary

This section named some approaches to detection and tracking of hands, faces or persons in images. Similarities to the approach maintained in this thesis were pointed out as well as delimitations.

3 Design of an interactive interface

This chapter describes the approach to a generic interaction interface for service robots. The first section explains how an interactive system should present itself towards a user. In the second section an approach to a generic interaction system design is proposed. The following sections describe the principles that are used to build a scenario based part of such a system.

3.1 Goal oriented interaction for service robots

A (mobile) service robot is a robot that provides services, i.e. performs certain actions to fulfil a task or mission, to users within a certain environment and context. The service robot is not personally associated with a single user. Communication (task specification) has to be initiated by the users.

Interaction is used as a mean to specify the particular service that should be performed in the respective situation. This implies that the robot has not only all primitive behaviours available, that are needed for navigation, planning and performance of tasks, but is also equipped with an interactive interface that makes an unskilled user capable of communicating with the robot.

In the following sections, the demands an interactive interface for such a robot has to comply with, will be discussed.

3.1.1 Use cases

First, the question is "why and when would a person want to interact with a service robot?". This section tries to answer that question. The cases of interaction between user and service robot can be reduced to the four basic use cases shown in figure 3.1. The actor "User" is connected to all four cases. On the robot's side it is useful to separate the primitive behaviours that involve the robot itself as action performing actor and tasks or system functionalities. The latter are provided by the interactive interface and can use primitive behaviours. For example, a grasping behaviour would be a primitive behaviour that is involved in a fetch-and-carry mission or task. Thus,

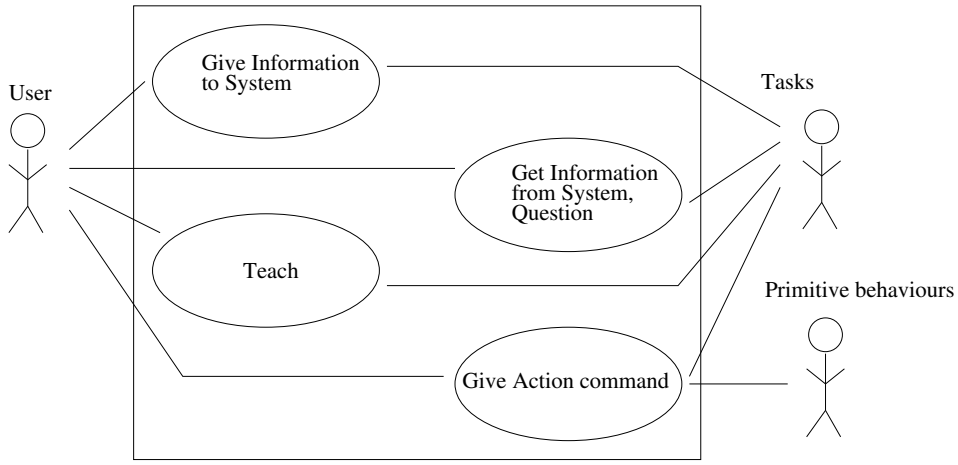


Figure 3.1: *The four basic use cases involving human robot interaction*

	Type	
	Information	Action
Originator: Robot	*Question*	*Command*
Originator: User	*Explanation*	*Teach*

Figure 3.2: *The four use cases classified by originators and type (action or information). Of course in all four cases the communication has to be two-sided, but the diagram refers to the information or action providing partner.*

the two actors are introduced. The case "action command" can involve either tasks or only primitive behaviours, it is therefore connected to both robot actors.

The use cases can also be classified according to figure 3.2 that shows them in reference to the active part of the communication event. "Active" in this case means "action performing or information providing". In all cases the initiative is on the side of the user. In the upper left corner the case "question" refers to the robot as an information providing actor, up right the robot is action performing for "command", down left it is the user who delivers "information" and down right the user is the one to perform some action to "teach" the robot.

The borders between those cases are fluent. As more than one use case can occur within one communication phase, certain scenarios might need both, user and robot, to perform actions. Especially the case "teach" might require the robot to perform actions (like moving to a certain position to get all the information it needs), although the user is considered the primary acting communication partner. The

following scenario explains more detailed, how a communication between user and robot can involve more than one of the use cases.

```
User : Hello Robot [establish communication]
Robot: What can I do for you? <in basic communication state>
User : Follow me [command: follow]
Robot: OK <follows>
User : Now I want to show you something [teach]
Robot: OK <"watches">
User : This is the new mail box <points> [teach]
Robot: Storing ‘‘new mail box’’
       to map at position *current position*
Robot: Anything else I can do? <back to basic communication state>
User : Uhm, what’s the time? [question]
Robot: It is *time*
User : Thank you robot, bye. [stopping communication]
Robot: Bye <returning to wait state>
```

This scenario suggests also, that the first step (establishing communication) is common to all use cases and has nothing to do with the respective use case itself. This is also true for the end of the communication. As the service robot is not permanently attached to one user it should be released so that it is clear that the communication with this particular user is finished.

3.1.2 Recognising the actual user

In order to be able to establish the communication, the user has to be recognised. This is in fact one of the most important parts of an interactive interface for a service robot. Additionally the user has to be represented internally, so that she can be distinguished from other persons being around. Mechanisms to do this will be pointed out in the respective section of the system design.

3.1.3 Establishing communication and giving feedback

The initiative for establishing a communication is considered to be on the user’s side. This assumption was also made in [PASM00] and it seems adequate when designing interaction systems for a service robot. It holds only for the initial phase of communication between a user and the robot. Of course, the system should have the ability to address a person, if the situation requires this, as pointed out in section 3.1.5. This is in fact a delimitation to a personal assistant that has to take initiative when reminding persons of certain actions as in [MPR+02]. However, for the work presented in this thesis it is adequate to make the assumption, that the user has to initiate the start of communication.

There are different possibilities to express this initiative and, as pointed out in section

2.1.2, the user should always know if the robot is aware of its surroundings. Thus, a possibility of "moderate initiative" should be given, for example, if someone walks up to the robot within a certain distance and stays in the field of view, she should be considered a possible user and be addressed, or at least informed, that the robot has noticed her presence and can provide services. The other form of initiative would be to address the robot directly, which should result in an appropriate reaction like searching for the user and offer its services.

Depending on available sensors and feedback mechanisms the system has to keep the focus of attention on the actual user and make this perceptible. A bad example would be a robot that is focusing on a random person when heading towards a group of people in which the user is present. Therefore, the system has to provide some kind of active tracking ability.

Apart from the feedback that is given by "facing" the user, the system should, depending on output facilities and context, give appropriate feedback about its current state. This feedback has to be perceptible for the user at any time of a communication phase. A bad example is a robot that gives feedback via a display, but turns the display away from the user due to for example a rotation that is needed to perform a certain action.

3.1.4 Communication model

As the system should be able to handle certain scenarios according to respective use cases, it is possible to suggest a particular model for the communication process. It is the user who initiates communication, the robot is supposed to react to this. Now the user has to state what she would like the robot to do, which should trigger an appropriate reaction. Following this principle the whole communication is somehow turn taking, as it is always one event that triggers a reaction and brings the communication into a next step or phase. This can be utilised for modelling the communication process.

3.1.5 Mission (re)scheduling and organising users

This section describes, how an interactive interface should deal with bystanders and irregular situations. An assumption that has to be made is, that some representation of users is available that allows, to recognise them. The idea of having a scheduling mechanism that allows to cope with the example situations described in the following is to be seen as a suggestion. Once the communication with one user is established, the system is exclusively attached to this user, with one exception. Consider the use case "command": If the given command involves the robot leaving the user in, for example, a fetch-and-carry scenario, it should be possible to allow bystanders to establish communication as well. Nevertheless, the system has to be aware that it is

still connected to the first user, so that it can report errors and problems to her at any time. A mechanism that can solve this problem, which was already mentioned in section 2.1.2 with respect to [HSE02], is to use a state based architecture and a scheduling mechanism that allows rescheduling for certain missions depending on the system's state. Some examples and suggestions will be given in the following. The examples explain, how the system should behave, section 3.6 refers to the tasks for the scheduling module. The general scenario is a service robot that meets a bystander when performing a fetch-and-carry mission for a user.

Providing information

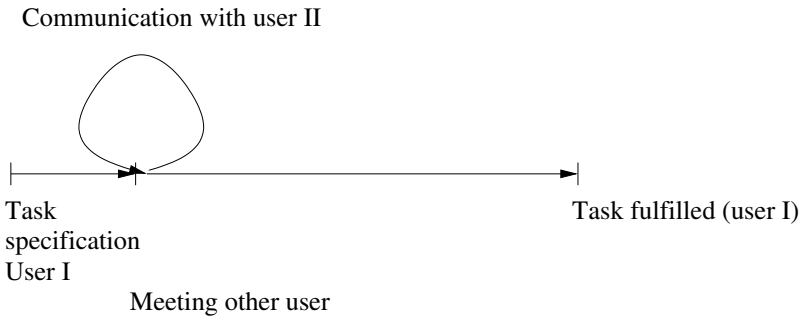


Figure 3.3: *The interrupted action is not changed in any way. Communication with another user is performed in a closed loop, after which the system returns to the stacked task at the point where it was left.*

In this case, the robot meets a user who only asks for information. This means to start a second communication phase with the respective dialogue which involves some information exchange (for example the user asks the robot about the time), complete the communication and continue with the interrupted mission. Figure 3.3 shows this in a diagram. The mission is the same, no rescheduling has to be done, and the system can "forget" about the second user after the information exchange is finished.

Performing mission independent actions without rescheduling

Such a scenario could be, that the robot is blocked by something or itself blocks something, but a person is present. This person initiates communication with the robot to resolve the problem by navigating the robot to a better position. After that, the robot continues with its mission from the new position. In this case the mission itself remains the same, but some new steps in planning the way or self localisation may be necessary. Figure 3.4 shows this in a diagram. In this situation the system does not have to store any information about the communication with the second user.

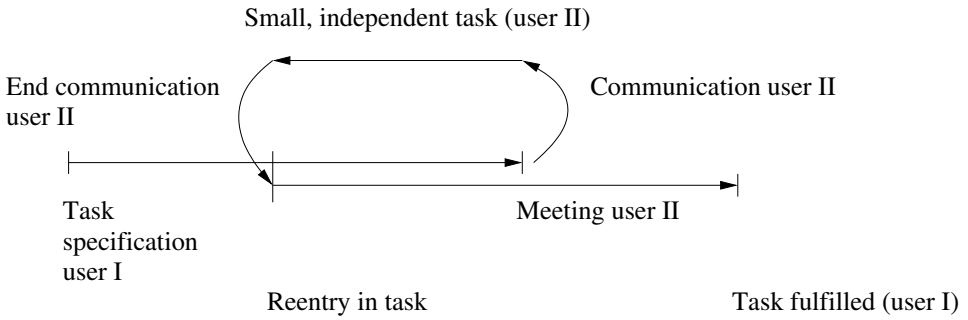


Figure 3.4: *The mission itself is not changed, but actions have to be re-planned, for example the reentry might be spatially different from the interruption point.*

Rescheduling missions – adding new task

Here, the second user realises that the system could add a second fetch-and-carry mission to the one specified by the first user, as the second mission is a subset of the initial one. For example, the robot's mission is to deliver user I's mail from the mail box to the user's office. The second user's office is between the first office and the

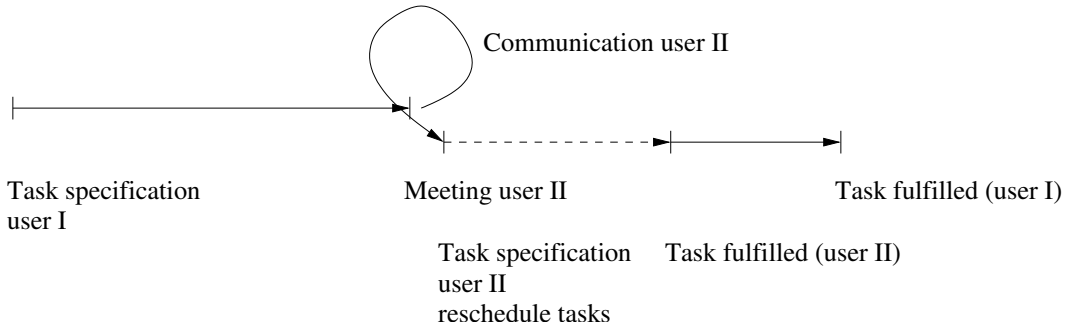


Figure 3.5: *Missions can be combined, so they are rescheduled.*

mail box. So the second user would like to have the robot deliver also her mail to her office. The mission is similar, the route is about the same, but the tasks themselves have to be expanded, as shown in figure 3.5. In this case the system would have to decide, whether it is possible to combine tasks or not. It has to be possible to reject a task or mission when combination is not possible.

Reporting error – mission abortion

If the robot can not complete the desired action, for example, because the route to the mail-box is blocked, the system has to realise this error and has to report it to the user. This is one important reason why the current user should be known to the system until she makes clear that the services of the robot are not needed any longer. Figure 3.6 refers to such an error scenario. In this case the mission could be removed from the schedule.

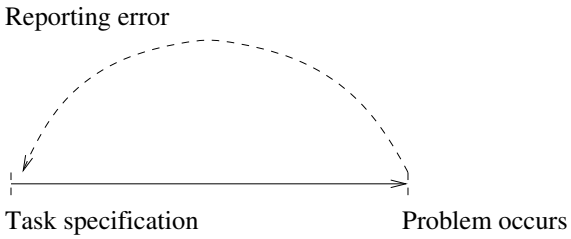


Figure 3.6: *An error occurs and the action has to be aborted*

3.1.6 Summary

This section outlined the basic ideas of how an interactive interface for a service robot should appear to users. The basic ideas used for the following design approach are the attention part of communication, which means detecting the user and keeping her in the focus of attention and the communication phase itself embedded in a scenario based approach.

3.2 An architecture for an interactive interface

The previous section described the desired behaviour of an interactive interface. This section now focuses on how this behaviour can be achieved. First, a general approach to an architecture is described, as it seems adequate to the author. Figure 3.7 shows, which general components would be required and how the components of the system can be connected to each other. The central component of the system is the coordination and decision module, referred to as the "control module". All information is gathered and decisions for appropriate actions and reactions are made here. The design of the control module itself is presented in section 3.3. The scheduler is considered the system component that should provide the task scheduling within respective missions and can handle rescheduling necessities. It is not designed for implementation in this thesis, but a general idea how such a scheduler should work is presented in section 3.6.

Generally, the system has to provide modules and components for the interpretation of sensory and other input data coming directly from the user. These interpretation modules build a separate layer between user and control module. Therefore, they can be kept flexible and exchanges can be made without having any effect on the control module itself.

The feedback that has to be given to the user is generated in the output module. For the system presented here, this output module is not designed explicitly, as it seemed more important to concentrate on the input interpretation first. In general the idea would be to provide a module, that provides directives on an abstract level and can then handle those directives depending on the hardware and modalities available on

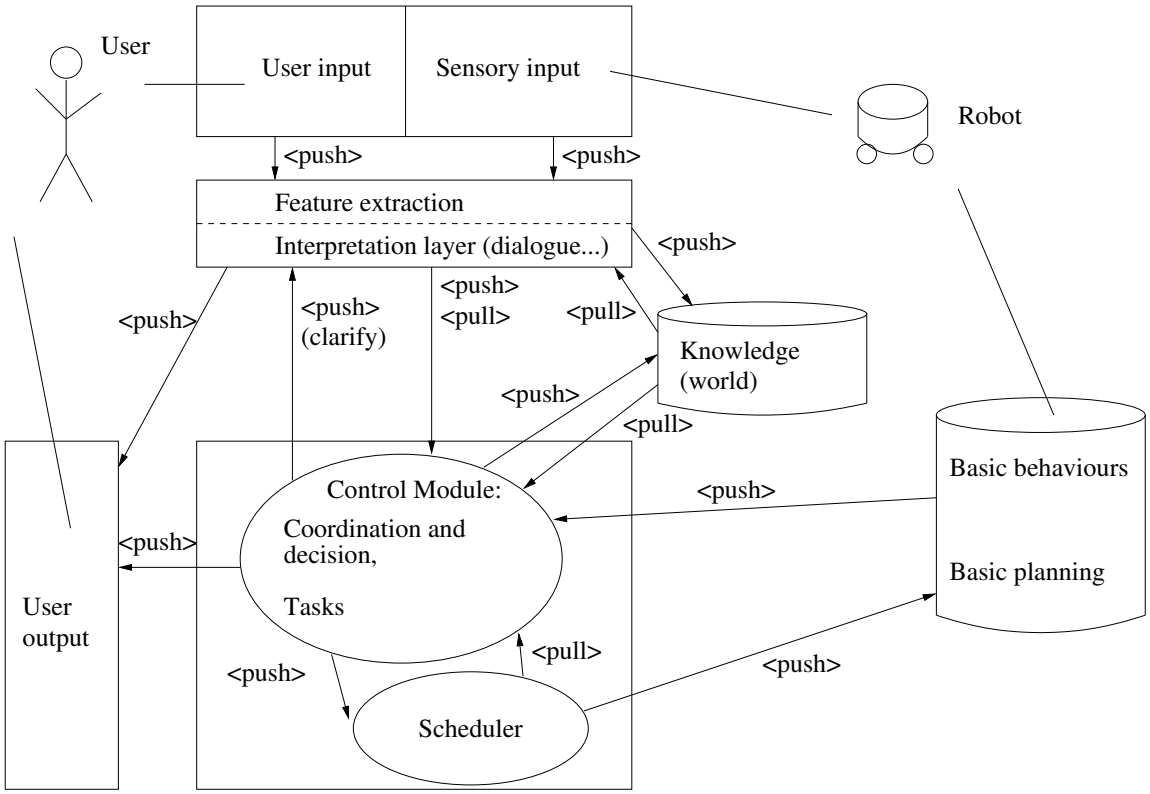


Figure 3.7: *An architecture for interaction systems. The basic idea is to keep the coordination very generic, based on an input independent control language. The arrows mark the direction of information flow, <pull> indicates that the receiver has to ask for input, <push> suggests that information is sent when available.*

the robot's side.

The world knowledge has to accessible for both, the input interpretation modules and the control module, as it should be possible to handle certain situations within this layer directly. For example, a dialogue module could need the general knowledge to interpret the dialogue for a given context. On the other hand the knowledge should also be available for the control module, as certain decisions might have to be based on the general knowledge as well as on the system's state.

3.2.1 Connection types

For the connections of the modules two types are proposed: Push and pull. A push type connection is needed in case the data is transmitted

a) regularly and used as a synchronising basis for the system, or

b) asynchronously and irregularly in terms of a certain abnormal event.

A pull type connection is used, if the respective data is transmitted in the form of a synchronous actively initiated data access.

3.3 Coordination and decisions

The control module is to some extent the heart of the interactive interface. Here, all decisions depending on interpreted inputs are made. As presented in chapter 2, there are many possible approaches to integrate information from different modalities and sensors. Thus, the question is now, what kind of approach would meet the demands of an interactive interface for a service robot. The first section of this chapter tried to state, how a service robot should "behave", this sections discusses how this behaviour can be achieved.

3.3.1 High level control of communication

Regarding the use cases for a service robot, it seems obvious that three different phases of communication can be found in all of the cases: a) Establishing communication, or in other words, get into the robot's focus of attention and b) the communication phase itself that is related to the use cases and c) releasing the system from communication. This implies also, that there should be a possibility to have the system doing nothing, i.e. waiting for the proper event that leads to the first communication phase. The four phases suggest a state based approach as they are entered sequentially, triggered by certain events. The phases pointed out here are strongly related to the state based approach presented in [ZDH+03], which worked well for the particular sequentially structured scenario. This relation to a generally state based sequential structure lead to a finite state automaton as the basic control structure for a scenario based approach.

The basic automaton

A finite state automaton can be defined as a quintuple $\{\mathbf{S}, s_0, \mathbf{X}, \delta, \mathbf{S_a}\}$ where the set $\mathbf{S}$ contains the states, S_0 represents the start state of the automaton, $\mathbf{X}$ the accepted input alphabet and δ defines the transition function. $\mathbf{S_a}$ consists of the accepting state of the automaton. In this case, the set of states would consist of

- a "wait" state, in which the system observes the environment for particular events, which is also the accepting state,
- a "start communication" state, in which the user somehow has to get into the focus of attention,
- a "communication running" state, in which the user has control over the robot's actions via the interaction system and
- a "going home" state, in which the system goes back to the "wait" state, which could for example involve moving back to a "home" position.

The start state is obviously the "wait" state and the accepted input alphabet consists of every event of the environment that can be interpreted by the respective module.

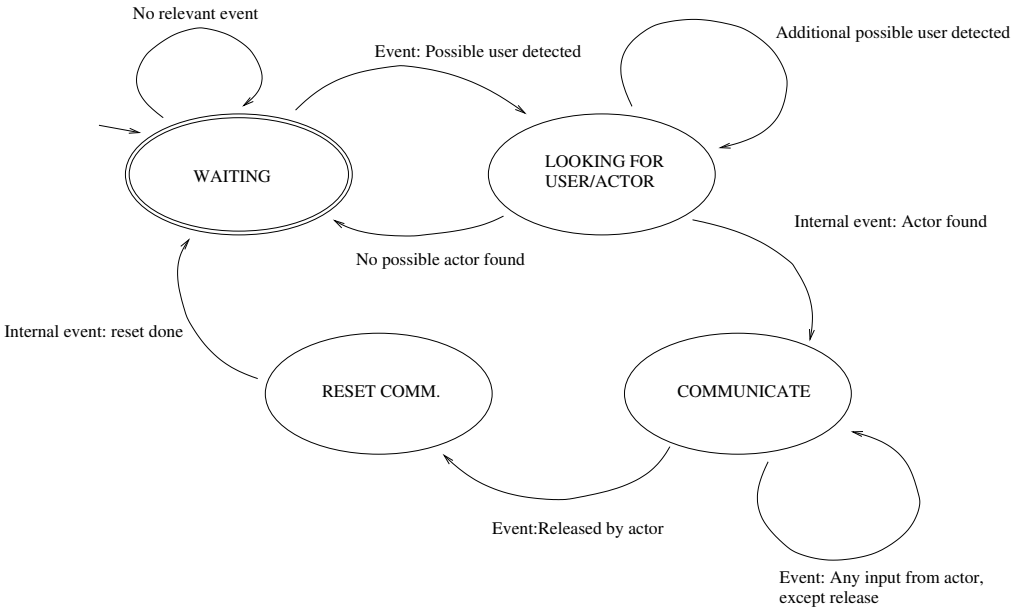


Figure 3.8: *The basic finite state automaton for interaction control. The start and accepting state is marked with a double surrounding line. State switches depend either on external irregular events and inputs or on the system's perceptions.*

The transition function is explained with the help of figure 3.8. The figure introduces the particular user as "actor". This notation will be maintained for the following sections, as it allows to distinguish between a general user of the system and the particular one who is the one to communicate with the system at a certain time. Unfortunately this expression can be confounded with the UML-Use Case-Analysis definition of an "actor" (see [FS00] for details), but references to this more general notation will be indicated respectively.

Events, that control the automaton can be

- explicit external events and input from the user or
- implicit events resulting from the ongoing interpretation of the input data.

An explicit external event in the "wait" state could be a person who is walking up to the robot, which – depending on the used sensory systems – might cause a "moving person perception", that initiates a state switch. In the "communicate" state external events are, for example, commands or questions uttered by the user, perceived gestures that can be interpreted within the context, etc. One special event in this state is the occurrence of a releasing input, like for instance a "good bye" uttered by the actor or the click on some "communication stop" button. This causes a next state switch.

Implicit events are independent of the actor's intentions. An example is the detection

of the actor. The system is triggered to search for the actor by her appearance as an explicit external event, but the implicit event "actor found" results from the triggered data interpretation. The user can not explicitely force the detection by any action or utterance.

As the presented automaton describes only the control loop on a very abstract level, it seems obvious that the states have to be refined and might be replaced by two or more sub-states, particular sub-automatons or other types of subsystems. The type of this refinement depends on the states and the types of input considered.

3.4 Proposed modalities

So far a rather generic approach to an interactive interface was described. The following sections will refine this approach to a design for a specific set of modalities and sensory data types.

The following paragraph motivates a particular set of data types as one possible set to handle at least one example scenario based on the "teach" use case.

3.4.1 Scenario related demands

In the first sections of this chapter the demands to comply with were pointed out as

- keep the user in the focus of attention and let her know this fact,
- be able to observe actions and explanations in a teaching scenario, and
- accept and interpret control input.

These demands to the behaviour lead to some needs for the system, as presented in the following.

3.4.2 Demand related needs

The following system components can cope with the respective demands:

- Robust and fast person tracking ability. Can be done for example with
  1. laser range data
  2. stereo vision
- Active face tracking. Can be done for example with
  1. vision based face detection, combined with position information (person tracking) and a controllable camera

2. vision based face detection, combined with position information (person tracking) and output on a graphical interface to show the focus of attention

- General feedback. Can be given for example with

  1. text to speech output
  2. graphical output on a respective interface
  3. textual output on some screen (uncomfortable)

- Observing the user's actions (pointing gestures). Can be done for example with

  1. vision based tracker and gesture recognition, combined with position information (person tracking)
  2. stereo vision and gesture recognition
  3. map on graphical user interface for pointing to positions and mapped objects

- Accept and interpret control input and explanations. Can be done for example with

  1. speech recognition and processing
  2. vision based control gesture or sign language recognition
  3. textual input (very uncomfortable)
  4. command buttons on a graphical interface

The listed components can be seen as suggestions, which techniques can be used to handle the demands.

3.4.3 Available components

Due to external circumstances the decision for the set of modalities has to be made according to already available components and hardware, which are

- a single camera on a pan tilt unit
- a laser range finder
- a skin colour detection based visual head and hands tracker (2D)
- a speech recognition system
- a text to speech system for spoken output

These components can be used as a basis to propose the following approach.

3.4.4 Proposed set of modalities

Taking the needs and the available components and hardware into account leads to the following set:

- laser data based person tracking in combination with vision based face detection for active tracking (using pan tilt unit)
- spoken control input
- text to speech output for general feedback ("dialogue")
- vision (2D) based tracking of hands and head for gesture recognition, combined with position information form laser based person tracking.

The following sections will describe, how this set of sensory types and modalities can be used to achieve the system behaviour pointed out previously.

3.5 Designing the system components

The primary components of the system are – related to the states of the basic automaton and the use cases – the user detection and tracking as well as the communication. The following sections describe the approaches to those components according to the types of input data proposed in the previous section. Additionally, the reset step will be described.

3.5.1 Determining the actual user and tracking

Once a possible user is detected, it has to be determined, if in fact an actor is present. This is done according to figure 3.9 on page 40. The laser range data is searched in parallel for the two types of features indicating the presence of a person, motion and shape in the "wait state". Whenever movement is detected, the information is combined with the shape cue to build an initial set of possible person hypotheses and the "looking for actor" state is entered. Another way to achieve this set of hypotheses is to take every person-like object that results from the shape cue for initialisation, if an utterance that can be interpreted as an address was perceived.

The hypotheses are checked successively according to the distance to the robot. During this process their positions are continuously updated with the help of the laser data interpretation and a tracking module.

Each hypotheses is assigned a state flag that indicates the role of this possible person for the system. The states are `person`, `to_be_asked`, `waiting_for_answer`, `asked`, `actor` and `not_a_person`. An additional flag that can be added is `probably_lost`, which is used, if the respective possible person could not be assigned a feature when

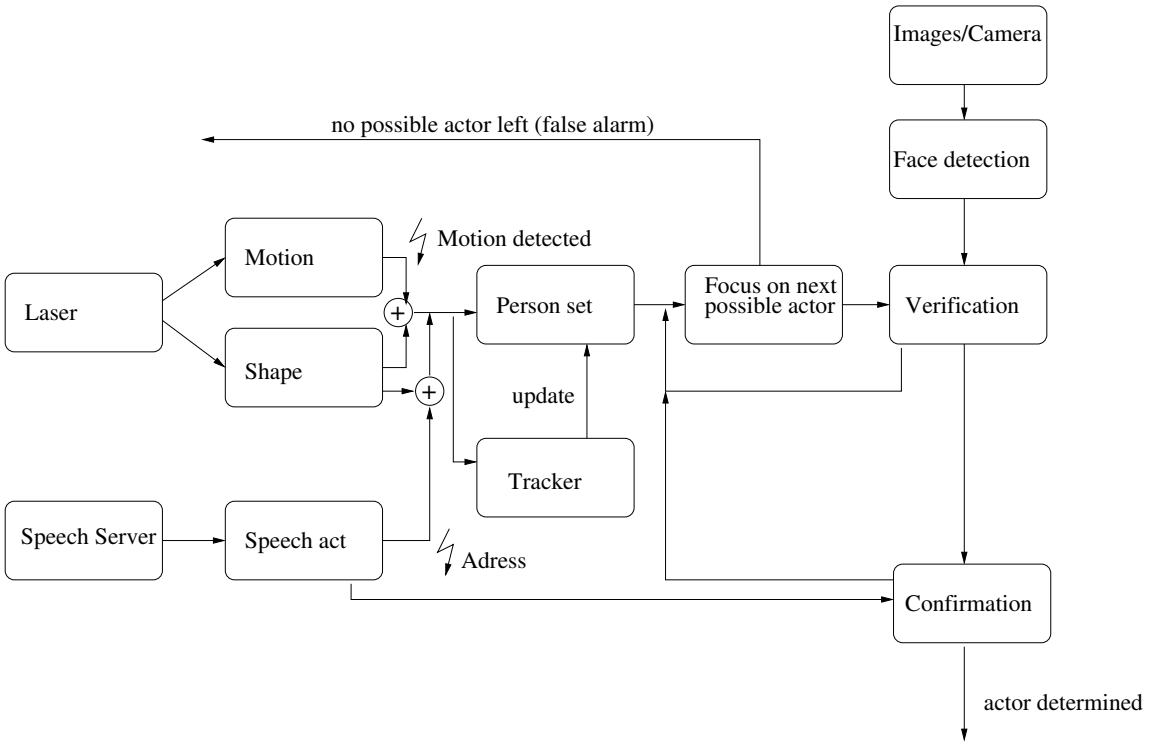


Figure 3.9: *The process of the detection and determination of the actor*

positions are updated.

Either the set of hypotheses is searched for the closest hypothesis having the state `person` or the one, that has already been verified by face detection and is now in the confirmation process as `to_be_asked` or `waiting_for_answer` is still in the centre of interest after the update.

If the state of the actual hypothesis is `person`, the vision based faced detection is used for the verification of the "person-hypothesis". If verification fails, the hypothesis is assigned `not_a_person`, in case of a success the state is changed to `to_be_asked` and, when the system uttered a request for confirmation, set to `waiting_for_answer`.

The system expects now a confirmation or rejection, which sets it in the communication state and the person to `actor`, if the actor is confirmed, or back to the search within the set of hypotheses, with this possible actor set to `asked`. If no actor is found and no possible actor is left in the set of hypotheses the system switches back to "wait".

3.5.2 Communication

When communication is established, i.e. the actor is confirmed, the system needs to keep the focus on her. Therefore, the tracking and position update loop is maintained

during communication as long as no action is required that makes the robot move out of the scene. Figure 3.10 shows this as a separate process. The motion and

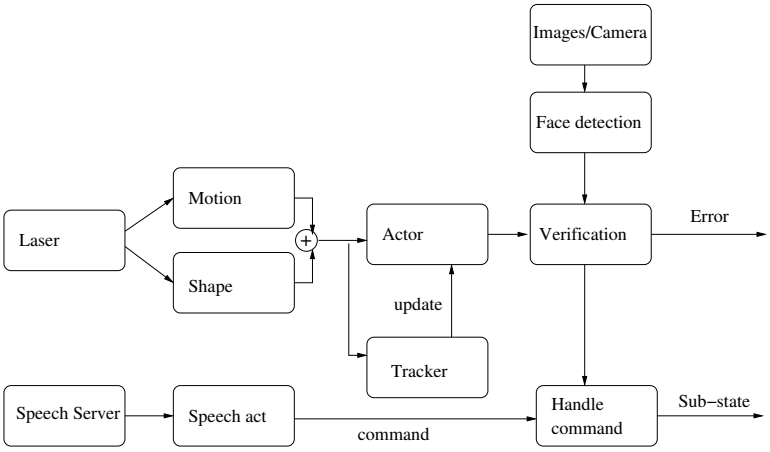


Figure 3.10: *The check for the presence of the actor in the communication phase.*

shape cues from the laser data interpretation are used to update the actor's position. If this update or the following verification with the face detection fails, the actor is marked as lost and the system switches to an error state. Otherwise the interpreted input from the speech server is used to determine the demanded action. The system switches into the respective sub-state.

Communication supported by speech and gestures

As the scenario that should be handled involves a "teach" sequence, this section concentrates on the description of the integration process for speech and gestures. Figure 3.11 shows the combination of those modalities after the respective state is reached. In this case the vision based head and hands tracker is used to determine a certain motion of one hand which will be interpreted as a pointing gesture. The resulting position is used to be assigned to the object name, resulting from speech interpretation. The speech system would accept an explanation only, when this particular sub-state is reached. The handling of spoken input and integrated representation of information will be described in the following section, as it is important in all states of the system.

3.5.3 Control input: Language processing

Language, or in this case speech processing, is proposed as the central modality for the control module. Most state switches in the controlling automaton are triggered by some explicit utterance. Therefore, it is useful to take a closer look into the structure of commands and other utterances. Considering the four basic use cases, user utterances can be represented as *explanation*, *question* or *command*, with the assumption that the use case "teaching" involves the basic types *command* and

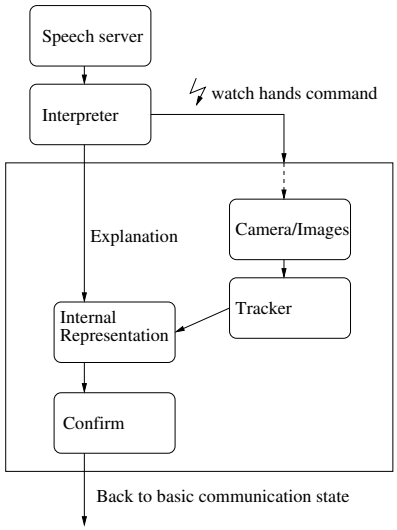


Figure 3.11: *The integration of speech and gestures depending on the system's state.*

explanation. Additionally, some other types of utterances are needed, independent from the modality. These would be *address* and *response*, which are necessary for the control of communication (getting the attention of the robot, confirming or rejecting on questions of the robot, etc.).

Those five types of utterances are not very specific, therefore it is necessary to refine them in a taxonomy of utterances. To make things simpler, those utterances will be called "control input" in the following, with respect to the idea that the representation presented here can be used for different types of input data. Figure 3.12 shows the taxonomy for some examples of specific spoken utterances. This taxonomy is not complete, it is obvious that, in particular for the control input "command", lots of additional specifications could be made. However, with such an abstract representation it is possible to add a new "command" quite easily.

When taking a closer look into the control inputs it becomes clear that they are too abstract in their basic form. Thus, a mechanism is needed to explain, for example for a "watch" command, what object this command is related to. Therefore, the control inputs are represented as a structure, related to the typed feature structures used in [Top02] with respect to [Den02] and [DW97]. For example, a "deliver" command, drawn from the input "Robot, deliver the mail to the living room" can be represented as:

```
ControlInput:
    [ Command:
        [
            Command type: DELIVER
            Command object: MAIL
            Command direction/location: LIVINGROOM
```

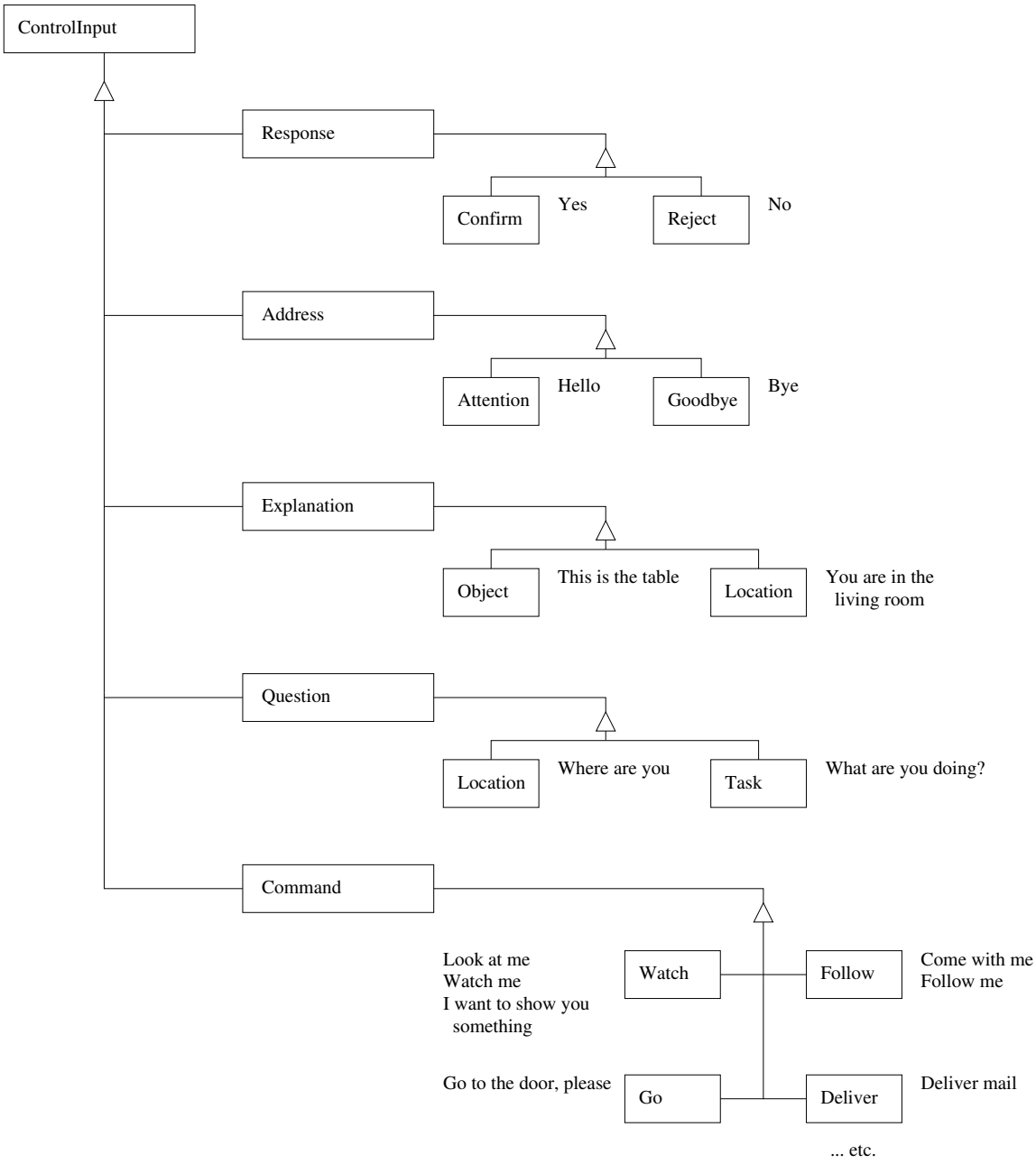


Figure 3.12: *The taxonomy for different types of control input.*

```
            ]
        ]
```

With this representation it is also possible to use a particular representation for objects and location depending on a world model. For this thesis the objects and locations are represented as strings and interpreted respectively. This is sufficient for the used parsing strategy and interpretation level of speech.

3.6 Scheduler

In section 3.1.5 the utility of rescheduling tasks was explained. This idea is not designed to implementation level here, but some basic principles can be presented anyway. When the use cases were described, high level and basic behaviours were separated. Some commands, as described in the section above, might cause the coordination module to invoke a basic behaviour, like for example "go to the table". In this case only the position of "the table" has to be known and the task is rather basic. It is not useful to make an interruption and rescheduling of such a mission possible. A command like "deliver mail to me" needs more tasks, like

1. leave the room,
2. go to mail box,
3. pick up mail for user,
4. go to user's office,
5. enter room and
6. "hand over" mail.

In this case it could be possible to store these tasks in a scheduling module to make an interruption possible. For example, as in the scenario in section 3.1.5, a second user could meet the robot during subtask 2 (go to mail box) and ask it to deliver her mail, too. Rescheduling is possible, and the new plan could be:

1. go to mail box,
2. pick up mail for user I,
3. pick up mail for user II,
4. go to user II's office,
5. enter room,
6. "hand over" user II's mail,
7. leave the room,

8. go to user I's office,
9. enter room and
10. "hand over" user I's mail.

Whenever a task is done and no interruption occurred so far, the scheduler sends the following task to the basic planning level. In this level it is assumed that a planning module exists. This module is responsible for planning the way from A to B (from the room to the mail box), refine the "pick up mail" task into approaching and grasping and handle these phases, etc.

3.7 Summary

This chapter presented the principles that were used to design an interactive interface based on some example scenarios. The chapter gave an idea of how an interactive system should behave towards a user, and specified needed modules and components. An abstract representation for control input was presented. This representation can be used for the main input type. Most systems might implement this based on spoken input (as done in the implementation work for this thesis) but others might be based on a set of gestures or sign language. Other input data interpretation (vision and laser data) was presented rather superficially, but will be explained more detailed with the background of an implementation in the following chapter.

4 Experimental implementation using laser data, speech and vision

This chapter describes the implementation of a scenario based part of the interactive interface design described in the previous chapter. The implementation combines the proposed set of modalities and sensory types. Some of the required components already existed, or could be derived easily from existing programs, but others had to be implemented from scratch. In general, the system components are kept modular so that an easy exchange is possible. The implementation gives an example for the principles of input coordination presented in chapter 3 and concentrated on the following questions:

- Is it possible to integrate simple components on a rather abstract level to derive an interactive interface to control a robot? In [ZDH+03] this question was already answered positively by integrating dialogue and vision based tracking on a high level of abstraction. In that case, though, the two integrated modalities dialogue and vision based face tracking were run in parallel but did not influence each other. In this implementation speech and a combination of vision and laser data based tracking are used to control the system. This means that integration of results from different input cues is not only sequential, but might be continuous within the respective state of the sequential process.

- Is it possible to use a state based gesture and speech integration concept that allows to use a tracking system for dynamic gestures in order to recognise pointing gestures?

- Does the integration of different modalities and sensory systems help to achieve an interactive system that follows the principles of interaction pointed out in chapter 3?

4.1 Background for the implementation

The underlying principles for the implementation were described in chapter 3. In the following sections the concrete implementation of those ideas will be presented. The system should be able to handle the following main scenario:

- A user walks up to the robot
- the robot detects the user and determines her as actor
- the user wants to explain something to the robot
- the robot observes a pointing gesture and an explanation.

In order to achieve this, it was necessary to implement the complete basic FSA as described in chapter 3. Within the communication state some sub-states are implemented to make related scenarios possible as well to show the flexibility of the approach. Some assumptions about the interaction in the scenario have to be stated and will be presented before the implementation work is explained.

4.1.1 Interaction assumptions

The following assumptions are useful to keep the main interest on the integration of modalities and not on the respective modules themselves.

- People who want to interact with a robot or other person would be fairly close to their interaction partner, so the field of interest for the robot is thresholded in terms of distance.
- People would come closer to their communication partner, if the distance is too long in the first place.
- If somebody decides after a rather long time being in a certain room to communicate with somebody else, who has also been in this room for the same time, she would verbally address the communication partner.
- People who want to communicate would at least initially turn their face towards the communication partner.
- People who want to communicate would always try to stay in the focus of the communication partner and would not try to irritate the partner by moving around a lot. An exception to this is of course a situation in which the partner (or robot) is asked to follow.
- If one person communicates obviously with another person (or in this case a robot), a third person would usually not walk between the two communicating persons, if there is another way to walk by.
- The robot is not moving while waiting for somebody to interact with it.

4.2 The coordination module

As proposed in chapter 3, the control module is implemented as a finite state automaton corresponding to the one presented in section 3.3.1, with

$\mathbf{S} = \{$IDLE, WAITING, SEARCH_ACTOR, ACTOR_FOUND$\}$

$S_0 =$ WAITING

$\mathbf{X} = \{\{$INTERPRETED LASER DATA$\}, \{$INTERPRETED VISION DATA$\}, \{$INTERPRETED SPEECH DATA$\}\}$.

Including the necessary sub-states and the error state, the whole FSA of the control module is presented in figure 4.1 on page 49. The sub-state SEARCHING is needed

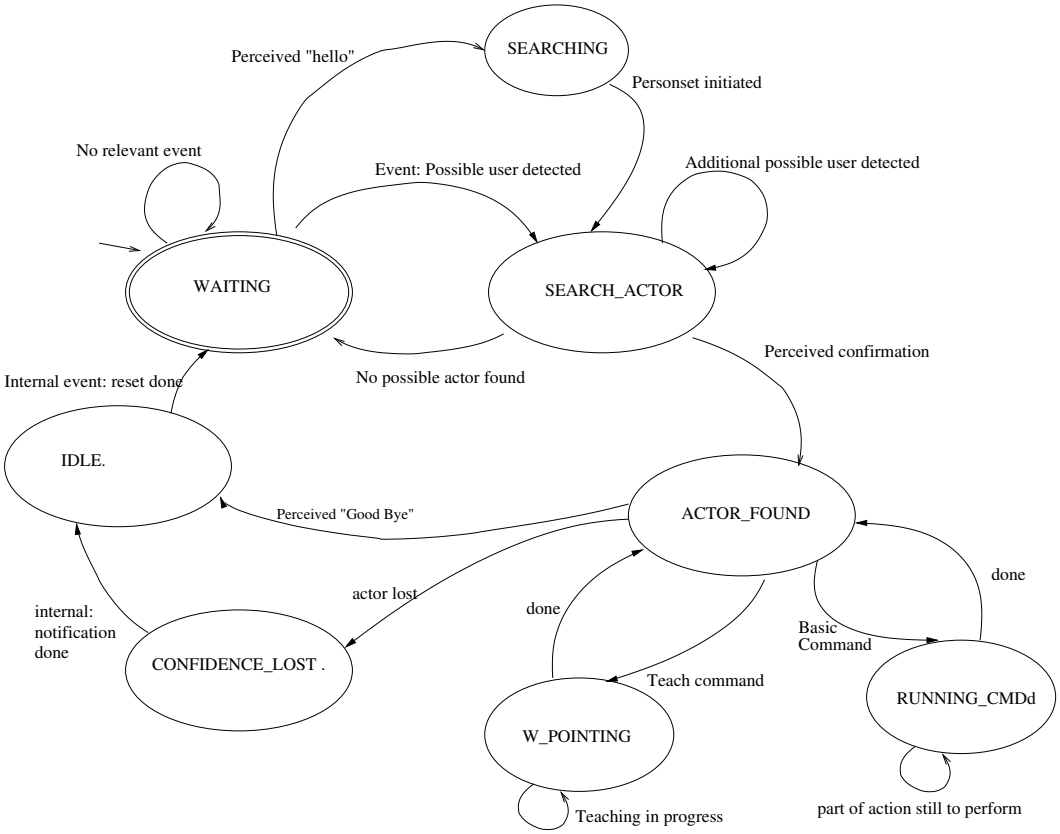


Figure 4.1: *The FSA used for the implementation. The figure shows the whole automaton including the error state* CONFIDENCE_LOST *and the necessary sub-states.*

to initialise the person set for the SEARCH_ACTOR state, without the perception of a moving person. Otherwise the initialisation is done immediately after the perception occurred. When the basic communication state ACTOR_FOUND is reached, the system can be triggered to switch into two different sub-states, either W_POINTING or RUNNING_CMD. The first is used in the "teach" use case and is reached, when the system is instructed to observe the actor's actions. The latter is used to define

the system's state in case that a command occurred, which can be handled by the current underlying planning system. This connection to the planning system will be described more detailed in section 4.4.6.

The following sections describe the handling of the input data and the different states with the input accepted respectively.

4.3 Modalities and types of input data

The implementation work is done for three different types of input data: Laser range data, images and speech. With these the two modalities speech and vision based gesture recognition are supported by the position information achieved from the laser range data. The basic control input type is speech and the user detection is based on laser range data and image processing.

Some of the modules for handling the input were available already. This was the case for speech recognition and visual tracking. For speech recognition the system ESMERALDA developed in Bielefeld (see chapter 2 and appendix A) was used. The visual tracking could be based on the work of Fredrik Sandberg, presented in [San99]. Other modules had to be added, which was the case for the handling of laser data to achieve position information and the interpretation of spoken input.

The interpretation of the results from the available vision based tracking system had also to be implemented, as the system in its original form could only recognise dynamic gestures. The system is embedded in the ISR-System that is developed at the CAS group. More details about this system are explained in appendix A. Figure 4.2 on page 51 shows the implemented system with the modules for handling the input. The input from the laser range finder is coming in on a push connection to make sure that it is not tried to get data when no scan is available. For the speech handling process also a push type connection is used to get every utterance processed immediately when it arrives. For the image handling a pull connection is sufficient, as image processing is needed in certain states only, as will be explained in section 4.4. The tracker for person positions is a separate module, which keeps it flexible for changes of the tracking approach. It will be explained together with the handling of laser data in section 4.5.1 as it is based on results from this module. First, the handling of the persons will be explained, to make the description of the system's state more understandable.

4.3.1 Handling person hypotheses - the person set

During the search for the actor usually more than one person hypotheses are created. As all the hypotheses that turn out to represent objects rather than persons are still useful when positions are updated, all objects that could be persons are grouped into

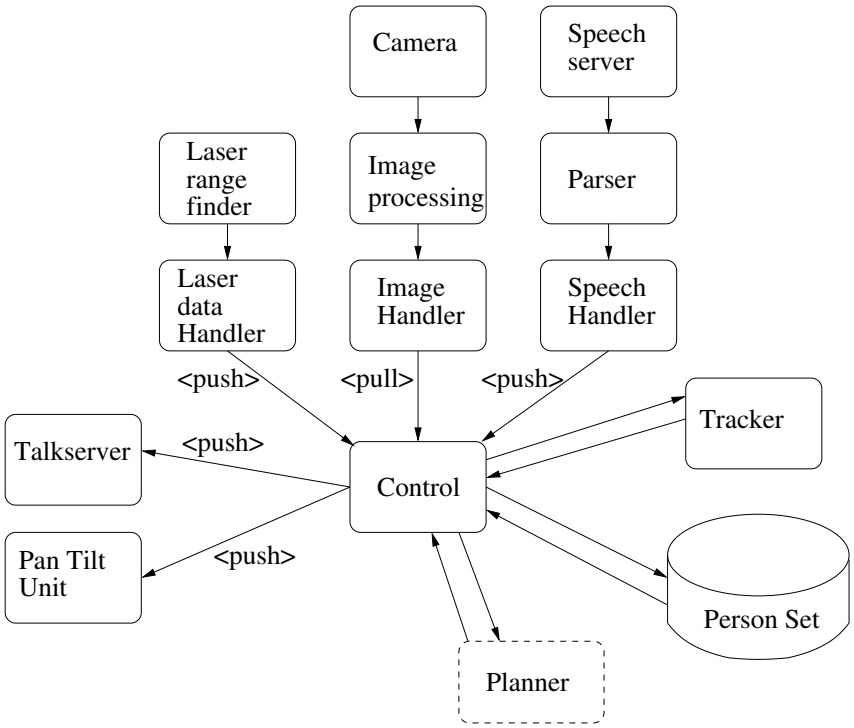


Figure 4.2: *The different modules for handling the input*

the person set. Within this set each member is representing an observed object. To each set member are assigned:

- A position relative to the robot,
- a head height, which is determined with results from image processing,
- an interaction state as described in section 3.5.1, that determines if this object or person should still be considered as a possible actor and,
- a confidence level.

The confidence level is used to decide, whether the object still can be considered a person. For example, if it is not moving and no verification of the person hypothesis with image data can be given for a certain time, the confidence level decreases, so that the "person" is rather considered an object. In the following descriptions of the system's state also the influence of the interpreted sensory data on the person set will be explained.

4.4 States of the system

This section described the states of the system by explaining influences of inputs on the state switches and the person set.

4.4.1 Observing the environment: WAITING

Initially, the system is waiting for either verbal input or laser detected movement. The state is related to the first part of the component for user determination described in section 3.5.1.

If the speech handling perceives a greeting, the system switches to the state SEARCHING to find all possible persons being around. The other way to leave the state WAITING is, when person caused movement is registered. Incoming laser data is analysed with the help of the laser handler module. The results are hypotheses for person shaped objects and moving persons. Those are grouped into the person set. Thereupon the system switches to state SEARCH_ACTOR to determine the person of interest.

4.4.2 Searching persons without movement cue: SEARCHING

This state is only reached if a greeting is observed in WAITING state. In this case the assumption is, that a possible actor is somewhere around among all person shaped objects, but not necessarily moving. So the laser data handler is asked for person hypotheses to built the person set.

4.4.3 Searching for the person to address: SEARCH_ACTOR

In this state comparably many actions are performed as shown in section 3.5.1. First, the positions of the objects and possible persons are updated. The basic idea to do this updating or tracking step was using a particle filter according to [SBFC01]. The proposed way of statistical data association combined with tracking using a particle filter would in fact have provided the possibility to track all persons being around very robustly.

However, in the scope of this work it is not necessary to track all moving objects or persons over a long time, but find one person of interest - the actor - among other persons. This can be done with a straight forward approach to detecting and updating the persons' positions which will be explained in section 4.5.1.

After the positions are updated, the current person of interest is chosen from the person set. The assumption here is, that the actor is probably very close to the robot, if not the closest person anyway. With the pan tilt unit the camera is focused on this person.

Due to the camera movement the actor gets the feeling of being observed by the robot, which makes it a lot easier for a person to communicate with the machine. Now, an image is grabbed and the image handler module is used to decide whether a face can be found at an appropriate image position or not.

If a face is found, based on skin colour detection, the confidence-level for this possible person is raised, indicating that in fact a person is observed. The idea of using the skin colour detection as verification only is based on the fact, that the space of hypotheses for "face" can be reduced drastically by isolating the region where to look for faces. Therefore, it is not necessary to search for a face, before the camera is positioned in an interesting direction.

This idea was also used in [KLF+02], where both cues, laser range data results and image processing were combined by the technique of anchoring. In the work for this thesis, the results are combined in a cooperative way, each confirming result from image processing or laser data handling is used to increase the confidence-level for the current person. Respectively, confidence is decreased, if the hypothesis can not be confirmed. This is done according to the design decisions presented in chapter 3. A detailed description of the face detection process itself can be read in section 4.5.2.

If the confidence-level for the current person of interest exceeds a threshold, the person is asked if some service should be provided and marked as possible actor. Additionally, the head height for this person is now fixed according to the results of the face finding algorithm, so that at every time the camera can be directed straight to the actor's face.

If verification keeps failing for several tries, the confidence-level falls below a minimum threshold. Thus, the "person" is not longer considered a person and the next – if existing – possible person gets in the centre of interest.

With the assumption that the actor – who really wants to communicate to the robot - would not try to run away from the robot and would therefore stop at a certain position, it is reasonable to consider a confident result after a couple of tries, all providing nearly the same result, at least within a threshold.

The system remains in this state, sticking now to the possible actor, until a confirmation comes in from speech handling. In this case the person is set to be the actor and the system state is set to ACTOR_FOUND. If no confirmation comes in within appropriate time or a rejecting utterance is recognised, the person is marked as already asked and the next interesting possible actor object is picked as current person. If no more interesting persons can be picked, the system resets via IDLE.

4.4.4 Accepting commands: ACTOR_FOUND

In this state the system accepts commands generated from results of the speech recognition. Those commands can be such known by the planner, which means that they are passed on directly. In this case the system switches to the RUNNING_CMD

state. Other commands can be those involving more interaction with the person, like tracking the person's actions. If one of those commands used internally appears, the system switches to the related sub-state. The processing of the recognised sentences is explained in section 4.5.3. If confidence for the person becomes too low, because of detection failures either with the laser handler or the image processing, the system is switched to the error state CONFIDENCE_LOST.

4.4.5 Recognising gestures: W_POINTING

This state represents the context of watching a pointing gesture. If it is reached, the system determines, if the distance from robot to actor is appropriate for the vision based tracking module. If this is not the case, an optimal position is calculated and the robot is moved there. This is done by sending a respective command for a movement to a certain poaition relative to the current position to the planner (see section 4.4.6). If the distance is considered appropriate, the visual tracker is started. The tracker is integrated in the image handling module and was available when the work was started.

Results of the tracker are used to determine, if the actor is moving a hand, and if so, this hand is tracked. When the movement stops, the system considers the gesture as finished and stores the hand position relative to the robot. An assumption is, that the actor is pointing in the same plane as she is standing in. This assumption has to be made, because the image processing is based on one camera, so no depth information for the image is available.

During this process the system expects and explanation of the object or location the actor pointed to. If this explanation is achieved, it is combined with the observed position. As this is an experimental implementation, the information is not stored, but repeated together with the position.

After this the user is asked, if something more can be done, and the system is switched back to ACTOR_FOUND.

4.4.6 Running basic tasks: RUNNING_CMD

Within the framework of ISR (details are described in appendix A), it is possible to communicate via socket connections with the basic planner of the robot server. The planner itself is able to handle some commands that can be sent as strings of a certain format. The connection to the planner can be used to pass on a command string that is generated in the speech interpretation, for example a respective "move to <position>"-command, generated from a respective user utterance.

Further, the connection can be use to ask for the state of the process. Thus, in this

state the system continuously asks the planner about its progress and waits for it to report, that the particular action is performed completely. Thereupon the state is switched back to ACTOR_FOUND. The system asks, if anything more can be done.

4.4.7 Resetting: IDLE

This state is reached, whenever the speech handling module receives an utterance that is considered a "Good bye", or when an error occurred. The person set is cleared and the system starts newly with the initial state WAITING.

4.4.8 Error handling: CONFIDENCE_LOST

Due to time constraints the error handling is very simple. If the actor is lost, a respective message is generated and the system is reset to the IDLE state. In chapter 6 some ideas for a better error handling will be discussed.

4.4.9 Summary

This section explained the states of the implemented system in a rather high level of abstraction. The idea was to describe, how the system behaves according to those states. The underlying principles for the handling of interpreted data were already described in chapter 3 and therefore were left out in this section.

4.5 The different modules

In this section the handling of the input data itself will be described, at least for those modules that had to be implemented during this work.

4.5.1 Handling laser data

When a new laser scan comes in, the data is run through a median filter. This is done to reduce the noise in the scan. This filter technique is mostly used in the field of image processing, but works of course also for one dimensional data. Median filtering or rank filtering has two advantages compared to the simpler mean filtering (according to [FPWW]):

- The median is a more robust average than the mean and so a single unrepresentative data value in a neighbourhood will not affect the median value significantly and
- No unrealistic values are created, but one of the existing values in a neighbourhood is used to represent a certain data point. This preserves sharp edges, which helps when looking for certain patterns in a laser scan.

In this case a medianfilter of width two was used, so for each data value the two predecessing and two successive values are used for the filter process. After the filtering the data is stored in the laser handler, so that two consecutive scans can be compared.

As mentioned in chapter 2, the two cues used to detect persons in those two scans are shape and movement, which will be described in the following. Further, the approach to the updating of person positions is explained.

Shape

For the shape cue the idea proposed in [Klu02] is used: A human body causes a convex pattern in the data, at least under the assumption that the person is not aligned perfectly to another object. This assumption is reasonable for the context of this experimental scenario.

The filtered scan data is searched for edges, i.e. neighboured data points with a certain minimum difference between their range values. According to their directions the edges are marked as left or right edge (left and right seen from the person's perspective). Each pair of a left and the next right edge, that represents a convex pattern of appropriate size, is used to build a first person hypothesis. Only the last left edge (if a couple of left edges occur after each other) and the first following right edge are considered a respective pair. The appropriate size (as angle it should cover) of a person is computed from the distance of the pattern and a threshold for the average size of a person.

However, lots of objects in an every day environment cause a convex pattern with the size of a person's body in a laser scan. Figure 4.3 shows a typical laser scan of the environment of the used robot. Thus, a second cue is used to decide whether a person is present or not in the case, that the robot was not addressed directly. In such a case, all hypotheses resulting from the shape cue are used to build the person set. After an explicit address the presence of an actor is highly probable, and together with the assumption that the actor is rather close to the system, she will be detected sufficiently well without the second cue. This second cue is movement.

Movement

With the assumption that the robot is not moving itself when observing the environment, the detection of moving persons can be based on a comparison of two consecutive laser scans. When a second data set comes in, the difference between the scans is calculated for each corresponding pair of data points. In this set of differences a moving person causes one of two typical patterns, which are shown in figure 4.4. The data is searched for such patterns as follows:

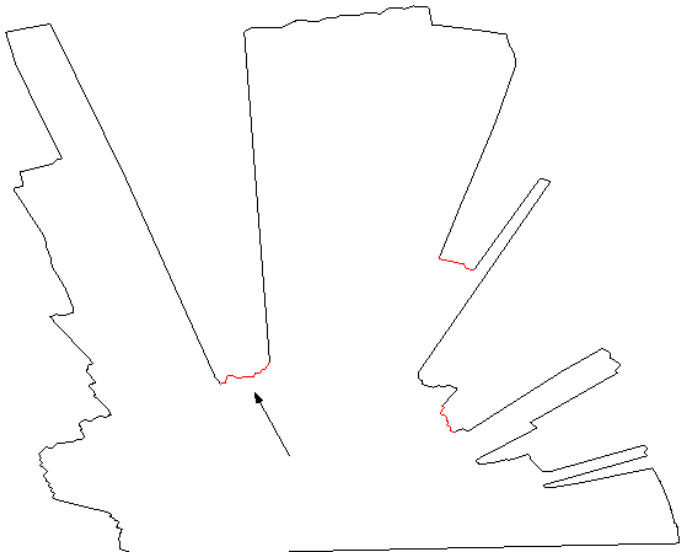


Figure 4.3: *A laser scan that shows one person, marked with the arrow and some other objects that could be persons. Scan data points were connected to poly-lines to make the scan easier to interpret visually.*

- If a peak (both, negative or positive) is detected, a search for a corresponding peak of the other sign (positive or negative, respectively) is started at the end of this one.
- If the distance between the end points of the respective peak corresponds to a certain threshold, the area is stored as person caused movement.
- If a peak only in one direction but of person size occurs, this is also considered an area of person caused movement.

The areas, in which movement was detected are thereupon mapped to the hypotheses for positions of possible persons, calculated for the second, actual scan.

The likelihood for each of the observed objects to be a person is increased or decreased according to the mapping of the two cues. In [SBFC01] was presented, how such a movement cue can be achieved in case that the robot is moving initially. In this case the two scans would have to be mapped to each other before a difference can be calculated. For the presented system this was not in the centre of interest, but as the laser handler is a module that is independent from the control system, it could be changed to achieve the possibility of having the robot move initially.

Update – The tracker

Originally, the idea was to base the tracking of the actor and other persons being around on the approach presented in section 2.3.2 with reference to [SBFC01]. However, when a straight forward approach of assigning the closest possible feature to

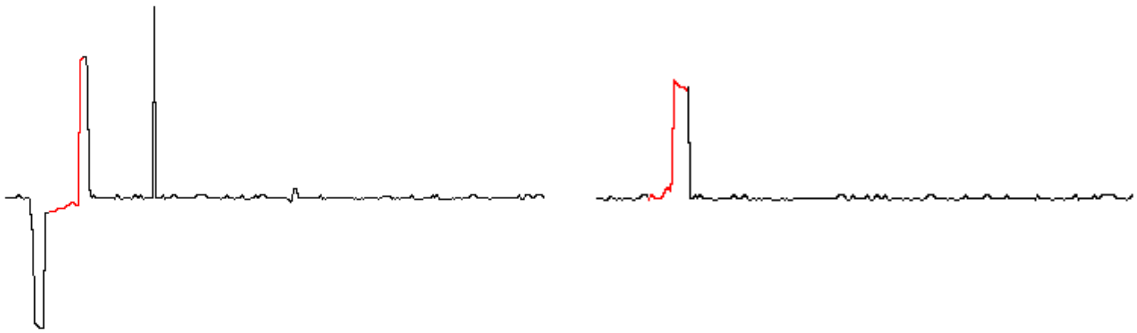


Figure 4.4: *These to pictures show the typical patterns a moving person causes in the difference data of two scans. Left, a move crossways to the scan lines is represented; the right picture shows the pattern for a move that was directed almost exactly in the direction of the scan. The single peak in the left picture can be ignored as noise.*

each person was tried to test the principles of combining image processing and laser data based tracking, it seemed sufficient for test purposes. Of course, as will be pointed out in chapter 5, this tracking approach causes the tracking related system drawbacks. Those are in fact not too dominant, so the implementation is kept on the straight forward level.

4.5.2 Handling vision data

The control module triggers the image handler to grab a new image for processing, whenever results from image data are needed. The image itself is kept in the handling module, which makes the control module independent from the used hard- and software for image grabbing. Whenever an image is grabbed, the available features are drawn. In this case, the image processing is based on skin colour detection, thus all skin colour blobs[1] are isolated in the image data. This is done with the help of the respective skin colour based blob detection provided in the system presented in [San99], which was available when the work was started.

The blob detection uses HSV-histograms to determine skin coloured areas in the images. Details about the user independence of the blob detection are presented in chapter 5. The system uses a colour model that is achieved with a support program to determine the skin colour of the user(s).

The detected blobs are now used either for verification of a person's presence or to observe actions.

[1]In the field of image processing a "blob" is a set of connected pixels with the same colour value in the image. This value can be expressed in different colour spaces, most common are RGB (red, green, blue) or HSV (hue, saturation, value).

Verification

If the presence of a person has to be verified, the set of blobs is searched for one blob of appropriate size and position, that represents a face. The minimum and maximum sizes in pixels are calculated from distance d in cm, which is known from laser range data, the opening angles of the camera (α for width and β for height), the average minimum and maximum size of a face ($minWidth$, $maxWidth$, $minHeight$ and $maxHeight$ in cm) and the image size $pixWidth$ and $pixHeight$ in pixels to

$$minimum = \frac{minWidth}{d * tan(\alpha)} * pixWidth * \frac{minHeight}{d * tan(\beta)} * pixHeight \tag{4.1}$$

and

$$maximum = \frac{maxWidth}{d * tan(\alpha)} * pixWidth * \frac{maxHeight}{d * tan(\beta)} * pixHeight. \tag{4.2}$$

The person (or object) to be verified can be assumed at a rather central position, due to the adjusted camera. Therefore, the result of the verification is positive, if a blob of appropriate size can be found within a distance threshold from the y-axis of the image. The distance to the x-axis is not considered determining here, but will be used to calculate the height of the blob according to distance and camera tilt in the control module. This height is checked for appropriateness. The thresholds are very weak here, which causes a rather high false alarm rate but less detection failures if, for example, a person is seated and addresses the robot. However, together with the position cue results are sufficient, but could of course be improved by using more information about the face (shape, relation to other body parts, etc.).

Tracking for detection of pointing gestures

When the system is in the W_POINTING state, which means that it somehow expects a pointing gesture, the visual tracking system of [San99] is used to determine, which hand is moving. The moving hand is then tracked until no more movement is registered and the final position of the hand in the image is used to derive a position relative to the robot. As stated before, it has to be assumed that the hand was moved in the same depth as the actor is standing, because no depth information could be drawn from image processing. However, the question, if this particular tracking system could be used in the context of the state based interactive interface, can be answered positively, but some improvements would have to be done, as suggested in chapters 5 and 6.

4.5.3 Handling speech data

Speech data is processed in two different levels. When data from the speech server - i.e. speech recognition - comes in, it is passed on to the parser. When an utterance is analysed completely the speech handler - knowing about the system's state - processes

the parser result and switches states if necessary or sets a planner command which is then passed on to the planner. This design makes it possible to change the parser if more natural language dialogue handling becomes necessary, without changing the handling of parsing results.

Speech acts

According to the control input taxonomy presented in section 3.5.3, a taxonomy for speech acts was used. In this particular case the basic control input type was implemented as speech act, because only speech is considered relevant for control input. As the experimental system is kept rather limited in terms of accepted utterances, only the sub-types ADDRESS, RESPONSE, COMMAND and EXPLANATION are needed and implemented. The following section explains, how the speech acts are generated from speech recognition output.

Parser

Human natural spoken language without any constraints is not regular. It is not even context free, if the difference between grammatically correct written language and spontaneous speech is considered. Humans tend to repeat parts of sentences or start sentences in the wrong way, realise their errors and correct them.

Thus, a parsing system for real natural language would need exponential time, according to [Röß02], where the author finally chose to build a parsing system for a context free subset of German, which could be parsed in cubic time. The simplest kind of language is, of course, a regular one. For this type a parsing automaton would be sufficient, parsing could be done in linear time. This requires to reduce the used language to a very restricted subset of (in this case) natural English.

Taking a closer look into the language used here, shows that it actually is sufficient to work with such a restricted subset of English. Together with the idea of word or pattern spotting, as mentioned in section 2.2.1, the parsing process for this example system could be kept rather simple.

The parser is represented by another finite state automaton $\{\mathbf{S}, S_0, \mathbf{X}, \delta\}$ with

$\mathbf{S} =$ {WAITING_FOR_MSG, WAITING_FOR_UTTERANCE, PARSING_START, PARSING_WANT_TO, PARSING_ATTENTION, PARSING_RESPONSE, PARSING_COMMAND, PARSING_EXPLANATION, PARSING_CMD_OBJ_1, PARSING_CMD_OBJ_2, PARSING_EXPL_OBJ, PARSING_COMPLETE}

$S_0 =$ WAITING_FOR_MSG

$\mathbf{X} =$ {ROBOT, HELLO, BYE, YES, NO, WATCH, WANT, LOCATE, LOCALIZE, DELIVER, STOP, THIS, SHOW, YOU}

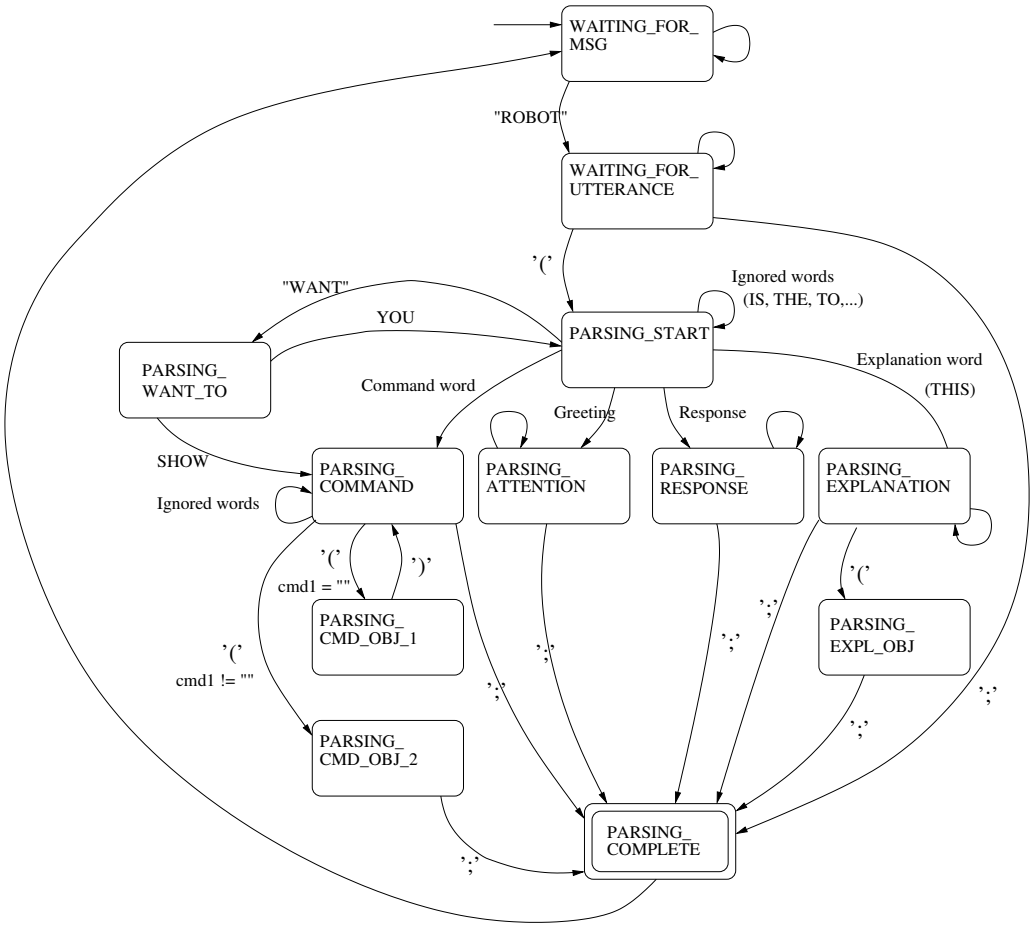


Figure 4.5: *The parser as finite state automaton.*

A technical constraint to reduce the signal to noise ratio of speech recognition was the idea of having a certain start word for each sentence[2], which sets the automaton from the initial state WAITING_FOR_MSG to the message accepting state WAITING_FOR_UTTERANCE. The incoming utterance is read until a known keyword appears. According to this keyword the automaton state is switched, as shown in figure 4.5, and incoming words are used to build a respective speech act. Objects of COMMANDS are not analysed within the parsing, but set into the speech act as strings. The structure for the representation offers the possibility to integrate an object hierarchy to analyse objects according to some ontology.

Utterances recognised by the speech server are closed with a semicolon, which makes it easy to decide whether the utterance is complete or not. If a complete utterance could be parsed the parser returns a filled speech act and is set back to the WAITING_FOR_MSG state. If the semicolon is read but no useful utterance could be parsed, the parser returns an error message and is set back to WAITING_FOR_MSG.

[2]The current start word is "ROBOT", but could be set easily to something else. It is even possible to use the parser without any start word.

This can cause problems if the actor speaks very slowly and adds long pauses after each word. If no input appears for a certain time, the speech recognition system closes the utterance, i.e. adds a semicolon. In this case the parser would recognise a series of messages that make no sense according to the current system state. In this case it returns an error message, that is used to produce a respective utterance so that the actor knows about the problem.

Speech handler

The speech handler knows about the current system state. Thus, it can update the system state according to the speech act resulting from the parsing. If the resulting speech act is either a command or an explanation, a filled object string is expected. If this is not present, the speech handler returns an error message which will be used to prompt the user. As the speech handling module does not store the state of the dialogue and therefore loses information about previous speech acts, the user will be prompted to repeat the complete utterance. Here a better designed dialogue system could help, for example in analogy to the system presented in [Den02].

Summary

This section presented the implemented modules and the algorithmic ideas used for them. It has to be stated, that all the methods were implemented straight forward, as it was more in the centre of interest to integrate the working modules than to use highly specific approaches in each of them. As each input data type is handled in a respective module, it would be possible, to use other approaches without changing the control structure.

4.6 Graphical display

In order to be able to follow the internal process when testing the system, a graphical display tool was implemented by using the Qt librabry for C++. This graphical display can not be seen as a component of the system, as it served only for test purposes and has to be displayed on a second computer. Additionally, some small test programs were implemented that allowed to test single abilities of the components.

5 Experimentation

This chapter describes the results that were achieved with the implemented system. Due to time constraints and some drawbacks, which are explained in section 5.4, no extended user study could be done. However, it is possible to show the advantages of the presented approach in some experiments.

5.1 General

Generally speaking a reliable system could be achieved with the presented approach. The drawbacks result mostly from the implemented modules, thus the system can be improved by changing these.

5.1.1 Abilities of the system

Consider the list of demands for the "learning" service robot in the "clean the coffee table" scenario, that was already presented in chapter 1. The robot should:

1. Realise that it should pay attention
2. Detect the person that it should pay attention to
3. Distinguish this person from other people possibly being around
4. Understand that it should follow this person
5. Follow the specified person without bumping into obstacles, may they be moving (other people) or not
6. Recognise a pointing gesture towards the mentioned coffee-table
7. Recognise the object pointed to as "coffee-table", store a model of the table and maybe the current position
8. Interpret and understand the explanation about the table
9. Remember the instructions when the command "clean the coffee-table" is given, find the table again and clean it.

Compared to this list the following demands could be fulfilled:

Attention

With the help of the combination of laser range data based position information and image processing, the first three tasks can be solved. Either triggered by movement or by a greeting, the system is able to determine the respective user. The system fails eventually due to erroneous results of the skin colour based verification. These situations will be explained in section 5.4. If more than one person is around, the additional integration of speech helps to determine the actual user. The detection of person-like objects in the room with the laser data is very reliable, as long as the user is not perfectly aligned with some other object. No significant detection failures can be reported even though the author and test user was wearing black clothes most of the time, which might cause problems due to absorption of the laser light.

Communication with the user

With the connection to the available planning system of the ISR environment (see appendix 5) the use of basic commands is possible. If the desired action requires a certain distance between user and robot, this distance can be achieved by sending the robot to an appropriate position. In this case the system keeps the robot within useful distance thresholds. This mechanism can also be used to maintain a not intimidating distance to the user.

Combining gestures with information from speech recognition

Due to the fact, that the system is state based, the integration of spoken information with a perceived gesture is possible on a high level of abstraction. As the system is an experimental implementation the bundled information is not used for a learning procedure, but could be used for this purpose. The speech acts offer the possibility to assign different types of information in a data structure.

5.2 Integration results

This section describes, in how far the integration of different types of input data helped building the interactive interface. One goal was, to determine the right, actual user from either a group of people or at least out of a certain amount of person hypotheses. The following section presents the results achieved by combining laser, vision and speech data for this process.

5.2.1 Static scene

In this first experiment is presented, how the integration of different sensory data helps to reduce the space of hypotheses even in a static scene. Such a situation would be given, if a user, who is not moving, addresses the robot. Figure 5.1 shows the hypotheses that can be achieved from skin colour blob detection compared to

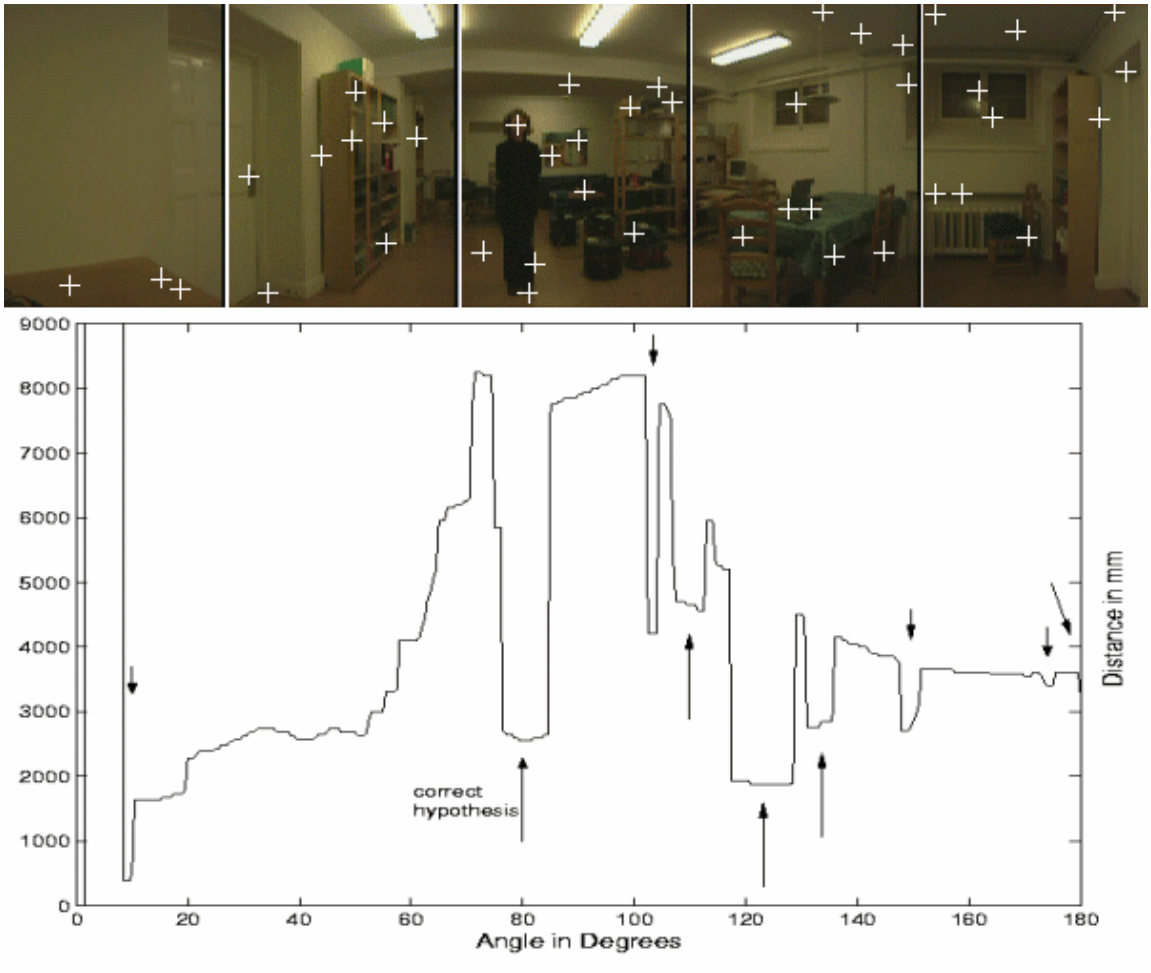


Figure 5.1: *Hypotheses for skin colour blobs are marked in the images, the person hypotheses generated from laser data are marked with the arrows. The scan is displayed in polar coordinates, to match it with the images.*

those derived from laser range data. The hypotheses in the images are marked with crosses, those in the laser data are represented by the arrows. Arrows going up (below the scan) show only those hypotheses that remain after the size check. Arrows going down show the additional five hypotheses that result, when only the check for convex patterns is made. The scan data is filtered already, so that single peaks are smoothed. The leftmost scan points are considered "out of range", they might be resulting from some reflections at the door. The scan data is printed in polar coordinates, which makes it possible to relate the scan to the images, but distorts the scan data. The hypotheses from image processing are not checked in terms of size, as no depth information is available with the single camera. For the scan data it is possible to check size at once, which was done for the hypotheses shown in the figure.

This shows that the space of hypotheses for laser range data is much smaller than

Method	Actor hypotheses
Vision without distance information	43
Laser range data without size	9
Laser range data with size	4
	Face hypotheses
Vision with distance information and size checking	1-4 per hyp. from laser data
Vision with position within image (centred)	0-1 per hyp. from laser data
	Combined actor hypotheses
Laser data and vision	2
with interaction assumption "distance"	2

Table 5.1: *Hypotheses from laser and vision*

for image data, but still too big with factor four (if size checking is used). Now the combination of both is done. Figure 5.2 shows a part of the laser scan with the two remaining hypotheses, if the check for a skin colour blob of appropriate size and position (centred according to the x-value) is made for the face hypotheses. Hypotheses from laser data are verified in the order of their distance to the robot,

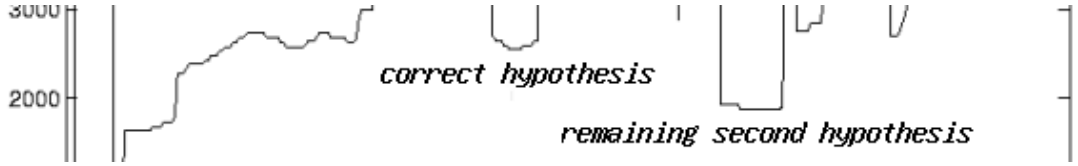


Figure 5.2: *Only two hypotheses remain. One is correct, the other represents in fact a chair.*

closest first. In this case the first to be checked is the hypothesis second from the right, which represents in fact a chair.

Now the combination with speech can help, which makes it possible to ask the remaining "persons", if they are the actual actor. The chair would not respond within a time out, which would make the system switch to the next remaining hypotheses.

In table 5.1 the successive reduction of the hypotheses is represented in numbers. For the general result it is clear, that together with the assumptions that were made about the user and with the help of the speech system, the right user is determined in two verifying steps. The assumption, that the actor is to find within a certain distance to the robot, reduces the number of actor hypotheses from four to two. However, as

the presented approach was rather heuristic than probabilistic, the hypotheses are checked successively according to the distance. Calculating a likelihood for each of them would have involved to move the camera in all considered directions, which is confusing for the actual actor.

5.2.2 One person moving

The following section explains, how movement ranks the hypotheses, so that static objects are not longer considered a person, which makes detection even easier. Only the results from the laser data are presented, as this is the only cue that is used to rank the possible users for the verification step. Figure 5.3 on page shows the change

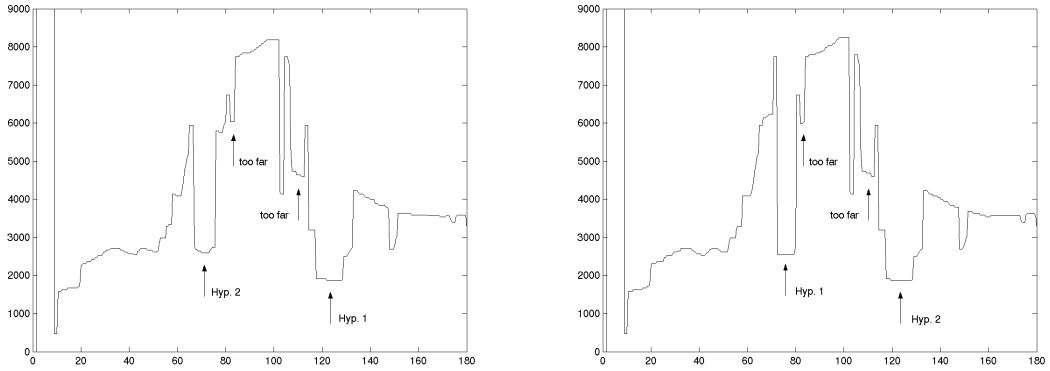


Figure 5.3: *One person is moving, the other hypotheses represent static objects. When the movement is detected, the ranking for the first two hypotheses is flipped.*

in the ranking of hypotheses if movement is used as additional cue. Without this, the situation is about the same as in the static scene, but when the user starts to move, the ranking for the hypotheses is changed. Now the actual user would be the first to be verified with the skin colour detection. Thus, the actor is determined in one verification step.

5.2.3 Two persons moving

In this experiment two persons were moving in front of the robot. First, without movement, hypotheses would be ranked according to distance. When the two persons move, the order is changed, so that the static object will be the last of the three to be checked. When the two persons change their positions (in terms of distance), the order for them would be flipped too, as long as the skin colour verification did not succeed for any of them. In this latter case, the determining process sticks to one user until spoken input allows to decide finally, if this is the right user. The scans in figure 5.4 on page refer only to the ranking of hypotheses from laser data, not to verification results.

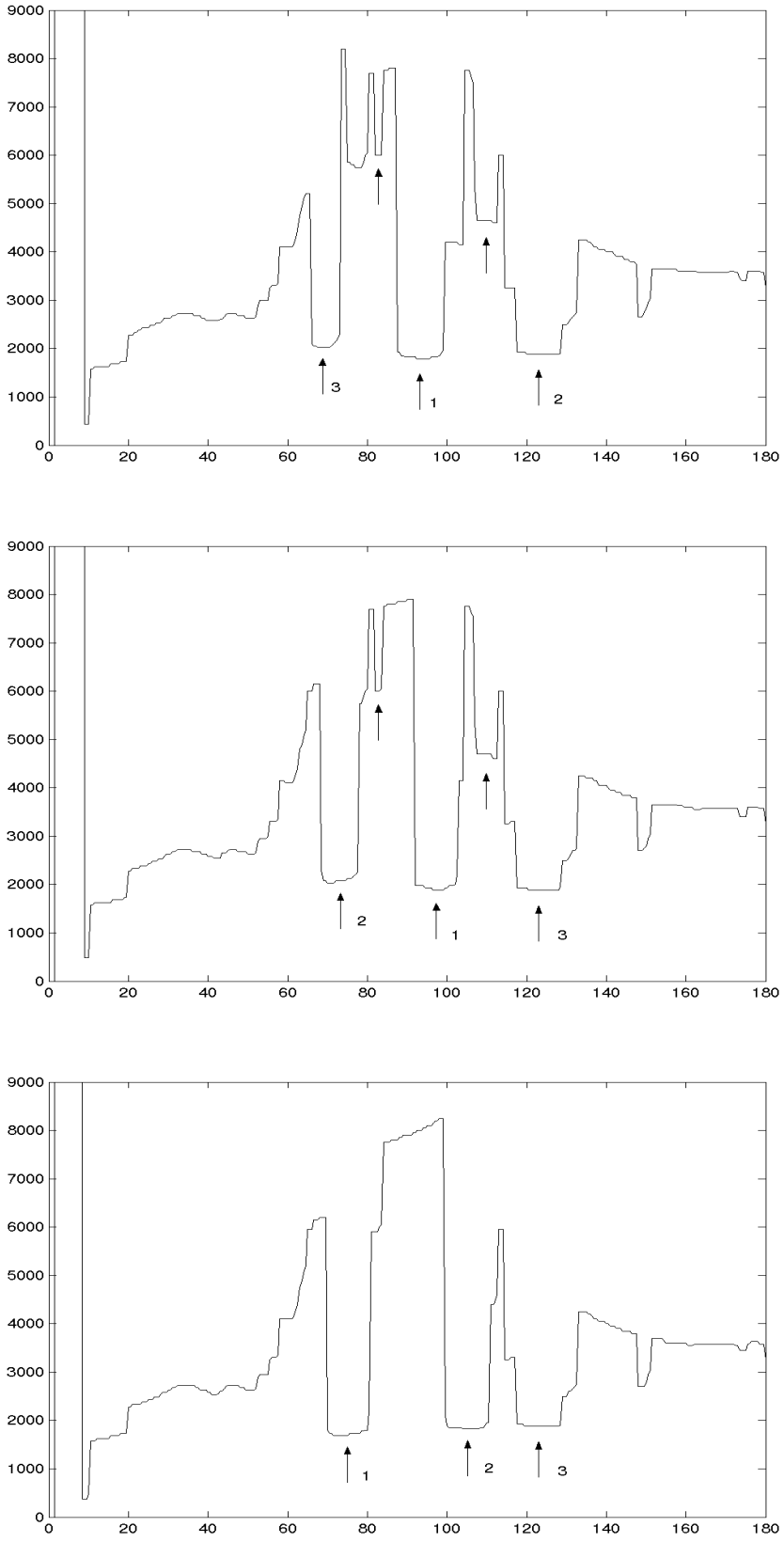
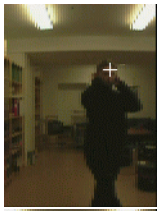


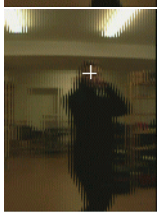
Figure 5.4: *The two persons start moving and hypotheses are ranked in a new order.*

5.3 Test in a scenario: Speech and gestures

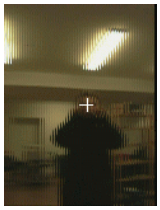
This section shows two image sequences together with the textual output. First, the user has to be detected. When this is done, the camera is not only following the person but is focused on the face. The following part of the sequence shows, how the actor gets in the focus of the camera. This could only be done with the integration of the skin colour blob detection and the position information from laser data. Without the confirmation from the speech processing, it would not have been possible to give this particular user the "actor" flag. This shows, how the "attention" part of interaction can be supported by the combination of the three used types of data.

5.3.1 Sequence 1

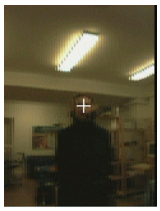




```
New personset initialized
SEARCH_ACTOR
```



```
TALK: Can I do something for you?
```

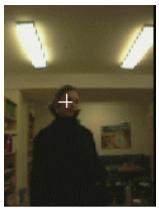


```
Parsing:
ROBOT --> (reading new utterance)
 () (YES ) () ;

 [ SPEECH_ACT:
     [ Response :
        Response type: Confirmation
     ]
 ]
Could parse a complete message
```

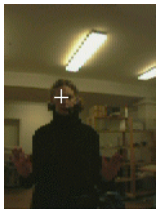
Now, the system focuses on the actor, while asking, what in particular should be done, as no further information was perceived so far. The actor explains, that she would

like to show something, which implies, that a pointing gesture is to be expected.



```
TALK: What do you want me to do?
```

```
Parsing:
ROBOT --> (reading new utterance)
 () I / WANT ? TO ? SHOW ?
 YOU ? SOMETHING ? LIVINGROOM ? ;
```

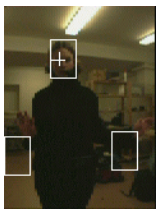


```
 [ SPEECH_ACT:
     [ Command :
        Command type: Watching
        CommandObject: HANDS
        Direction:
        PlannerCmd:
     ]
 ]
Could parse a complete message
```

The camera moves down to get the focus on the hands. The visual tracker is initialised, indicated by the boxes in the images. Both hands are tracked, to determine, which hand is moving. The head is tracked too, to maintain the assumptions that are needed for the tracker (see [San99]). On of those assumptions is, that the hands are always at a lower position than the head.

```
TALK: I am WATCHING your hands
TALK: I am WATCHING your left hand
Parsing:
ROBOT --> (reading new utterance)
 () (THIS IS (THE DINNERTABLE ) ) () ;
```

```
 [ SPEECH_ACT:
     [ Explanation :
         Explanation type: ObjExplanation
         ExplanationObject: DINNERTABLE
     ]
 ]
```



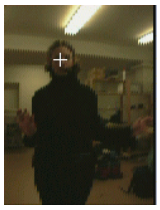
```
Could parse a complete message
TALK: Your hand stopped
TALK: You pointed to DINNERTABLE
      at position 1166 and 1087
```

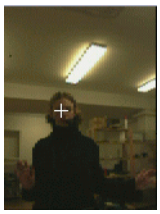
When the hand stops, the tracker is also stopped and the final position of the hand,

that moved before, is used to compute the position relative to the robot (x- and y-coordinates in mm). This shows, that it is sufficient to have a gesture recognition running only when the communication requires this. If the visual tracker and interpretation of its results had been running in parallel to the attention part, it would have been obviously very expensive in terms of calculation time. So one of the general results for the integration of speech and gestures is, that both support each other:

- Gestures give the missing deictic information and
- spoken input allows to start a gesture recognition only when needed.

When the tracker has stopped, the camera is directed to the face of the actor again and the actor is asked, if something else should be done. In this case the answer is "good bye", which makes the system return to the starting state.





```
TALK: Anything else I can do for you?
Parsing:
ROBOT --> (reading new utterance)
 () GO / BYE ? ;

 [ SPEECH_ACT:
     [ Attention :
        Attention type: GoodBye
     ]
 ]
Could parse a complete message
State is IDLE
```

This scenario based experiment shows, how the integration of speech and gestures is working. Due to the drawbacks of the system, that will be described in the following section, the tracking of the hands might produce wrong results. However, assuming a robust module for tracking of the actor's hands, the interpretation of a hand trajectory as a pointing gesture is possible, because of the state context.

5.3.2 Sequence 2

This section refers to a test scenario with a second user, which shows in an example that the interface, especially the skin colour detection, works for more than one user. During the implementation it could be stated, that at least four different users could be detected as persons, based on the image processing verification. The crosses are left out in this sequence, to make the images less confusing.

```
New personset initialized
SEARCH_ACTOR
```

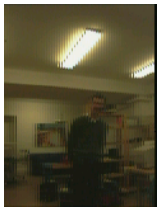
The user moves in front of the robot and the system detects him. The camera is moved in the appropriate tilt angle to maintain the user in the focus of attention.

```
TALK: Can I do something for you?
Parsing:
ROBOT --> (reading new utterance)
 () (YES ) () ;

 [ SPEECH_ACT:
     [ Response :
        Response type: Confirmation
     ]
 ]
Could parse a complete message
TALK: What do you want me to do?
```

This example shows also one of the drawbacks of the system which would in fact make a user study not possible at the moment: The speech recognition was not trained sufficiently to deliver reliable recognition rates. In this example the user said "Robot, could you please deliver mail to the living room", which caused first an error, as only a part of the utterance reached the recogniser, and thereupon caused a wrong hypothesis, when some noise was recognised as "STOP"-Command. To handle such false-positive failures of the language processing, a more enhanced dialogue-module can help, that asks for a command confirmation, before any action is started.

```
Parsing:
ROBOT --> (reading new utterance)
 / IS ? IN ? THE ? MAIL ?
 TO ? THE ? LIVINGROOM ? ;
TALK: If you said something, repeat please!
Parsing:
ROBOT --> (reading new utterance)
 () (STOP ) () ;
```



```
[ SPEECH_ACT:
    [ Command :
       Command type: Controlling
       CommandObject:
       Direction:
       PlannerCmd: STOP

    ]
]
Could parse a complete message
TALK: Sending command STOP to planner
```

Despite the fact that in this case the system sent the wrong command, the example shows in principle, how the command is passed on. As a conclusion it can be stated, that it was possible to explain the use and behaviour of the system in a few sentences to a user who was in fact not familiar with robots in general.

5.3.3 Summary

This section presented the results that could be achieved with the implementation presented in chapter 4. The most obvious advantages of the system are related to the fact of the integration of different modules. As pointed out in the following section, these modules did not even have to be extremely robust to achieve an overall satisfying result.

5.4 Drawbacks

Most of the obvious drawbacks of the implementation are caused by the used components. The problems evolving for each of the modules will be presented in this section.

5.4.1 Tracking persons

The implemented interface can be tricked by a person crossing the line between robot and actor. As no real tracking approach was used, the actor might be assigned the wrong feature after such a crossing. This problem can be solved rather uncomplicated by using a particle filter based tracker for the persons being around. The principles of ranking the hypotheses would not be destroyed by such a change.

5.4.2 Verification with skin colour based face detection

The verification step is the most sensitive in the first phase, when the actor has to be detected. Figure 5.5 shows an image where a skin coloured blob is found in appropriate image position - but is a part of the floor. This problem is related to

a) b) c) d)

Figure 5.5: *Four images representing the failing process of detecting a face. From left to right: a) a skin colour blob from the floor is found, b) the same blob is detected, where the user's face is not, c) again, d) thresholds are exceeded, the blob is taken as a face. To show this effect, no check for the appropriateness of the computed head height is made, which results in the camera focusing on the legs of the user.*

the fact that no depth information for the blobs itself is available. Every blob that appears of right size in the depth of the user is considered a face. With a height threshold only very unlikely results could be prohibited, but considering a sitting user and tall people, those thresholds would have to be rather weak. Better results could probably be drawn from a face detection that is based on different cues, like colour and shape.

5.4.3 Vision based tracking for gesture recognition

As the hand and head tracker is also based on skin colour blob detection only, false alarms might cause false-positive failures. The tracker in its original form was run on a static camera under the assumption, that the person to be tracked would be at a defined position right in front of the camera. With the idea of maintaining a certain distance to the user, this constraint can be held for the distance, but due to movement and the following camera, tracking results might not be as good as in the original setting ([San99]). In situations similar to the one presented for the face detection the tracker could still find blobs to track. Therefore no error would be reported, which gives the impression, that the user's hand was tracked correctly in a situation, where the tracker was actually focused on a part of a bookshelf.

5.4.4 Speech processing

For the speech processing the drawbacks were obvious, when different users tried to communicate with the robot. The used speech recognition is in general speaker independent, but as the recognition was tested by one user only during implementation, the recognition rate was somehow optimised for this person and no further tests were done. However, as speech interpretation was connected to the system

state, the recognition problems did usually not trigger a false reaction but a question to repeat the input. In one case though, the execution of an unwanted command can be triggered. This can happen, when the actor is determined and any kind of command input is accepted. A false-positive recognition of an utterance could then lead to a "false" reaction, as shown in the second scenario presented previously. A dialogue component that verifies spoken input could cope with that problem.

5.4.5 Summary

This section presented the drawbacks of the implemented interactive interface that result mostly from drawbacks of the used components. For each of the problem classes a suggestion was provided, how the respective problem could be solved. In the case, that none of the presented fail-situations occurred, the system as a whole works sufficiently well. The fact that different types of input data were combined helped in ambiguous situations just as the hypotheses stated.

6 Conclusion and ideas for future work

This chapter presents the conclusion that can be drawn from the presented work and experiments. Additionally, some ideas for future work are given.

6.1 Summary

The thesis presented the design of an interactive interface for a service robot and an implementation of parts of such a system. The implementation was done to proof basically three hypotheses:

- The integration of different types of sensory data reduces the space of hypotheses when persons have to be detected and tracked. This can be helpful for integration in terms of determining and tracking the actual user.
- With a state based system approach it is possible to achieve a possibility to recognise certain gestures based on a context, which helps to reduce the false alarm ratio a continuously running gesture recognition would produce.
- A state based approach allows to achieve a fully integrated system that can handle the basic scenarios (use cases) in which a user would want to communicate with the robot.

With the implementation and respective experiments it was possible to support these hypotheses. Though, no long term user study was done to measure the usability in real world conditions. In general, the system achieved with the approach presented allowed to confirm the hypothesis, that integration of laser range data and vision for user detection and tracking is useful.

The implementation of system components was done rather straight forward. This offers the opportunity to improve the system by using more robust approaches as named in section 6.2.

For the tracking component of the system incoming laser data was analysed and searched for person like objects and areas of movement. Together with a vision

based face detection this allowed to detect and track the user rather robustly even without a complex approach to tracking.

The use of the available skin colour detection might be questioned. Though the hypotheses space can be kept small with the laser range data based detection, a face detection and head and hand tracker based on skin colour exclusively tends to produce still a high amount of false alarms, which do not cause any error but wrong conclusions.

Speech was proposed as primary modality for control input. The respective parsing was done under the assumption, that only a small regular subset of English was required to control the system under test condition. Structures, similar to typed feature structures, were used to represent a hierarchical system of control input types, so called speech acts. This allowed to distinguish between different types of utterances so that the interpretation could be done according to the system state. The use of typed feature structures allowed to assign attributes of arbitrary type to the speech acts. For the presented implementation objects of the speech acts were represented as strings, but in principle it is possible to think of a more complex object representation.

6.2 Future work

This section describes some ideas for future work, basically considering an improvement of the implemented system.

6.2.1 General

In general it is an important goal for an interactive interface to be robust enough for enhanced user studies. For those user studies it would be important to design them in a way that allows to draw conclusions about the utility as well as the usability. This involves long term studies, in which the interface would have to be running under real world circumstances.

A first step to more robustness would be an enhanced error handling together with a dialogue, that allows to claim confirmation of certain actions and corrections.

To improve the error handling it could be useful to introduce different types of error states. One possibility of separating errors is their reason. Thus, as an example, the following error types can be distinguished:

- dialogue error – the dialogue did not lead to any result
- communication base error – the user (actor) is lost

- communication error – observed utterances and other information can not be matched

- action error – some internal error caused a problem during a particular action should be performed

- system/hardware error – at least on of the system components does not work properly

Depending on these types of errors a recovery could be handled respectively.

Apart from these general ideas most of the system improvements can be done with improved modules.

6.2.2 Modules

The laser interpretation module could be improved by integrating the assumption, that the robot is actually moving, when communication should be established. This could be done by a method related to the one proposed in [SBFC01], where a scan matching technique is used. As the detection of users with the laser data works reliably, it does not seem necessary to improve the method for building the person hypotheses itself.

One module that would have to be improved is the tracker. Related to the person set it would be useful to have a reliable tracking algorithm for the possible persons during user determination. For the communication phase it would be interesting to see, if it is necessary to have a fully developed tracker running for every moving object or if it is sufficient to track only the actual user, once she is determined. A tracking approach with the required reliability can be a particle filter as described in [AMGC02].

The communication phase can be improved by using a more reliable recognition approach. As stated in [Vac02], the recognition rates for the approach presented there were not very good due to a high false alarm rate. This can possibly be improved by using a combination of the context based approach of this thesis with a recognition approach, as described in [Vac02]. A use of a gesture recognition that is based on skin colour detection only can definitely not be recommended, as even with the context information the situation may be interpreted falsely due to the occurrence of skin colour in the background.

6.3 Conclusion

Despite the mentioned drawbacks the design principles make an approach to integrated interactive systems possible. Even with relatively simple modules for the different data type interpretation an overall reliable system could be achieved. Future improvements and thereupon conducted user studies should be considered to test the approach under real world circumstances.

A Technical details

System environment

For the implementation the Intelligent Service Robot (ISR, [AOLC99]) environment developed by the Centre for Autonomous Systems (CAS[1]) group was used. This environment makes it possible to have different behaviours running at the same time on a mobile robot so that for instance obstacle avoidance can be run parallel to a "following person" behaviour.

The speech recognition system ESMERALDA, developed by the Applied Computer Science group at the Faculty of Technology, University of Bielefeld, Germany ([Fin99]) was already integrated within ISR. It provides sentences recognised according to a given grammar and lexical word-list.

A gesture recognition system based on the work by Fredrik Sandberg ([San99]) can also be found but is only working for motion gestures and only if the acting person stands relatively close to the camera so that hands and face appear big enough to be recognised. Still this work could be used as a basis for the gesture based interacting part of the system.

The ISR project includes five Nomadics Technologies robots in the CAS laboratory at KTH but is also used on other systems, e.g. as presented in [KLF+02]. One of this robots, equipped with the hardware described in the following section, was used for the implementation and tests. Figure A.1 on page 82 shows the robot (a Nomad200) that was used for implementation and tests.

[1]For general information see http://www.nada.kth.se/cas/

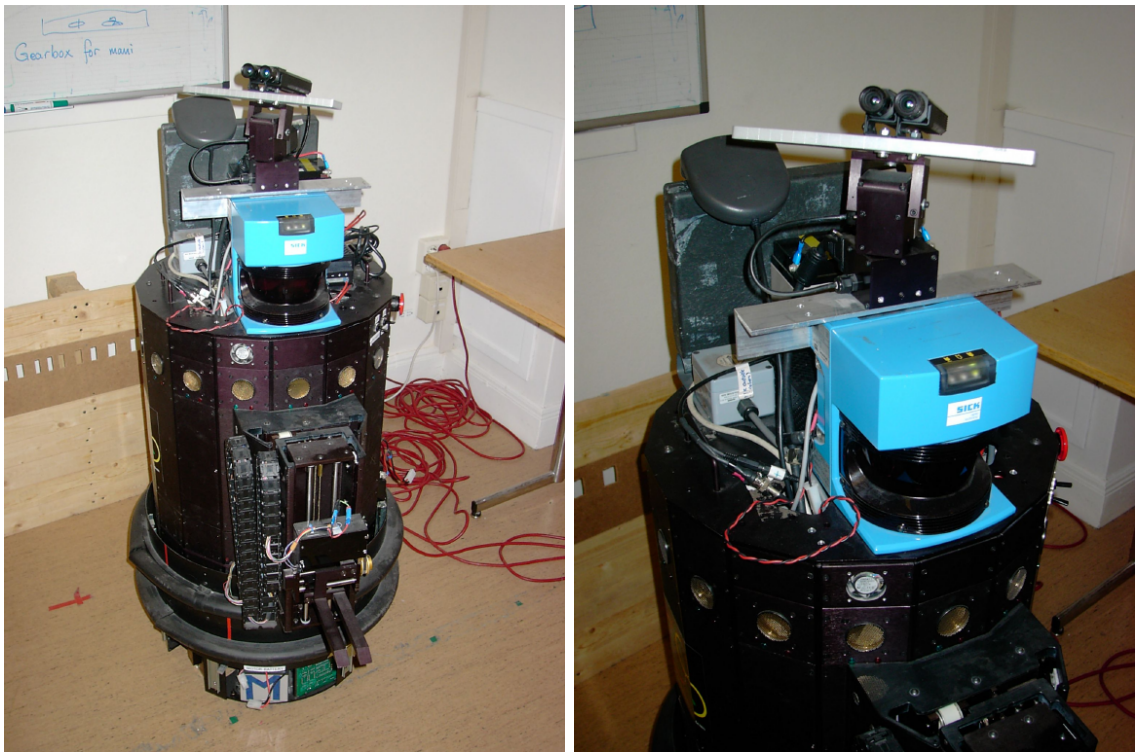


Figure A.1: *Asterix as it was used for the experiments. Currently it is equipped with two independent cameras, one is used for landscape format pictures, the other one is rotated by 90° to produce portrait format pictures. The latter is mounted centred respective to the pan tilt unit and was used for implementation and experiments. As only one framegrabber card is available at the moment, merely one camera is indeed connected.*

Hard- and Software

The following hard- and software was used for the implementation:

System	PC (standard, 450MHz) running with Linux (Redhat 4.1), kernel 2.2.19
Laser range finder - Height - Covered angle - Resolution	SICK PLS 200-114 93cm 180° angle: 0.5°, distance: 1cm
Camera - Field of view - Framegrabber - Driver	Sony CCD color video camera module XC-999P 60° up/down and 40° left/right Matrox Meteor Framegrabber Card version 1.5.4 for Linux
Pan Tilt Unit - Pan - Tilt	Directed Perception PTU-46-17.5 $\pm 159°$ $31°$ to $-47°$

B

Ein Interaktionssystem für einen Serviceroboter – Entwurf und experimentelle Implementierung

Deutsche Zusammenfassung der englischsprachigen Diplomarbeit

1 Einleitung

Der Gedanke an einen Serviceroboter, der selbständig lästige Aufgaben im Haushalt ausführt, ist verlockend. Bei näherer Betrachtung der alternden Gesellschaft und den daraus erwachsenden Problemen für z.B. das Pflege- und Betreuungswesen stellt sich jedoch heraus, daß der Gedanke nicht nur verlockend ist, sondern bald schon eine echte Notwendigkeit für seine Umsetzung bestehen könnte.

Mobile Roboter sind bereits in der Lage, viele Aufgaben zu erfüllen, die entsprechenden Nutzern das Leben ein wenig erleichtern könnten. Auch Ansätze, auf möglichst natürlichem Weg mit einem Roboter zu kommunizieren, existieren, sind aber meist auf eine Modalität wie zum Beispiel Sprache beschränkt. Interessant ist es jetzt, auch unter Berücksichtigung entsprechender psychologischer Studien zur Akzeptanz von autonomen Systemen, wie z.B. in [PR97] beschrieben, Ansätze für integrierte Systeme zu untersuchen. Diese integrierten Systeme sollten es möglich machen, mit dem Roboter so zu kommunizieren, daß ihm beispielsweise neue Informationen über eine neue Umgebung auch durch einen ungeübten Nutzer vermittelt werden können.

Die vorliegende Arbeit stellt einen Entwurf für eine interaktive Bedienschnittstelle vor und erklärt, wie die vorgenommenen Entwurfsentscheidungen mit entsprechenden Studien und verwandten Arbeiten in Verbindung stehen. Eine experimentelle Implementierung zeigt, wie es möglich ist, einzelne, interaktive Komponenten auf einem relativ hohen Abstraktionsgrad zusammenzuführen. Die Implementierung stützt sich auf die Modalitäten Sprache und Gestik, die mit Hilfe von Positionsinformation aus Laserscandaten, Bildverarbeitung und Spracherkennung gestützt werden.

1.1 Überblick

Die Zusammenfassung der englischsprachigen Diplomarbeit gliedert sich dem ursprünglichen Text entsprechend in sechs Abschnitte. Die Abschnitte stellen im Wesentlichen eine Zusammenfassung der entsprechenden Kapitel der Arbeit dar. Im Abschnitt 2 werden Grundlagen und der Stand der Forschung in den relevanten Gebieten vorgestellt. Die Abschnitte 3 und 4 geben einen Überblick über den Entwurf und die Implementierung des zugrundeliegenden Systems. Experimentelle Ergebnisse behandelt Abschnitt 5 und Abschnitt 6 gibt dann schließlich eine Zusammenfassung sowie einen Ausblick auf zukünftige Arbeiten wieder. Dieser Abschnitt entspricht einer Übersetzung der vollständigen Zusammenfassung der englischen Abhandlung.

2 Grundlagen und Stand der Forschung

In diesem Abschnitt werden einige Arbeiten aus den Bereichen vorgestellt, die für den Entwurf und die Implementierung relevant sind. Zunächst wird eine Einteilung der Ansätze für die Mensch-Roboter-Interaktion in sozial motivierte und zielorientierte Interaktion vorgenommen.

2.1 Interaktion aus unterschiedlichen Perspektiven

In [Bre98] wird ein System zur motivationalen Regulierung von Interaktion zwischen Roboter und Mensch beschrieben. In diesem Fall wird also die soziale Komponente der Interaktion untersucht. Mit dem System soll überprüft werden, inwieweit sich Motivation und Emotion auf einen Roboter übertragen lassen. Die Interaktion selbst steht im Mittelpunkt des Interesses. Die im Weiteren vorgestellten Arbeiten werden eingeteilt nach der Anzahl der Modalitäten, die sie betrachten, bzw. nach ihrer Einordnung in verschiedene Ebenen interaktiver Schnittstellen.

In der vorliegenden Arbeit wird Interaktion unter einem eher pragmatischen Aspekt betrachtet. Ein Mensch möchte mit einem Roboter agieren, um diesen zu einer bestimmten Aktion zu bewegen. Die Interaktion ist gewissermaßen das Mittel zum Zweck. Daher ist es angebracht, im Folgenden von einer interaktiven Bedienschnittstelle (interactive interface) zu sprechen und nicht von einem Interaktionssystem. Die vorgestellten Grundlagen und Arbeiten beziehen sich alle auf diesen Blickwinkel der zielorientierten Interaktion. Trotzdem sollten psychologische Studien und Grundlagen nicht außer Acht gelassen werden, da die in diesem Gebiet erzielten Resultate natürlich auch hier gelten.

2.2 Integrierte Systeme

Der Abschnitt gibt einen Überblick über Arbeiten, die bereits mehrere Modaliatäten für die Interaktion integrieren und so – zumindest teilweise – bereits lauffähige Gesamtsysteme präsentieren können. Grundsätzlich kann eine Klassifikation solcher Systeme in zustandsbasiert oder kontinuierlich-kooperativ vorgenommen werden, wobei die zustandsbasierten Systeme noch in sequentiell und konkurrierend einteilbar sind. Diese Einteilung wird unter anderem verwendet in [MAC97].

2.2.1 Zustandsbasiert

Ein Beispiel für ein zustandsbasiertes System wird in [ZDH+03] gegeben, in dem Dialog und bildbasierte Gesichtsverfolgung in einem der Systemzustände parallel betrieben werden. Dieser Ansatz hat die generellen Entwurfsentscheidungen in dieser Arbeit maßgeblich beeinflusst. Ebenfalls als zustandsbasiert ist der Ansatz für den Roboter des Nursebot Projektes zu rechnen. In diesem Fall gehen die Autoren in

[BFG+00] und [MPR+02] von einer Zustandshierarchie aus, die den Roboter kontrolliert.

2.2.2 Kontinuierlich

Beispiele für kontinierlich arbeitende Systeme sind in [DZER02] und [PASM00] beschrieben. In beiden Fällen werden die Eingaben aus verschiedenen Modalitäten fortlaufend verarbeitet und integriert.

2.3 Graphische Eingabeschnittstellen

Graphische Schnittstellen spielen eine Rolle in den Arbeiten, die in [EMA02] und [MAC97] sowie [HSE02] oder auch [PASM00] beschrieben werden. Für die Interaktion zwischen Mensch und Roboter könnten sie zukünftig eine größere Rolle spielen, als das bisher der Fall ist, da sie durchaus unterstützende Wirkung haben können. Die Frage, wo ein solches Bedienelement anzubringen ist (auf einem persönlichen digitalen Assistenten oder am Roboter), ist allerdings noch nicht beantwortet.

2.4 Sprache

Die Verarbeitung gesprochener Äußerungen kann in drei wesentliche Ebenen eingeteilt werden: Erkennung von Wörtern und Phrasen, Interpretation und Dialog. Beispiele für die erste Ebene liefern [Fin99] und [WJM+91] sowie [WHH+89]. Unterschiedliche Ansätze für die Interpretation (basierend auf einer Grammatik bzw. auf Mustersuche) werden in [Röß02] und [ZDH+03] beschrieben. In [Den02] schliesslich ist ein Beispiel für ein Dialogmanagementsystem gegeben.

2.5 Gestik

Die Gestenerkennung ist ein sehr breit gestreutes Gebiet. Verschiedene Systeme für 2D- und 3D-Bild-basierte Gestenerkennung sind in [San99], [PSA98], [NR99, NR00] und [Vac02] beschrieben.

2.6 Lokalisierung und Verfolgung von Personen

Ein sehr wichtiger Teil eines Interaktionssystems ist die Verfolgung des Benutzers, so daß es möglich wird, den Benutzer im Aufmerksamkeitsfokus zu halten und dies auch durch entsprechendes Systemverhalten zu suggerieren. Dieser Abschnitt gibt eine generelle Beschreibung für Verfolgungsalgorithmen und nennt einige Beispiele für entsprechende Systeme.

2.6.1 Allgemeine Ansätze

Ein Überblick über verschiedene Verfahren zur Verfolgung von Objekten mit Hilfe von Datensequenzen ist in [AMGC02] gegeben. Zwei verschiedene Verfahren werden

besonders herausgestellt, zum einen der *Kalmanfilter*, zum anderen der Ansatz des *particle filtering*.

2.6.2 Lokalisieren von Personen in Laserdaten

Für die Lokalisierung von Personen in einem Laserdatensatz gibt es im Wesentlichen zwei Möglichkeiten: Zum einen die Suche nach einem charakteristischen Muster in den Daten, oder die Registrierung von Bewegungen mit Hilfe aufeinanderfolgender Datensätze.

Ansätze, die nach einem Muster suchen, beziehen sich meist auf das Muster von Beinen, die in einer entsprechend niedrigen Ebene vom Laser erfaßt werden. Diese Herangehensweise wird zum Beispiel in [SBFC01] oder [FZ00] beschrieben. Eine andere Möglichkeit ist, nach einem Körpermuster zu suchen, was dann sinnvoll ist, wenn der Laser zu hoch angebracht ist, um nach Beinen suchen zu können. Generelle Überlegungen dazu sind in [Klu02] dargestellt.

Bei der Registrierung von Bewegungen hängt die Vorgehensweise davon ab, ob sich der Roboter selbst bewegt oder nicht. Im letzteren Fall reicht es, zwei aufeinanderfolgende Datensätze direkt zu vergleichen, im ersteren müssen noch die Daten miteinander abgeglichen werden (scan matching), wie beispielsweise in [SBFC01] beschrieben.

2.6.3 Lokalisieren von Personen in Bilddaten

Ein einfacher Ansatz um Personen in Bildern zu detektieren, ist die Suche nach zusammenhängenden Bereichen von Hautfarbe (skin coloured blobs), die dann als Gesicht oder Hand interpretiert werden. Ein generelles Problem hierbei ist, daß im Allgemeinen sehr viele Objekte der Umgebung eine Farbverteilung aufweisen, die derjenigen von Hautfarbe sehr ähnlich ist. Dennoch liefern die entsprechenden Verfahren zunächst eine gewisse Anzahl von Hypothesen. In [San99] ist ein Ansatz für die Erkennung von Kopf und Händen, basierend auf der Detektion von Hautfarbenregionen, beschrieben. Die beschriebene Arbeit wird für die in dieser Diplomarbeit erläuterte Implementierung als Grundlage für die Erkennung von Gesichtern und Handbewegungen verwendet. Andere, aufwendigere Verfahren sind Kombinationen verschiedener Charakteristika, wie zum Beispiel in [BBB+98] vorgestellt.

2.6.4 Kombination von Bild- und Laserdaten

Ein Ansatz, der die Erkennung von Personen durch eine Kombination von Laserdaten und Bildinformation realisiert, ist in [KLF+02] vorgestellt. In diesem Fall werden die unterschiedlichen Sensorinformationen mit einer Verankerungstechnik (anchoring) an eine Person, bzw. ein verfolgtes Objekt geknüpft und so auch miteineinander verbunden.

3 Entwurf eines Interaktionssystems für Serviceroboter

Bei dem Entwurf des Systems wird darauf geachtet, die für wichtig erachteten Prinzipien der Interaktion nicht zu verletzen. Generell wird von davon ausgegangen, daß das System in der Lage sein soll, mit bestimmten Szenarien umzugehen. Diese Szenarien werden in Form einer Use Case Analyse in vier Gruppen (aus Sicht des Benutzers) eingeteilt: Informationsanforderung, Informationsbereitstellung, Aktionsausführung (Kommando) und Lehren. Ausgehend von der Annahme, daß in jedem dieser Fälle zunächst einmal eine Form der Kommunikation hergestellt werden muß, bzw. nach Erledigung aller gewünschten Aufgaben wieder beendet werden muß, lassen sich die Szenarien in drei Phasen einteilen. Dies wiederum führt dazu, den gesamten Vorgang der Kommunikation zwischen Benutzer und Roboter als zustandsbasiert zu betrachten. Damit erscheint es sinnvoll, als allgemeinen Koordinationsansatz für das System einen endlichen Automaten zu wählen. Dieser Automat wird mit vier Basis-Zuständen beschrieben: Warten, Kommunikationsabbau, Kommunikationsphase und Kommunikationsende. Für die einzelnen Zustände ergeben sich abhängig von bereitgestellten Funktionalitäten des Systems entsprechende Unterzustände. Dies ist vor allem in der Kommunikationsphase der Fall, da hier abhängig vom Szenario (use case) die Verabeitung von Eingaben erfolgt.

Zusammen mit einem allgemeinen Ansatz für eine Architektur wird eine Menge von Modalitäten und Sensortypen vorgeschlagen, die das gewünschte Systemverhalten gewährleisten kann. Es handelt sich in diesem Fall um eine Kombination von Laserdaten und Bildinformation für das Erkennen und Fokussieren des Benutzers, sowie einer Integration von Sprache und Gestik für die Behandlung eines Lehrszenarios. Für Kontrollinformationen wird ebenfalls Sprache vorgeschlagen.

In der einleitenden Phase der Kommunikation wartet das System auf ein bestimmtes Ereignis, um dann die Suche nach dem Benutzer starten zu können. Ein solches Ereignis kann eine wahrgenommene Bewegung oder ein gesprochener „Gruß“ sein. Die Ergebnisse der Suche nach personengleichen Mustern und Bewegung werden zusammengeführt zu einer Menge von Benutzer-Hypothesen. Dies ist notwendig, da davon ausgegangen werden muß, daß mehrere Personen anwesend sein könnten, bzw. im Falle, daß der Roboter angesprochen wurde, eine unbewegliche Person aus einer Menge von personenähnlichen Objekten herausgedeutet werden muß. Aus dieser Menge wird jeweils eine Hypothese gewählt und in das Sichtfeld der Kamera gebracht. Mit Hilfe einer Gesichtsdetektion wird versucht, die Hypothese „Person“ zu verifizieren, gelingt das nicht, wird sie verworfen und die nachfolgende Hypothese wird gewählt. Gelingt die Verifikation, wird der wahrscheinliche Benutzer angesprochen und um eine Bestätigung gebeten. Mit Erhalt der Bestätigung gilt Kom-

munikation als hergestellt und der Automat wechselt in den entsprechenden Zustand. Kommt keine Bestätigung, wird die Hypothese verworfen und entsprechend weiter verfahren.

In der Kommunikationsphase werden Äußerungen des Benutzers entsprechend verarbeitet. Dazu ist es notwendig eine Reihe von entsprechenden Unterzuständen des Kommunikationszustands einzuführen. Ein solcher Unterzustand ist derjenige für eine Lehrsituation. In diesem erwartet das System Erklärungen und Zeigegesten. Ist beides erkannt, wird die Information, die aus der Geste zu erhalten ist, in die Repräsentation der Erklärung eingesetzt und so beides fusioniert.

Für die Interpretation der Spracheingaben wird eine Hierarchie von Äußerungstypen vorgeschlagen. Ausgehend vom Basistyp *Eingabe* wird unterschieden in *Antwort*, *Kommando*, *Ansprache*, *Erläuterung* und *Frage*. Diese Ausprägungen können durch Strukturen, ähnlich typisierten Merkmalsstrukturen (Typed Feature Structures), beschrieben und so noch weiter verfeinert und mit Attributen beliebigen Typs versehen werden.

4 Implementation für Laserdaten, Bildinformation und Sprache

Die Implementation umfaßt Module für die Interpretation der Laser- und Sprachdaten, einen Ansatz für das Verfolgen des Benutzers sowie ein Modul zur Interpretation der Ergebnisse der bereits vorhandenen Hautfarbenregionendetektion. Die gesamte Koordination wird in einem endlichen Automaten durchgeführt, der in diesem speziellen Fall acht Zustände hat. Diese Zustände sind die vier Basis-Zustände des generellen Entwurfs zusammen mit zwei Unterzuständen der Kommunikationsphase, einem Fehlerzustand und einem Unterzustand der Benutzererkennungsphase, der notwendig ist, um den Fall eines empfangenen „Grußes“ zu behandeln. Die einzelnen Module sind flexibel gehalten, so daß sie gegebenenfalls ersetzt werden können.

4.1 Laserdaten

Die Laserdaten werden auf zwei Typen von Mustern untersucht. Zum einen sind dies konvexe Bereiche im aktuellen Scan, die auf angemessene Größe untersucht und dann als Hypothese für die Position einer Person angegeben werden. Zum anderen handelt es sich um Bereiche, in denen Bewegung festgestellt werden kann. Dies wird aus der Differenz zweier aufeinanderfolgender Scans berechnet. Eine sich bewegende Person verursacht eines von zwei charakteristischen Mustern in diesen Differenzdaten, nach dem entsprechend gesucht wird.

Für das Verfolgen von Personen wird aus Zeitgründen auf einen echten Trackingansatz verzichtet. Mit einem naiven Verfahren ließen sich allerdings bereits ausreichend gute Ergbnisse in den Tests erzielen, so daß der Einsatz eines Partikelfilters, der ursprünglich geplant war, nicht notwendig erscheint. Für ein System, das unter realen Bedingungen eingesetzt werden sollte, empfiehlt sich allerdings der Robustheit wegen der Einsatz eines solchen Filters.

4.2 Interpretation der gefundenen Hautfarbenbereiche

Die Bereiche, die mit Hilfe des vorhandenen Systems ([San99]) als potentielle Gesichter erfaßt sind, werden auf eine angemessene Größe und Position im Bild überprüft. Dies ist möglich, da der Abstand des „Gesichts“ zur Kamera bekannt ist. Auch die Position im Bild sollte einigermaßen zentral sein (zumindest gemessen am Abstand zur Längsachse) da ja die Kamera mit Hilfe der Dreh-Kipp-Plattform so positioniert wurde, daß die zu überprüfende Person fokussiert werden kann. Wird ein Bereich als Gesicht erkannt, wird, wiederum mit Hilfe der Abstandsinformation, die Höhe im Raum, d.h. die „Größe“ der Person berechnet. Diese kann dann wiederum auf Plausibilität geprüft werden.

4.3 Spracheingaben

Die vom Spracherkenner ESMERALDA ([Fin99])gelieferten Hypothesen werden mit Hilfe eines Mustersuche-Ansatzes interpretiert. Die Muster, bzw. Wörter werden in einem endlichen Automaten verarbeitet, was möglich ist, da es sich bei den hier verwendeten Eingaben um eine recht kleine, reguläre Untermenge englischer Sprache handelt. Für umfassendere Tests und Sprachmengen empfiehlt sich der Ansatz einer grammatikbasierten Analyse, da dieser im Endeffekt flexibler sein dürfte. Der Parserautomat generiert entsprechend der gefundenen Wörter die bereits erwähnten Äußerungstypen in Form von typisierten Merkmalsstrukturen, die dann wiederum in einem zweiten Interpretationsschritt entsprechend des Systemzustands verarbeitet werden können. Diesen zweiten Schritt übernimmt ein separater Interpretierer, damit die Parsingstrategie unabhängig von der Weiterverarbeitung der erkannten Äußerungen bleibt.

5 Experimentelle Ergebnisse

Mit den durchgeführten Experimenten (auch mit unterschiedlichen Benutzern) läßt sich feststellen, daß wie erwartet die Kombination von Laserdaten und Bildinformation dazu beiträgt, auch mit sehr einfachen Ansätzen eine Person zu erkennen und zu verfolgen. Mit der durch diese Kombination steuerbaren Kamera kann dem Benutzer durchgängig der Eindruck vermittelt werden, im Mittelpunkt der Aufmerksamkeit des Systems zu stehen. Dies ist ein wichtiger Punkt für die Interaktion. Mit der generellen Idee, ein zustandsbasiertes System zu entwerfen, kann eine Reduktion der falsch-positiven Ergebnisse einer Gestenerkennung erreicht werden. Das System erwartet nur dann eine Geste, wenn es in dem entsprechenden Zustand ist.

Probleme in den Tests resultierten im Wesentlichen aus den Komponenten, nicht aus dem Ansatz zu ihrer Integration. So ist besipielsweise die Hautfarbendetektion sehr anfällig für falsche Alarme, die unter Umständen zu Fehlinterpretationen führen können. In diesen Fällen ist die Fehlerbehandlung sehr schwierig, da das Konfidenzniveau sehr hoch ist, also eigentlich kein echter Fehler vorzuliegen scheint. Auch der Spracherkenner bereitet gelegentlich ähnliche Probleme, die aber mit weiterem Training möglicherweise schon vermeidbar sind.

6 Zusammenfassung und Ausblick

Dieser Abschnitt gibt im Wesentlichen die übersetzte Fassung der originalen Zusammenfassung der englischsprachigen Arbeit wieder.

6.1 Zusammenfassung

Die vorliegende Diplomarbeit behandelte den Entwurf einer interaktiven Schnittstelle für einen Serviceroboter und die Implementierung von Teilen einer solchen. Für diese Implementierung waren drei wesentliche Hypothesen die Grundlage:

- Die Integration verschiedener Typen von Sensordaten erleichtert die Suche nach der Person, mit der eine Kommunikation aufgebaut werden soll dadurch, daß sich der Hypothesenraum für detektierte Personen reduzieren läßt.

- Ein zustandsbasiert koordiniertes System erlaubt die Reduzierung von falsch-positiven Hypothesen bei der Gestenerkennung dadurch, daß die Wahrscheinlichkeit, eine Geste erkannt zu haben, durch den Systemzustand gesteuert werden kann.

- Ein zustandsbasierter Ansatz erlaubt es, ein voll integriertes interaktives System zu entwerfen, das in der Lage ist, bestimmte Szenarien zu behandeln, in denen ein Benutzer mit dem System kommunizieren möchte.

Mit der Implementierung und entsprechenden Experimemten konnten diese Hypothesen im Wesentlichen bestätigt werden. Allerdings war es nicht möglich, eine Langzeit-Benutzerstudie durchzuführen, mit der die Einsetzbarkeit eines solchen Systems unter echten Bedingungen getestet werden könnte. Trotz dieses Mankos konnte deutlich gemacht werden, daß vor allem im Bereich der Benutzerverfolgung durch die Kombination verschiedener Sensoren sehr gute Ergebnisse erreicht werden konnten. Diese ist vor allem deswegen interessant, als kein komplexes und damit aufwendiges Verfahren eingesetzt werden mußte.

Der Einsatz des vorhandenen Moduls zur Detektion und Verfolgung von Hautfarbenregionen kann allerdings in Frage gestellt werden. In einer alltäglichen Umgebung dürfte die Verteilung von Hautfarbe in etwa ähnlich sein, wie in dem verwendeten, als Wohnzimmer eingerichteten Laborraum. Dies führt zu einer hohen Anzahl von falsch-positiven Antworten und fehlerhaften Resultaten der Handverfolgung. Die Hinzunahme anderer Charakteristika, wie zum Beispiel Kopf- und Handform erscheint hier sinnvoll.

Als primäre Eingabedaten für die Kontrolle des Systems wurde Sprache vorgeschlagen. Die Interpretation der Spracheingaben konnte unter der Annahme, eine kleine reguläre Untermenge englischer Sprache zu behandeln, mit einem Automaten in

linearem Aufwand durchgeführt werden. Die Ergebnisse der Interpretation wurden in Strukturen, vergleichbar mit typisierten Merkmalsstrukturen, repräsentiert, die es erlaubten zwischen verschiedenen Typen von Eingaben zu unterscheiden. Objekte wurden in diesem Fall als Zeichenketten repräsentiert, es ist aber denkbar, hier entsprechend komplexere Objektrepräsentationen zu verwenden.

6.2 Ausblick

Im Hinblick auf zukünftige Arbeiten könnten Verbesserungen am Gesamtsystem im Wesentlichen durch Veränderungen der Module erreicht werden.

6.2.1 Allgemeines

Ein Ziel für eine Verbesserung des Gesamtsystems wäre es, das System so robust zu gestalten, daß Langzeit-Benutzerstudien auch mit Personen durchgeführt werden können, die mit dem Umgang mit Robotern nicht vertraut sind. Solche Studien sollten in einer Form aufgebaut sein, die sowohl Aufschluß über die Benutzbarkeit als auch den Nutzen einer interaktiven Schnittstelle für einen Serviceroboter liefert. Ein erster Schritt in Richtung eines noch robusteren Gesamtsystems wäre die Nutzung eines echten Dialogmoduls, das es erlaubt, Aktionen zu bestätigen, bevor diese ausgeführt werden, um so die Mißverständnisse aus fehlerhafter Interpretation von Spracheingaben zu reduzieren. Weitere Verbesserungen sollten an den einzelnen Modulen ausgeführt werden, wie im Folgenden vorgeschlagen.

6.2.2 Module

Das Modul zur Interpretation der Laserdaten könnte um die Möglichkeit erweitert werden, einen initial bewegten Roboter zu erlauben. Dazu müßte vor allem zur Erkennung von Bewegungen eine „Scan matching“-Technik angewendet werden. Eine solche wurde beschrieben in [SBFC01].

Ein Modul, das in verbesserter Form wesentlich zu erhöhter Robustheit des gesamten Systems beitragen kann, ist die Verfolgung des Benutzers und eventuell anderer Personen. Hier müßten ausführliche Tests durchgeführt werden, um festzustellen, inwieweit es notwendig ist, alle Objekte fortgesetzt zu verfolgen, oder ob es ausreicht, nur den aktuellen Benutzer in die Objektverfolgung aufzunehmen. Geeignete Verfahren, wie zum Beispiel der sehr robuste Ansatz des Partikelfilters, sind in [AMGC02] vorgestellt.

Um die Kommunikationsphase selbst zu verbessern, empfiehlt sich der Einsatz eines Verfahrens zur Gestenerkennung, das nicht ausschließlich auf der Detektion von Hautfarbe basiert. Hier ist ein entsprechendes Verfahren, das allerdings einen Stereokamerakopf erfordert, in [Vac02] beschrieben. In den dort vorgestellten Tests mußte festgestellt werden, daß die Rate der falsch-positiv erkannten Gesten zu hoch

war, um eine ernsthafte Aussage machen zu können. Dieses Problem könnte durch den Ansatz, nur in einem gewissen Kontext die entsprechende Gestenerkennung zu nutzen, umgangen werden.

6.3 Fazit

Trotz der Nachteile, die in der vorliegenden Form das System instabil machen könnten, ist der vorgestellte Ansatz sehr erfolgreich. Selbst mit den recht einfach gehaltenen Modulen zur Interpretation der Sensordaten konnte ein insgesamt zufriedenstellend robustes Systemverhalten erreicht werden. Mit einigen kleineren Verbesserungen einzelner Komponenten ließe sich ein System erstellen, das für umfassendere Benutzerstudien oder für einen Einsatz in einer Testumgbung geeignet wäre.

a Technische Daten

System	PC (Standard, 450MHz) mit Linux (Redhat 4.1), Kernel 2.2.19
Laserscanner - Höhe - Abgedeckter Winkel - Auflösung	SICK PLS 200-114 93cm 180° Winkel: 0.5°, Distanz: 1cm
Kamera - Sichtfeld der Kamera - Framegrabber - Treiber	Sony CCD color video camera module XC-999P 60° auf/ab und 40° rechts/links Matrox Meteor Framegrabber Card Version 1.5.4 für Linux
Pan Tilt Unit - Rotation - Kippwinkel	Directed Perception PTU-46-17.5 $\pm 159°$ $31°$ to $-47°$

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