CHALMERS
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Multimodal Interactive System Design in the Scope of Performing Arts

Creating a Hybrid Sensing Robot for Ubiquitous Human Machine Interaction

Master of Science

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Department of Applied Information Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:

The cover shows the HySens robotic system interacting with the actor Robert Bolin.

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Abstract

Based on the idea of an immersive integration of robots and sensor technology in the future this master thesis explores and defines new human-robot interaction possibilities by building a robot that uses hybrid sensing of body mounted sensors, motion tracking and neural interfaces. Together with the virtual, responsive and adaptable space of a theatre environment new interaction strategies were tested, defined and evaluated to open up promising perspectives and to indicate possible enhancements of future human-robot interaction. The development of the robot resulted in a stage performance and interactive narrative in which an actor, by the means of thought, emotion and action, interacts with a robot on stage.

Keywords: interaction design, human-machine interaction, human-computer interaction, human-robot interaction, interactive system design, prototyping theatre, experimental theatre, theatre technology, body mounted sensors, brain-computer-interface, interaction strategies

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Another big thank you has to go to all my friends, my girlfriend and family who tolerated all my ups and downs and diverted me every now and then. I will always appreciate your friendship and kindness. Super cool!!

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Terminology

BCI: Brain-computer-interfaces refer to a group of devices, which measure the brain activity of human beings.

DoF: Stands for degree of freedom and refers to the number of joints on a robot arm.

GUI: The graphical user interface lets the user interact with eletronical devices through icons and visual representations on a screen.

HaM: Human and Machine. The project this master thesis is part of.

HRI/HMI: Human-robot and human-machine interaction describes the interaction between a human and an autonomous robot or machine.

HySense: Refers to the Hyper Sensing Interactive System built in this thesis. It contains subsystems like the robotic system, illumination and the sensors.

IK: Stands for inverse kinematics and describes a set of mathematical equations to determine the exact position of a robot arm.

MCS: The Multimodal Control System (MCS) is the program that controls and monitors the HySense system and serves as an operating point for a technician.

1. Introduction

1.1 Purpose

Robot technology and machines become increasingly integrated in our lives, in our everyday domestic lives as well as in broader socio-economic structures. Consequently, while the complexity of machines, computers and robots rises continuously the separation between human beings' capabilities of sense, expression and social affiliation and robots' technical aptitude to match and answer these skills vanishes more and more. In fact, this gap constantly decreases. According to researchers like Karamjit Gill, in the future there might be a profound symbiosis between human beings and machines based on the approach of a collaboration between humans' and machines' capabilities.[1] Yet this goal remains to be reached: Even in the scope of continuous technological progress most robots are unable to interpret human intentions and consequently lack fluent and plausible responses. However, when it comes to human machine interaction in general and human-robot interaction in particular the given difficulty as with all sophisticated technology is to find appropriate means of exchanging communicative information and to close the gap between the complexity and the intended intuitive character of interaction between the two participating agencies. Thus there is a great need of developing innovative ways of communication and interactive strategies with the aim of making new technologies accessible and user-friendly. Technological research thus has a high interest in creating intuitive and straightforward human machine interactions. One main aim is to make machines and robots capable of perceiving and interpreting information of their surroundings as well as to enable them to react and respond to these in a suitable manner.[2] One promising direction is the use of new technological means of measuring human body signals. As these can be tracked and registered, they might be used as communicative transmitters, which can be processed by advanced technologies or by robots.

This master thesis intends to investigate, explore and define the current borders of human-robot relationship and interaction. The research will be undertaken in the context of the *Interactive Institute* Gothenburg. In the institute, the major research focus is set on experimental IT and design as well as on the investigation of new technologies. Among a

[1] Cf. GILL, Karamjit S., ed. *Human Machine Symbiosis. The Foundation of Human-Centred System Design.* Berlin: Springer, 1996, 2.

[2] The question as to whether this is a desirable or a questionable development considering ethical and humanistic aspects cannot be taken into account broadly in this paper. However, the author is aware of the importance of this question.

broader range of research projects in the institute, the Human and Machine project (HaM) was started by the beginning of 2014. Its main goal is to explore and research the interaction between human and machine in a theatrical, technological and narrative context.

Focussing on the performing arts it becomes obvious that it is often undervalued in the actual spectrum and output it can provide in the field of technological research. In fact, theatre seems to be nearly ideal for this purpose: First of all, technology in all its facets happened to become an integral part of performance. Secondly, and all the more important, one of theatre's basic premises is interaction, i.e. the action of an actor and the reaction of an audience. This interactive nature of theatre thus serves as an image of real life communicative situations and by this it factually creates a perfect research space. It delivers ideal surroundings for developing a robot and testing different human-robot interaction strategies like responsiveness, articulation and interpretation. This will be realised in the scope of the underlying project: Using open source, sensor technology, neurofeedback and real-time robot control as well as data visualization a theatrical robot will be created. The development of the robot will result in a stage performance and interactive narrative in which an actor, by the means of thought, emotion and action, interacts with a robot on stage. The robot will serve as an equivalent actor who can influence the theatrical narrative to become partly interactive and unpredictable.

The complexity of the project calls for the collaboration of various stakeholders coming from the different areas of research. Next to the *Interactive Institute*, one main stakeholder of the project will be *Scenlaboratoriet*. Founded by Carl Heath and Robert Bolin, this group describes itself as follows:

> *Scenlaboratoriet* is an experimental and researching theatre and performance group. We in *Scenlaboratoriet* take our approaches from artistic, psychological and technological fields of research and try to pose and answer new questions pertaining to interaction, communication and what it is to be human in a digital era. We want to create new methodology in theatre and transmedia in areas such as co-creation, participatory design and interplay between fields of research.[3]

Carl Heath will be the producer and coordinator of the project. Robert Bolin, psychologist and master student at the *Malmö Theatre Academy* will be the author, actor and director of the stage performance. His research focus is set on composing the narrative structure, which deals with a protagonist who is trying to create his second self in a robotic counterpart. This narrative structure was gradually written around the parallel technological design of the robot as the progress in this design determined the storyline. The actual theatre performance is thus closely connected with the development of the robot. My task in the project and thus the topic

[3] "About Scenlaboratoriet." *Scenlaboratoriet*. Web. 30 Aug. 2014. <http://www.scenlaboratoriet.se/about.html>.

of the master thesis was to design, to build and to program the robot and to find ways of realising the interaction between the robot and the actor.

1.2 Delimitations

Composed in the context of the Interaction Design and Technology program at the *Chalmers University* in Gothenburg, the thesis is set in the field of computer science and interaction design. At the same time, it goes beyond this technological focus encompassing the fields of cultural studies, i.e. performance and drama studies and thus realises an interdisciplinary approach. While this is doubtlessly often strived for in the scope of the general cross-linking of the sciences, this also results in a growing complexity. Many different areas of research and interest are brought together. While the constant need for mutual coordination and agreement between the stakeholders might result in a deceleration of the working progress, the wide scope also offers new and promising opportunities ranging from the chances offered by the experimental space of the stage to the inspiration and challenge given by the need for a customized technological product designed for an immediate use. However, to realise this, a sophisticated working strategy must be the essential basis of the project.

Considering the complexity of the project – creating a full theatre performance including a robot actor, graphical interface, sensor control and ambient environment – the goal is to start with a first prototype and iterate through several stages as time allows. Due to the resulting limitations in time, no user studies or evaluations will be conducted. As a preliminary substitute, the experience gathered during the performances as well as the feedback of and discussions with the audience will be drawn from and elaborate on.

The above-mentioned limitations in time as well as the restricted amount of resources furthermore result in the necessity to select among a wide range of sensors. Although it would be gainful to test and iterate with various different kinds, only a selective number of sensors can be used for the underlying research purpose and the prototype.

1.3 Research Question

As robots and autonomous machines are a prospect of the near future and thus become ubiquitous, the question arises as to how information between these two communicators is exchanged and how human-robot interaction develops. Investigating how the nature of interaction between a human communicator and a machine/robot is influenced by the use of technology, a theatrical robot will be built using hybrid sensing of body mounted sensors, motion tracking and neural interfaces with the aim of exploring new interactive strategies and fluent interaction behaviour.

Thus the main question this thesis addresses is:

In the scope of the narrative surroundings of a theatrical performance, how can an actor-controlled human-machine interaction be established by the customized construction of a hybrid motion and biosignal sensing robot?[4]

The research in this area will then again boil down to the following sub-questions:

- How can a robot successfully be built and integrated into an interactive theatre performance in which the robot reacts partly autonomously depending on the actor's physical and mental state?
- How can the robot be controlled?
- How can information be understandably visualised for the audience?
- How can the development of a technologized and augmented body-to-machine interaction in the context of cultural products, e.g. a theatrical performance influence the general development of interaction technologies as well as envision and improve future human-machine interaction?

[4] The robot is in the following referred to as HySens robot (**Hy**brid **Sens**ing robot).

2. Background: Technique, Theatre and Interaction Design

The broader background of the research area of the master thesis is basically divided in two main areas: First of all, it is informed by the general role of technology in contemporary society and research. Regarding the object of research, one secondly has to consider the broader area of theatre and performance studies, because the prototype will be designed for a theatrical performance. In the following, a concise insight into these two complex fields of research will be given.

2.1 Automats and Technology in Society

The field of robotics, automats and interactive machines is considered to be a relatively young and recent phenomenon but is actually based on many years and centuries of research and exploration. Already in 1515 Leonardo da Vinci built a mechanical automated lion that could walk, shake his head and open its mouth.[5] This for its time vastly complex technology was built upon the work of the clock makers, whose automats and figures shaped the technology of the following centuries.[6] Bridging many years of further developments, in the beginning 20th century the Czech Karel Čapek coined the term "robot" while writing the play *R.U.R* (*Rossum's Universal Robots*), a dystopian science fiction drama.[7] In this context it's actually notable to mention that when the play premiered in Berlin the scenographer Frederick Kiesler devised a mechanical and interactive stage that used innovative technology like video projection and followed the approach of being coequal to the actors.[8]

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[5] Cf. BREAZEAL, Cynthia et al. "Interactive Robot Theatre". *Communications of the ACM* 46.7 (2003), 76.
[6] Cf. ibid.
[7] Cf. SALTER, Chris. *Entangled. Technology and the Transformation of Performance.* Cambridge: MIT, 2010, 280.
[8] Cf. ibid. 30.

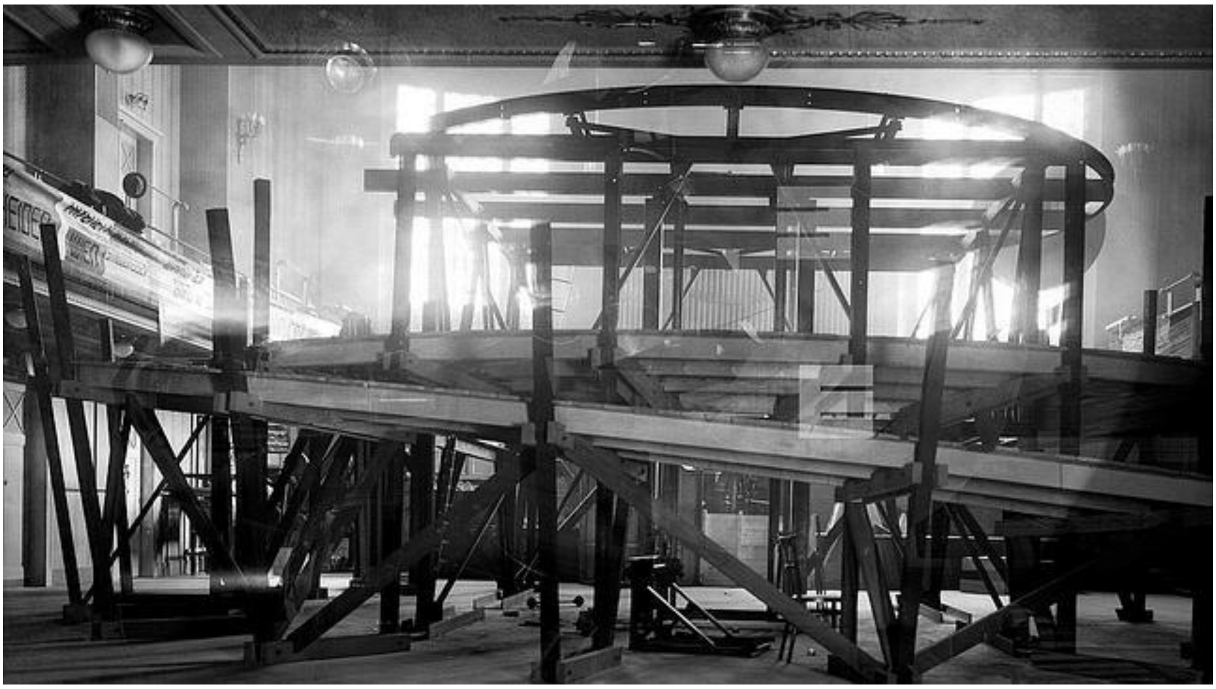

Fig. 1: Kiesler's stage design for Čapek's *R.U.R.*

In the following years the term "robot" evolved more and more approaching the understanding we have of it today. In 1964, Disney for example built an audio-animatronic automat that looked like the former United States president Abraham Lincoln. It was the most advanced anthropomorphic robot at its time.[9] Recently especially Japan has made great effort to innovate the field of anthropomorphic robots. Humanoids like Honda's *Asimo* are able to walk and perform with incredible smoothness and accuracy and are therefore considered as a turning point in research and development.[10] Since in-depth human-robot interaction needs on the one hand a precise and sleek motion, it on the other hand depends tremendously on the perception and response the robot is able to receive and give. Focussing on the field of human machine and robot interaction, current robot and autonomous machine research puts a lot of effort in key areas like perception, action and cognition.[11] The result can be seen in various kinds of recent autonomous robots and machines e.g. from Boston Dynamics,[12] self-driving

[9] Cf. DIXON, Steve. "Metal Performance: Humanizing Robots, Returning to Nature, and Camping About". *TDR* 48.4 (2004), 21f.
[10] Cf. ibid. 25.
[11] Cf. NOURBAKHSH, Illah Reza. *Robot Futures.* Cambridge: MIT, 2013, xviii.
[12] Boston Dynamics is an engineering and robotics design company (cf. Boston Dynamics. "Changing your idea of what robots can do." *Homepage Boston Dynamics.* Web. 30 Aug. 2014. <http://www.bostondynamics.com>).

cars like those produced by the *AutoNOMOS* project[13] or the music improvisation robot *Shimon* created by Guy Hoffman.[14]

Fig. 2: Boston Dynamic's *Atlas*

Fig. 3: AutoNOMOS project

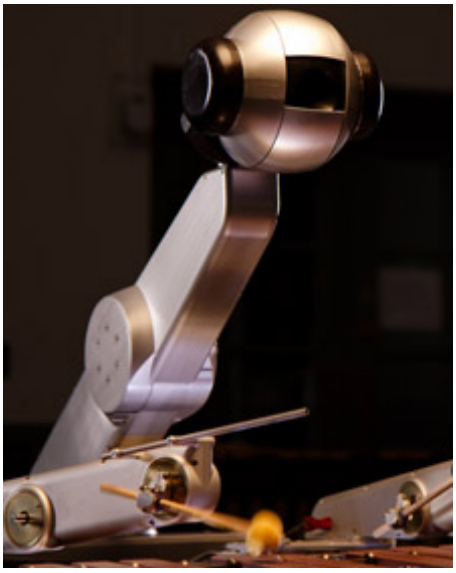

Fig. 4: Guy Hoffman's *Shimon*

The main reason why these new projects are made possible is to be found in the continuous development of new technology and sensors. Cameras are able to see and track the world around us, sensors like e.g. inertial measuring units (IMUs) are becoming so small that they fit in every smartphone and technology like brain computer interfaces (BCIs) and thus open a completely new channel of interaction. BCIs were for example used to let monkeys control the movements of robots. The monkeys' brain activity was mapped and then used as a trigger for the raising of the robot's hand.[15]

Summing up, contemporary technological innovations increase with a tremendous speed and therefore quickly shift current research frontiers. Thus the overall development of interaction design systems needs to be as quick as possible to match the output of these new technologies. One promising example for future research is the use of the theatrical space as an area of research. In fact, the connection between the stage and technology is more profound than one might assume at first sight.

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[13] AutoNOMOS is a research lab of the Freie Universität Berlin developing the technology of driverless cars (cf. "Welcome to the AutoNOMOS project!" *Homepage AutoNOMOS Lab*. Web. 30 Aug. 2014. <http://www.autonomos.inf.fu-berlin.de>).

[14] Cf. HOFFMAN, Guy. "Shimon Robotic Musician." *Homepage Guy Hoffman*. Web. 30 Aug. 2014. <http://guyhoffman.com/shimon-robotic-musician/>.

[15] Cf. DIXON, Steve. "Metal Performance: Humanizing Robots, Returning to Nature, and Camping About", 33.

2.2 Theatre and Technology, or: The Connection of Theatre with Interaction Design

As Barbara Kirschenblatt-Gimblett points out, "[T]echnology is integral to the history of performance."[16] Firstly, technology became a supporting design medium for dramatic arts. Already the Hellenic theatre played out dramas between human and machines by using crane-like *deus ex machina*.[17] Right from the beginning, artificially produced sound or stage constructions played an important role, too. Later, the technological development allowed for artificial light to create new and intense atmospheres. Running through the centuries, the general technological development was mirrored by theatrical performances: Media e.g. in the form of film snippets became commonly used material. However, the development exceeds the boundaries of technology as a simple stage property. Theatre groups such as *The Wooster Group*[18] and *Omnicircus*[19] or human-robot interaction researchers like Guy Hoffman[20] serve as perfect cases in point. In their creations, technology turns into more than a simple tool supporting the dramatic arts. It ascends the steps towards the actor, reaching an increasingly equal status. *The Wooster Group* for example uses screens to blur the lines between the actors' bodies and virtual images of bodies so that actual presence becomes a mixture of human life and virtually produced realities. The interface which is created in my master thesis, transgresses these apparently set limits still a little further: Technology is no longer presented as obviously subsumed under the human and controlled by him but as equal in status: "[H]uman and technical beings and processes are so intimately bound up in a conglomeration of relations that it makes it difficult, if not impossible to tease out separate

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[16] KIRSCHENBLATT-GIMBLETT, Barbara as quoted in: SALTER, Chris. *Entangled,* xxii.
[17] Cf. SALTER, Chris. *Entangled*, xxii.
[18] Main characteristic of the *Wooster Group*'s work is the new role of technology, which becomes an integral part of the theatrical performance. In *To You, the Birdie (Phèdre)*, for example, parts of the human body become doubled by screens. In the middle of the front stage, for instance, a screen is situated behind which the actor steps at specific points of time in the play. In this moment, the screen shows the hidden bodypart. Reality is enhanced by showing a different nature of the floor or by changing the garments worn by the actor. Furthermore, other characters only appear on screen without showing their natural bodily presence on stage. The human voice and other sounds of the performance are amplified and sometimes distorted by technical devices (cf. QUICK, Andrew. *The Wooster Group Work Book*. New York: Routledge, 2007).
[19] *Omnicircus*, a performance group around the main initiator Frank Garvey, produces robots and deploys them in increasingly complex multimedia performances. One example is their robot Goboy, "an anthropomorphic sculpture of […] clay mounted on the chassis of a motorized wheelchair" and "extraordinarily menacing" (GIMEIN, Mark. "Circus Roboticus. A Troupe of Robots Forces Audiences to Confront the Terrors of Late 20th Century Life." *Homepage Salon*, Salon Media Group. Web. 31 Aug. 2014. <http://www.salon.com/1999/09/27/omnicircus_robots/>).
[20] Guy Hoffman is a researcher in the field of human-robot interaction currently working in Israel. His projects deal with social robotics and the responsiveness of robots on human impulses making use of the theatrical stage to undertake his research (cf. HOFFMAN, Guy. "Research Interests." *Homepage Guy Hoffman*. Web. 30 Aug. 2014. <http://guyhoffman.com>).

essences for each."[21] To a certain degree, theatre may thus serve as a mirror acuminating the real conditions of our technological surroundings. Technology's role is doubtlessly interpreted as a major one immersing our lives with all sorts of devices. Theatre, though more unconditionally than it might be the case with regard to our real live situations, in this aspect follows the most general definition of the modern human being situated on the verge of the cyborgian. Dierk Spreen, for example, refers to Charles Hables Gray when defining the cyborg as self-regulated organism uniting in itself the natural and the artificial.[22] And Chris Salter highlights, "performance theorists and practitioners now see the contemporary body as something incorporated into larger than human systems – as something to be transcended through implants, prosthetics, sensors, actuators, and even genetic invasion."[23] In turn, theatre may be interpreted as an institution foreshadowing possible states or at least painting scenarios of technological developments in the (near) future. By this, theatre provides cultural-anthropological considerations tying to the core of our modern day society and reflecting its characteristic images and positions according to which people try to define themselves.[24]

This is in fact the reason why theatre may serve as an alternative object of research encouraging technological experiments and developments. It is here where we do find a medium that can provide us with special kinds of social, non-linear scenarios, which are well suited for plausibly testing new ways of interaction. As reacting on user or human expressions is a core functionality in the world of performing arts as well as in human machine and robot communication those two areas can be combined for the sake of gaining new insights for further research. This makes it possible to catch up with the extreme rapidity of the technological development propelling towards a world characterized by a variety of autonomous technology surrounding our daily lives.

A researcher already established in this field is Guy Hoffman. He contributes ground-breaking work using the stage to explore new ways of robot responsiveness and improvisation. For instance, he built a robotic desk lamp, which next to the use in other research projects was the focus of a theatrical performance in which actors interacted with it.[25] The robot was used for different research projects. Among others it was the focus of a

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[21] SALTER, Chris. *Entangled*, xxxii.
[22] Cf. SPREEN, Dierk. "Cyborgs. Diskurse zwischen Körper und Technik". *Die Figur des Dritten. Ein kulturwissenschaftliches Paradigma.* Eds. EßLINGER, Eva et al. Berlin: Suhrkamp, 2010, 30-51.
[23] SALTER, Chris. *Entangled*, 222.
[24] Cf. SPREEN, Dierk. "Cyborgs", 30-51.
[25] Cf. HOFFMAN, Guy, Rony KUBAT, and Cynthia BREAZEAL. "A Hybrid Control System for Puppeteering a Live Robotic Stage Actor." *Proceedings of the 17th IEEE International Symposium on Robot and Human*

theatrical performance in which actors interacted with it. While earlier (robotic) performances were built on the principle of a command-and-response behaviour, such as giving a specific cue triggering a robotic action, Hoffman introduced so-called beats which make possible an enhanced communicative situation by improving the fluency of interaction. Hoffman describes it as follows:

> To allow for a performance that is both expressive and reactive to the robot's human scene partners, we developed a hybrid control system designed for use by a single operator in a live stage setting. This system combines dynamic triggering of pre-scripted animation, parametric motion attributes, and real-time point-of-view eye-contact IK, a previous unachieved task. We have staged a production of a play specifically written for a robot and two human actors, and performed it three times.[26]

As a case in point, the robot gazed at the actors and followed their movements even exhibiting a human-like narrowing and widening of a technically realised iris. While the actors felt like interacting with a kind of external trigger, director Kate Snodgrass assumes that "they [the audience] forgot that the robot was being manipulated (if they ever realized this) and began to see the robot as another character in the play."[27]

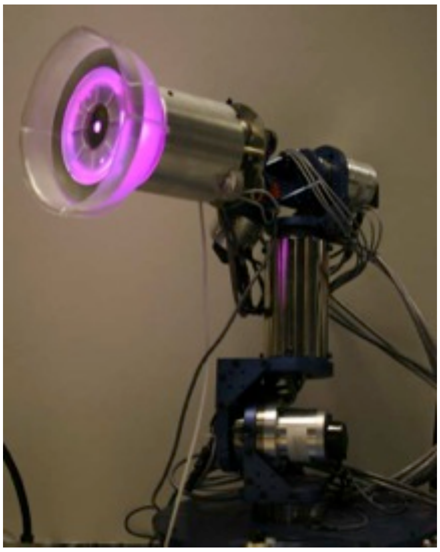

Fig. 5: Guy Hoffman's robotic desklamp

Fig. 6: Scene from a stage production using the robotic desk lamp

The *MIT Media Lab* also used the theatrical stage as surroundings for developing a robot, in this case an entertainment robot specifically designed for the interaction with the audience.[28] In the fictive day-time of the play, for example, the *Public Anemone* was awake and carried out specific daily routines such as drinking, bathing or even watering plants. It

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Interactive Communication, Technische Universität München, Munich, Germany, August 1-3, 2008, 345-359. Web. 30 Aug. 2014. <http://alumni.media.mit.edu/~guy/publications/HoffmanROMAN08.pdf>.

[26] Ibid. 359.

[27] Ibid. 358.

[28] Cf. BREAZEAL, Cynthia et al. "Interactive Robot Theatre", 81.

perceived members of the audience and responded to their communicative movements such as waving the hand, approaching or touching the robot and eliciting light and musical responses.[29]

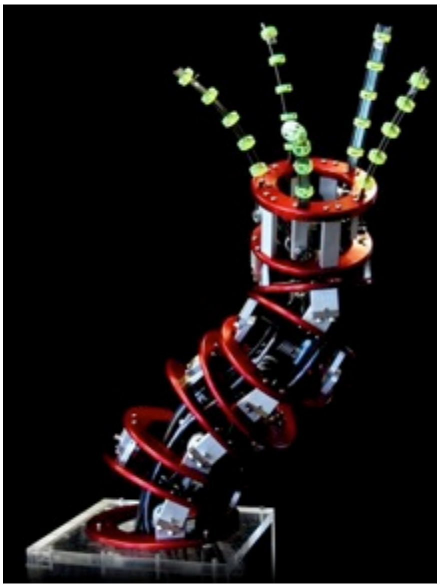

Fig. 7: MIT's *Public Anemone* without its silicone skin

Fig. 8: Interacting with the *Public Anemone*

All in all, "these elements created a physically interactive, ever-changing, multisensory experience that engaged the audience through sight, sound, scent, and touch."[30]

As becomes clear with regard to the two illustrated examples, the performance space can be used as a suitable research space for developing robots interacting with humans. The following reasons can be named for this:

1. The most profound reason is the basic condition of the theatrical situation itself. In the context of cultural studies, Manfred Pfister set up a communication model for dramatic texts:[31]

Fig. 9: Manfred Pfister's communication model for dramatic texts

[29] Cf. ibid.
[30] Ibid.
[31] Cf. PFISTER, Manfred. *The Theory and Analysis of Drama.* Cambridge: Cambridge University Press, 1988, 4f.

Briefly explaining only the aspects important for this context, an internal communication system (layer 1, dark-coloured area) can be described referring to the characters embodied in the stage play sending messages to receiving characters. This internal system corresponds with an external communication system (S4/R4), i.e. the actors and the audience. This is also what Erika Fischer-Lichte illustrates in her definition of theatre: "Theatre happens […] when a person A embodies X while S is watching."[32] She furthermore illustrates a semiotics of theatre, isolating a number of interdepending theatrical codes. Among others she names the kinetic signs separated into facial mimic expressions and bodily gestural and proxemic ones exhibited by the actors onstage. Next to this visual code she also refers to the acoustic signs generated in various ways by the human voice.[33] Pfister and Fischer-Lichte in fact provide the ideal vocabulary for describing the theatrical research environment. Here, the kinetic and acoustic signs for example work as triggers for the interaction between human and robotic actor fictively mirroring real-life interactions. They are perceived by audience members who might even also join in the action and by this blurring the lines between the internal and external communication system of drama.

2. Going beyond this mere theoretical description of the theatrical situation, there are various practical reasons for the use of the stage as research space. "The theatrical script places constraints on the dialogue and interaction. The storyline defines concise test scenarios. The stage constraints the environment […]."[34] By this the interactive surroundings allow for a restricted but detailed functionality of the robot "limiting the perception and actuation expectations of a robotic system."[35] Lu and Smart convincingly describe the chance of the custom-made constraints of the actor's motion to fit the actual robot's potential and thus at the same time highlight the high precision of the stage as a controlled environment where interactions can be repeated and varied with minimal effort.[36]

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[32] FISCHER-LICHTE, Erika. *Semiotik des Theaters*. Vol. 1: *Das System der theatralischen Zeichen*. 4th ed. Tübingen: Gunter Narr, 1998, 25 (my translation).
[33] Cf. ibid. 25f.
[34] BREAZEAL, Cynthia et al. "Interactive Robot Theatre", 80.
[35] HOFFMAN, Guy. "On Stage: Robots as Performers." *Robotic: Science and Systems Workshop on Human-Robot Interaction*, 2011. Web. 30 Aug. 2014. <http://guyhoffman.com/publications/HoffmanRSS11Workshop.pdf>, 1.
[36] Cf. LU, David V., and William D. SMART. "Human-Robot Interactions as Theatre." *20th IEEE International Symposium on Robot and Human Interactive Communication,* Atlanta, USA, 31 July-3 August 2011, 475ff. Web. 30 Aug. 2014. <http://www.cse.wustl.edu/~dvl1/publications/interactionsastheatre.pdf>.

3. On the other hand, to function as an actor in the theatrical performance, "a robot actor must be able to act/react in a convincing and compelling manner to the performance of another entity […]"[37] and thus mirroring real-life functionality. As Guy Hoffman puts it, the theatrical surroundings can thus "provide for a rich environment in which a robotic agent meshes its actions with a human partner, incorporating dialog, sensory processing, action selection, and action timing."[38] Lu and Smart convincingly state that it is a goal of both theatre and real-life human-robot interaction to achieve naturally fluent communication.[39]

4. Referring to Pfister's communication model for dramas, the audience plays an essential role in theatre. This might also be transferred to theatre as a research space: Here, the audience might function as an important instrument in the evaluation of the human-robot interaction and the robotic functioning. This feedback might then serve as another starting point for further technical development.[40]

Though fluent theatrical dialogs between an autonomous robot and a human scene partner have not yet been attained and fully scripted robots still have a lack of timing and responsiveness to human actors,[41] the theatrical space can provide us with the high potential of a virtual responsive space in which new developments can be made and tested at the same time. This space can be constrained, adjusted or merged into any scenario needed and might be additionally evaluated by the participation of the audience. Hence theatre coalesces with interaction design to an innovative symbiosis. Being designed for the purpose of entertaining and thus for an interaction with humans, robotics in this field exhibit characteristic qualities of a real-life experience and are thus well-suited surroundings for researching human-robot interaction. By this, they target the development of robotic assistants that cooperate with people as partners rather than as tools as "[s]ociable robots need to perceive, recognize, and interpret the behaviour of humans through multiple modalities, including vision, audition and touch."[42] This shows the deep connection of the theatrical research space with real-life surroundings starting from the basic assumption of the transferability of robotic stage

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[37] BREAZEAL, Cynthia et al. "Interactive Robot Theatre", 80.
[38] HOFFMAN, Guy. "On Stage: Robots as Performers", 1.
[39] Cf. LU, David V. et al. "Human-Robot Interactions as Theatre", 473.
[40] Cf. ibid. 478.
[41] Cf. HOFFMAN, Guy et al. "A Hybrid Control System for Puppeteering a Live Robotic Stage Actor", 354.
[42] BREAZEAL, Cynthia et al. "Interactive Robot Theatre", 78.

performance to actual social situations.[43] In the context of this thesis, this environment is used for developing an interactive system and furthermore for testing the functionality of the developed system in a real-time interactive situation.

3. Concepts and Frameworks

3.1 Human-Centered Approaches: Social and Cognitive Psychology

The importance of understanding the human mind with the help of social and cognitive psychology is essential when it comes to human-machine communication in general. Considering the ways of how humans receive, process and communicate information helps us to create more intuitive and insightful machines which ideally react to our individual psychological characteristics in the right manner. As Albert Mehrabian states, humans communicate to 93 percent non-verbally and out of these 93 percent 38 comprise the tone of voice (e.g. the pitch) and 55 are pure body language including gestures, posture and facial expression.[44] He furthermore points out that only 7 percent of our overall communicative actions are actually comprised of verbal communication.[45] When it comes to body language we actually have an even higher intuitive and subconscious output than it is the case with regard to our verbal language. Bodily and subconscious interaction can be divided into intentional gestures and unintentional gestures such as nose picking, scratching etc.

In fact, the latter were already used for basic research on human-machine systems under the aspect of how a computer or a machine can make sense and use of those behavioural clues.[46] Despite this profound insight, one has to keep in mind that the actual human-robot interaction still puts a lot of effort in the research of e.g. speech controlled interaction or more general discrete input systems. However, it seems to be promising to investigate certain behaviours, body language or emotional patterns and to use these as a tool

[43] Cf. LU, David V., et al. "Human-Robot Interactions as Theatre", 477.
[44] Note here the relevance of Fischer-Lichte's theory of the semiotics of theatre (see above footnotes 31 and 32).
[45] Cf. MEHRABIAN, Albert. *Silent Messages*. Belmont: Wadsworth, 1971, 44.
[46] For example cf. MITSUNAGA, Noriaki, et al. „Adapting Robot Behavior for Human-Robot Interaction". *IEEE Transactions on Robotics* 24.4 (2008), 911-916.

of interaction with machines and robots. It is only logical to follow the pioneering works in this field of human-computer interaction as the non-verbal communication seems to be more frequented and intuitive. Consequently, a non-verbal use in HMI or HRI must necessarily be the pragmatic consequence.

A useful theory to be used as a starting point is Edward T. Hall's concept of personal spaces.[47] As he points out, we can divide our surroundings in several distances and different comfort zones, so-called proximities. These comfort zones stand for different kinds of interaction – from public over social to intimate:

1. Intimate distance
2. Personal distance
3. Social distance
4. Public distance

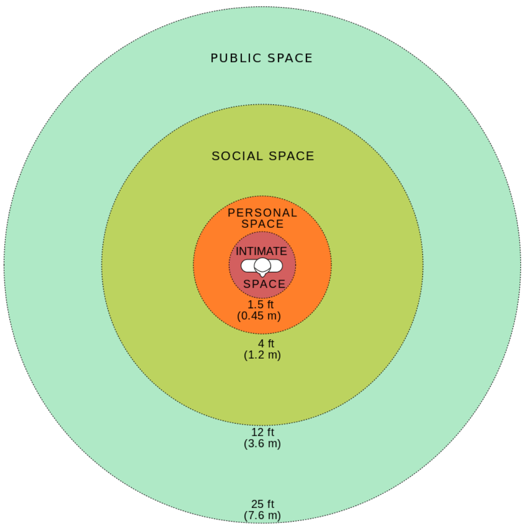

Fig. 10: Hall's personal reaction bubbles

This basic concept can help us in a very good way when it comes to HMI and HRI interaction: Making machines aware of those zones could change the mutual interaction combining the zone-ranges with the machines' estimation of what actions and effects should happen in that specific zone and how far it is allowed to influence that space.

A second relevant theory which might be used as a basic approach to investigate the area under discussion is Daniel Dennett's theory of the intentional stance.[48] In the scope of

[47] Cf. HALL, Edward T. *The Hidden Dimension*. New York: Anchor Books, 1966, 125-128.
[48] Cf. DENNETT, Daniel C. *The Intentional Stance.* Cambridge: MIT, 1987, 43-68.

his theory, Dennett distinguishes between three different stances helping humans to relate and make sense of entities in their surroundings, i.e. the physical, design and intentional stance. In reference to the physical stance, we are able to predict certain kinds of behaviour or action with the help of e.g. physical laws and empirical science. For example, the cook in the kitchen can predict the effect of leaving the pot on the burner too long.[49] The design stance is situated one layer above the physical stance: In this stance, we ignore certain physical details in order to focus and explain the actual behaviour of something and concentrate on the broader appearance of an entity. A computer user, for instance, might not have the faintest idea of how the computer is actually technically working.[50] This is due to the fact that we as humans don't care about the actual details of a thing as long as we are familiar with its behaviour. But if we are not able to empirically estimate the behaviour of something we start to predict specific aspects. This finally leads us to the stage of intentional stances. If our predictions about certain aspects prove to be invalid, we start to categorise things in a broader range by firstly analysing its behaviour and then trying to predict its intention. The basic principle of this estimation seems to be an interesting starting point for the interaction of machines with humans to predict certain kinds of behaviour and then to react on these behaviours. This would increase the overall interaction. For example a robot might recognise certain recurring patterns of action and thus learn to predict the occurrence of those behaviours. He might furthermore connect these with specific responses and exhibit those whenever the respective action takes place.

Another interesting theoretical concept which might be used as an incentive for developing human-robot interactions is the concept of flow by Mihaly Csikszentmihalyi.[51] *Flow* can be seen as a continuous balance between challenges an agent is confronted with and skills he has at his disposal. This becomes all the more relevant if it is transferred to the flow of interaction.[52] A well-functioning interaction or activity must be realised in such a way that an action can be undertaken without excessive demands for the agent: On the one hand it should be simple without being boring and on the other hand challenging but not resulting in anxiety.

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[49] Cf. DENNETT, Daniel C. "True Believers: The Intentional Strategy and Why It Works." *Mind Design II: Philosophy, Psychology, Artificial Intelligence*. Ed. John HAUGELAND. Cambridge: MIT, 1997, 60.
[50] Cf. ibid.
[51] Cf. CSIKSZENTMIHALYI, Mihaly. *Flow: The Psychology of Optimal Experience*. New York: Harper & Row, 1990.
[52] Cf. ibid. 69.

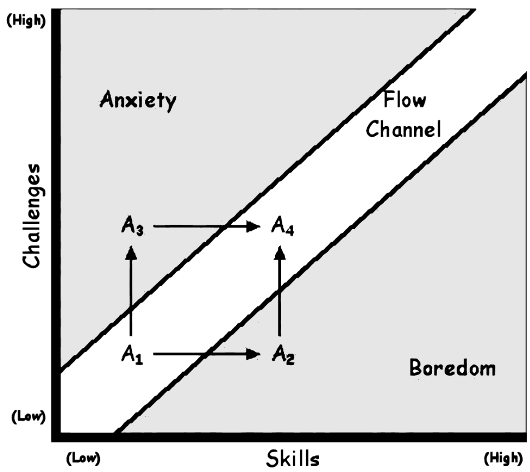

Fig. 11: Csikszentmihalyi's flow theory

According to Patrizia Marti et al., "the 'optimal flow' is the absolute absorption in the activity where the experience is guided by the personal feeling of the external world"; this experience is influenced by the four linked and interdependent dimensions of control, attention, focus, curiosity, and intrinsic interest.[53] On this basis, Csikszentmihalyi characterises nine dimensions of flow experience:[54]

1. Clear goals
2. Immediate feedback
3. Personal skills are well suited to given challenges
4. Action and awareness merge
5. Concentration on the task at hand; irrelevant stimuli disappear
6. A sense of potential control
7. Loss of self-consciousness
8. Altered sense of time
9. Experience becomes autotelic and intrinsically rewarding

In the context of human-machine interaction this means that a potential increase in interaction quality and overall experience can be reached sticking to the cornerstones of Csikszentmihalyi's flow theory. Marti et al. describe the flow experience in relation with the interaction of a person with the seal robot *Paro*, its appearance being that of a baby of a harp

[53] MARTI, Patrizia et al. "Experiencing the Flow: Design Issues in Human-Robot Interaction." *Proceedings of the Joint Conference on Smart Objects and Ambient Intelligence. Innovative Context-Aware Services: Usages and Technologies*, 2005, 69. Web. 30 Aug. 2014. <http://www.researchgate.net/publication/228652519_Experiencing_the_flow_design_issues_in_human-robot_interaction>.
[54] Cf. ibid.

seal covered with pure white and soft fur.[55] Describing the reactions of the users, Marti et al. state that "[p]eople who interact with this robot mostly report a sense of pleasure, enjoyment and involvement. […] They spend time stroking the robot, exploring its behaviour, stimulating the emission of sounds and the movements. Some kiss it and smile even if they are perfectly aware that it is not a living being."[56] To conclude one might say that a flow experience in the handling of a technological object arises when a system enhances the user imagination and the construction of meaning during the interaction with the object.[57]

This conclusion factually hints at another theory being of immediate relevance for human-robot interaction, i.e. the theory of responsive behaviour by Natalya Maisel.[58] Maisel researched the relationship between intimate partners and investigated what impact responsive behaviour has on this partnership and what kind of interaction processes lead to the perception of responsiveness. She determined three essential components of responsive behaviour:

1. Understanding
2. Validation
3. Caring

Understanding relates to the active interest in a conversation, the gathering of information and the correct understanding of it. *Validation* means the ability of the conversational partner to use the related contents as a means to support the partner's self-perception and self-esteem. *Caring* highlights the emotional interests in the communication and the partner's will to communicate emotions, feelings and concern.[59] Guy Hoffman applies this psychological theory to the area of human-robot interaction with the aim of translating the above-mentioned components for this purpose.[60] To create comfortable and enjoyable human-robot interactions, it is necessary to devise robots acting in a manner similar to humans, i.e. listening to conversational partners and displaying appropriate responsive behaviour as this has significant positive effects on the interaction and the personal well-being of the user.[61]

Considering these theories in the ideation of an actual working prototype calls for the choice of an appropriate variety of technologies and frameworks. This has to be done under

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[55] Cf. ibid. 70f.
[56] Ibid. 70.
[57] Cf. ibid. 73.
[58] Cf. MAISEL, Natalya C., Shelly L. GABLE, and Amy STRACHMAN. "Responsive Behaviors in Good Times and in Bad." *Personal Relationships* 15 (2008), 317-338.
[59] Cf. ibid. 318.
[60] Cf. HOFFMAN, Guy et al. "Robot Responsiveness to Human Disclosure Affects Social Impression and Appeal." *Proceedings of the 9th ACM/IEEE International Conference on Human-Robot Interaction,* Bielefeld, Germany, 2014, 1-8. Web. 30 Aug. 2014. <http://guyhoffman.com/publications/HoffmanHRI14.pdf>.
[61] Cf. ibid. 7.

the main premise of an interactive system that provides a high information rate und thus a certain flow of interactivity as well as a clear visual language. The following section will discuss technology and relevant implementations that aim for the goals described above.

3.2 The Interactive System

3.2.1 Sensor Technology

Since the emerging development of modern sensor technology, there is a vast amount of devices. Utilising them in interactive technology means to choose from a large variety, for example divided into discrete and continuous input devices. The prototype in this master thesis will make use of two different kinds of real-time input systems, bioelectrical signals and motion capture. Bioelectrical signals refer to those electronic signals that can be measured at the bodies of (human) beings. Possible measurement methods include e.g. electromyography (EMG), electroencephalography (EEG) or the heart rate.[62] Independent of the individual resolution of the different devices they usually provide a constant stream of data. This makes it possible to perceive even minor changes in the human physique and therefore react to them in real time. Quite recently these technological devices made a remarkable progress in development so that they reached a stadium where they are ready to leave the research lab and thus may become consumer products.[63]

One essential device for the project under discussion will be the brain computer interface (BCI). As Millán points out, "[t]he central tenet of a BCI is the capability to distinguish different patterns of brain activity, each being associated to a particular intention or mental task."[64] This enables to coordinate brain waves with specific levels of bodily arousal, which in turn allows for cued robotic reactions to these activities. This allows for completely new modes of interaction, going beyond such means of control built upon visible bodily gestures. With the help of BCIs an additional degree of freedom is reached in human-

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[62] Cf. ORTIZ, Miguel. "A Brief History of Biosignal-Driven Art: From Biofeedback to Biophysical Performance." *eContact! 14.2 — Biotechnological Performance Practice*, Montreal: CEC, July 2012, 3-8. Web. 30 Aug. 2014. <http://cec.sonus.ca/econtact/14_2/ortiz_biofeedback.html>.

[63] Cf. MILLÁN, José del R., et al. "Combining Brain-Computer Interfaces and Assistive Technologies: State-of-the-Art and Challenges." *Frontiers in Neuroscience* 4 (2010), 1.

[64] Ibid.

machine interaction, which is why BCIs will play an important role in the scope of the project under discussion.

Another technology to be used is motion capture which tracks movement or motion and transforms it into a digital 3D representation. This in turn makes it possible to transform this data into motions or positions of another animated object such as a machine, a robot or a computer program. As there is a variety of devices there is also a variety of techniques to capture movements and motions. They range from cameras, electromagnetic fields and ultrasound up to mechanical systems using potentiometers for capturing and recording.[65] Since Microsoft Kinect went on sale motion capturing can even be realized as a consumer on a semi-professional level.[66]

3.2.2 User Interfaces

The user interface is where human and machine interaction is realised. As most of the communication with interactive products happens visually it is of great significance to design these interfaces in an appropriate manner.[67] While user interfaces in the early computer times were mainly limited to represent information and helping the user to perform tasks in the most efficient way, today they cover a large variety of interactions ranging from tangible interfaces and augmented reality to wearable computing.[68] More and more user interfaces tend towards a mixture of these as they for instance combine screen with ambient representation. These combined interfaces will be an integral part of the prototype under discussion.

3.2.3 Information Visualisation

Today, information visualisation is a holistic practice delivering and representing abstract data in a meaningful way. It can be used to demonstrate relationships among different data and

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[65] Cf. MENACHE, Alberto, *Understanding Motion Capture for Computer Animation*. 2nd ed. Burlington: Morgan Kaufmann, 2011, 3.
[66] Cf. Microsoft. "Kinect for Windows." *Homepage Microsoft.* Web. 31 Aug. 2014. <http://www.microsoft.com/en-us/kinectforwindows/>.
[67] Cf. COOPER, Alan, Robert REIMANN, and David CRONIN. *About Face: The Essentials of Interaction Design.* Indianapolis: Wiley, 2007, 287.
[68] Cf. ROGERS, Yvonne, Helen SHARP, and Jenny PREECE. *Interaction Design. Beyond Human-Computer Interaction*. 3rd ed. Chichester: Wiley, 2011, 157.

makes it possible for the user to grasp overall concepts and connections.[69] Information therefore can be represented in many different ways. At the same time it is of great importance to display it in an appealing and readily comprehensible visual way. As Brian Suda states, “[w]ell designed data should provoke emotions, tell a story, draw the reader in and let them explore.”[70] This becomes all the more relevant considering the fact that humans acquire more information through vision than through a combination of all their other senses.[71] This means also that colour has a vast impact when designing interfaces or visualising data.[72] Colour not only communicates visual information but also evokes certain emotions, behaviours and moods.[73] Being aware of this should prevent us from using colours carelessly. Instead, we are called for putting them into the right context. When it comes to human and machine interaction and to designing an intuitive interface, one appropriate approach could be to orient the design by Plutchik's wheel of emotions.[74]

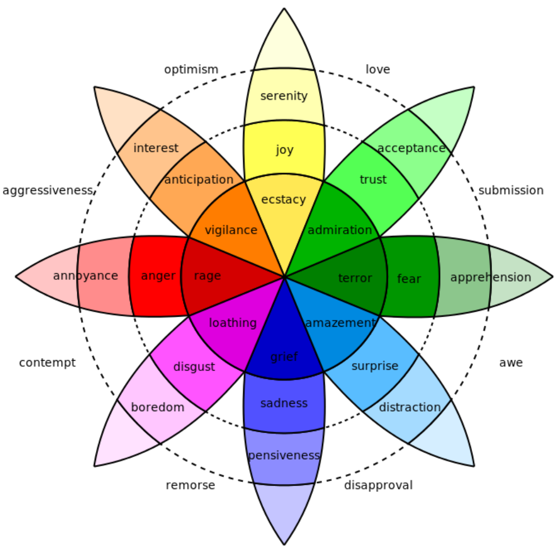

Fig. 12: Plutchik's wheel of emotions

The wheel shows a basic personal system where emotions are listed after the law of neighbouring and polarity. That means that opposing emotions can be interpreted as most

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[69] Cf. SUDA, Brian. *A Practical Guide to Designing with Data.* Penarth: Five Simple Steps, 2010, 1.
[70] Ibid.
[71] Cf. WARE, Colin. *Information Visualization*. 3rd ed. Waltham: Morgan Kaufmann, 2013, 2.
[72] Cf. GAZZANIGA Michael S., Richard B. IVRY, and George R. MANGUN. *Cognitive Neuroscience. The Biology of the Mind.* London: Norton, 2014.
[73] Cf. MILLS, Robert. *A Practical Guide to Designing the Invisible.* Penarth: Five Simple Steps, 2011, 80.
[74] Cf. PLUTCHIK Robert, and Henry KELLERMANN eds. *Emotion: Theory, Research, and Experience.* Vol. 1: *Theories of Emotion*. New York: Academic Press, 1980, 361.

dissimilar while adjacent emotions are more similar.[75] The represented emotions are coloured differently matching emotional states and their intensity. On the background of the facts mentioned above, it is advisable for the created interface to carefully choose the colours in use.

3.2.4 Cue and Beat System

As the whole interactive system of this project is set in a theatrical environment certain parts of the performance need to be cued and controlled in a static manner. In the theatre context a cue stands for a single action that needs to be triggered by a specific event. This cue usually contains settings and positions related to light, music or stage mechanics. In the case of robotics, positions, speech and sensors extend this approach.

As the cue system is strongly linked with a classical theatre approach, however, it can only partly serve a technological and responsive theatre such as the one we are aiming at. Especially when it comes to complex and interactive narrative structures the beat system introduced by Michael Mateas seems to be suitable. He defines it as follows: "In the theory of dramatic writing, the beat is the smallest story unit, the smallest unit of character performance that changes the story."[76] Adapted by the robot researcher Guy Hoffman, the beat system offers a more fluent and precise handling in human-robot interaction. As opposed to a cue, a beat can be seen as a smaller unit, which in our case describes a gesture of the robot and thus offers possibilities to be better timed to the actor's action.[77] A beat thus might improve the interaction by its higher degree of precision. This means that a scene will be subdivided into cues, which are then split up into several beats marking different actions and or animations.

3.2.5 Technological Approach – Scalability, Fault-Tolerance and Kinematics

Working within an interdisciplinary field of art, technology and robotics one has to consider certain approaches when it comes to create software and hardware systems for that specific

[75] Cf. ibid.

[76] MATEAS, Michael. *Interactive Drama, Art, and Artificial Intelligence.* Diss. Carnegie Mellon University, Pittsburg, 2002. Web. 30 Aug. 2014. <http://www.cs.cmu.edu/~dod/papers/CMU-CS-02-206.pdf225>, 225.

[77] Cf. HOFFMAN, Guy. "On Stage: Robots as Performers", 2.

field. From the software and hardware point of view the architecture needs to be fault-tolerant and scalable. Designing for scalability means to design for a later change in processing growth or an increasing number of elements or objects.[78] In the context of the master thesis and the HaM project, this means that there should always be the possibility of increasing the number of sensors, lights or associated microprocessors during iteration or at later stages. Thus it was possible to adapt the robotic system during the second iteration phase and scale it up from a small robotic arm with only two input sensors to a stage filling robot, with ambient lighting and an additional motion capture sensor.

As with all software and hardware systems there is the need for a certain kind of fault-tolerance, especially in the scope of theatre. The play created in the HaM project was planned to be running for roughly 45 minutes. During this time the system needs to be tolerant towards human input or software/hardware failures. The idea is to divide the interactive system into several subsystems, which are able to run independently and provide the possibility of reconnecting or restarting them.

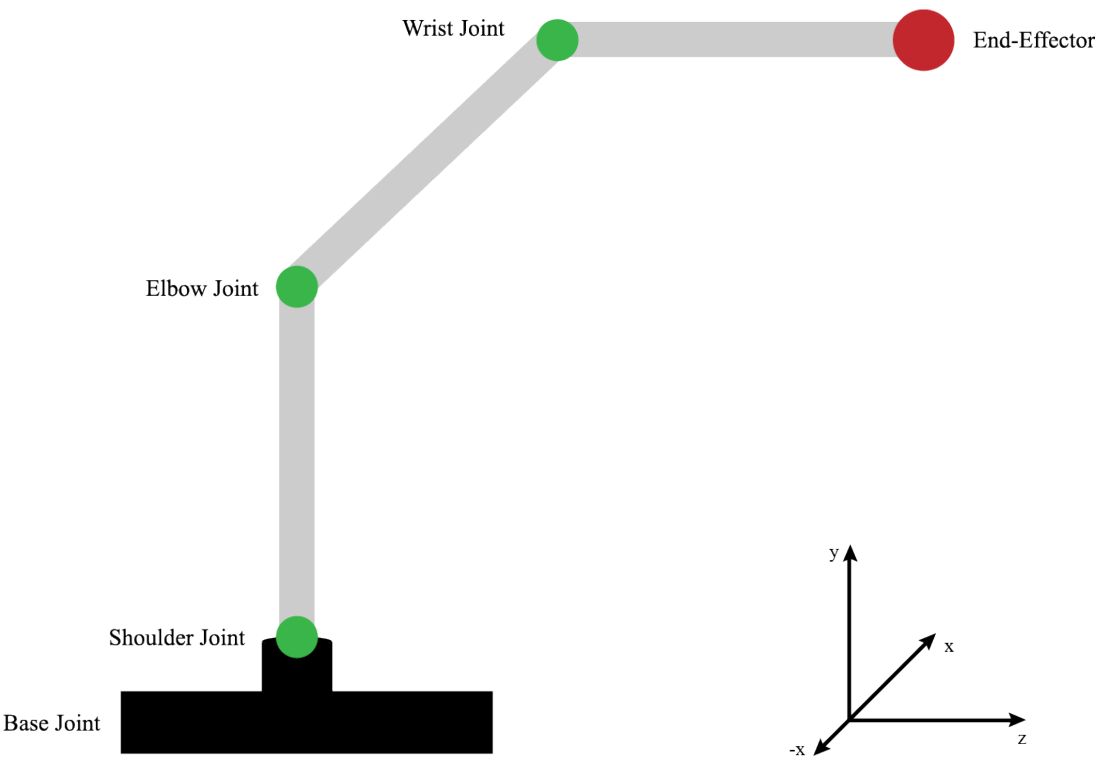

Fig. 13 Illustration of the robotic arm joints

[78] Cf. BONDI, André B. "Characteristics of Scalability and Their Impact on Performance". Proceedings of the Second International Workshop on Software and Performance, Ontario 2000. New York: ACM, 2000, 195.

Next to setting up software and hardware one main concern is to realise a straightforward possibility to animate and move the six degrees of freedom robotic arm. Due to the complexity of this task decisions were made to use inverse kinematics. Inverse kinematics use kinematic equations to calculate and control the position of the end-effector, while the end-effector in our case is defined as the centre of an open gripper tip.[79] The equation for the joint angles of the robot to be specified with the X, Y, and Z coordinates reads as follows:

$$baseAngle = arctan\left(\frac{x}{y}\right)$$

$$r = \sqrt{(x^2 + y^2)}$$

rShlWri = Distance shoulder joint to wrist joint.

The specific angle which forms when the end-effector grips an object from a specific position (gripAngle) needs to be specified manually:

$$rShlWri = r - (\cos(gripAngle) * gripLength)$$

zShlWri = Height from rShlWri to wrist joint.

z = Height from base to grip Point.

$$zShlWri = z - baseHeight + (\sin(gripAngle) * gripLength)$$

The calculation of the elbow angle is as follows:

ulna = Length elbow to wrist.

[79] Cf. PAUL, Richard. *Robot Manipulators: Mathematics, Programming, and Control.* Cambridge: MIT, 1981, 95.

shlElb = Length shoulder to elbow.

$$h = \sqrt{(zShlWri^2 + rShlWri^2)}$$

$$elbowAngle = \pi - arccos\left(\frac{h^2 - ulna^2 - shlElb^2}{-2.0 * ulna * shlElb}\right)$$

With the elbow angle we can determine the shoulder angle:

$$shoulderAngle = arccos\left(\frac{ulna^2 - shlElb^2 - h^2}{-2.0 * shlElb * h}\right)$$

And finally the wrist angle can be determined:

$$wristAngle = shoulderAngle - elbowAngle + gripAngle$$

The result is the elbow, shoulder and wrist angle in radiance, which can be applied to setting the server motors of the specific joints. This allows to set animation and position points of the robot arm in a Cartesian coordinate system.

4. Design Methods

As the field of research of the HaM project is rather new and not very typical of interaction design a lot of common interaction design methods cannot be easily applied to the prototype intended to be develop. They do not fit well or need to be configured to the iterative process under discussion. As considered basic methods of typical design processes such as brainstorming, mind mapping etc. are actually not custom-tailored for interaction design some more specific techniques were referred to which were potentially valuable for an application in the scope of the project under discussion. They will be briefly presented in the following.

4.1 Persona

During the ideation phase it is important to find a methodology that supports and functions well within the unusual field of human-robot interaction. As the project under discussion focuses on a normal robot arm as a prototyping tool it was important to make this very abstract version of a robot more accessible for people who are not familiar with this subject area. To reach this goal, a persona was created. They are generally described as follows: "Personas are rich descriptions of typical users of the product […]."[80]

4.2 Research through Design

Research through design can be circumscribed as a continued iteration throughout the entire design process. By continuously developing, experimenting and investigating new designs and prototypes one applies a basic and well-functioning method of interaction design.[81] This method lives from the constant critique of others, the reframing of problems and countless iterations on the design process. It can also be easily adapted to certain requirements of specific environments, to time as well as to resources.

4.3 Design Workshops

The design workshop can be used as a recurring routine supporting the project during all stages of the design process. They are "a form of participatory design consolidating creative

[80] ROGERS, Yvonne, et. al. *Interaction Design,* 390.
[81] Cf. MARTIN, Bella, and Bruce HANINGTON. *Universal Methods of Design. 100 Ways to Research Complex Problems, Develop Innovative Ideas, and Design Effective Solutions*. Beverly: Rockport, 2012, 332.

co-design methods into organised sessions for several participants to work with design team members."[82] Within the workshop all participants engage in the overall design focussing on the background of the specific project. They might collect ideas with the help of classical methods like brainstorming, mind mapping etc. This helps strengthening the inter-project communication and the collaborative working process and it furthermore sharpens the participants' minds for an intense creative thinking.

4.4 Wizard of Oz

The name of the Wizard of Oz-method is actually taken from the classic story about "a small shy man who operates a large artificial image of himself from behind a screen where no one can see him."[83] Applying the method, users experience a fully working prototype, which in reality is controlled by a researcher behind the scenes.[84] This apparently completely realised product can help triggering the creativity of an actual user who might now not simply criticise the product by filling in missing parts by imagination. Instead, the allegedly fully working product allows for a certain degree of freedom to envision completely new aspects of the product, which might not have been thought of before. But as the Wizard of Oz method is mainly limited to evaluative contexts and the project is set in the theatrical environment it is necessary to adapt the method to the theatrical context.

4.5 The Theatre System Technique

The Theatre System Technique extends the Wizard of Oz method as it provides the possibility not to hide the researcher who controls the system but rather to integrate him actively in the user testing process and thus giving him the possibility of playing through different scenarios or use cases "as if playing a role in theater."[85] Considering a representative design process it becomes clear that this technique might be used both for evaluation and design.[86]

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[82] Ibid. 140.
[83] ROGERS, Yvonne, et al. *Interaction Design,* 395.
[84] Cf. ibid.
[85] SCHIEBEN, Anna, et al. "The Theater-System Technique: Agile Designing and Testing of System Behavior and Interaction, Applied to Highly Automated Vehicles." *Proceedings of the 1st International Conference on*

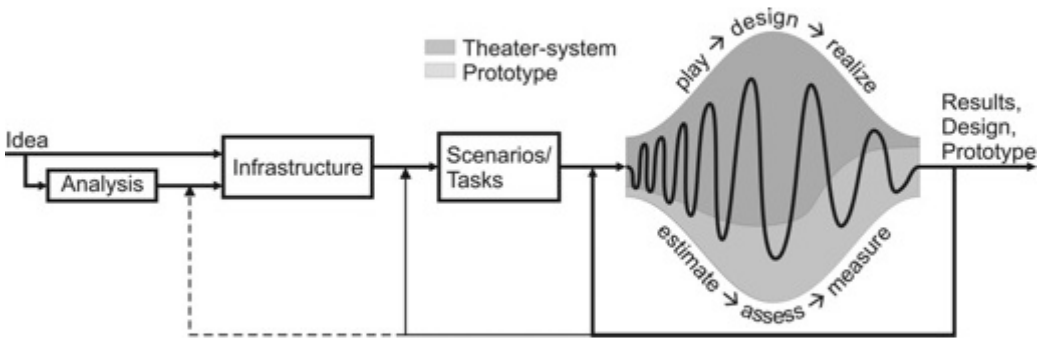

Fig. 14: Schematic depiction of the design process using the theatre-system technique

With the help of the illustration of fig. 13, Anna Schieben explains a typical design process with the theatre-system as follows:

> Based on initial ideas and an early analysis of the design challenge, an appropriate infrastructure has to be set up and adapted. This includes the adaptation of the theater-system itself for the emulation of the automation behaviour and interaction in the chosen scenarios and tasks. During the iterative design process, prototypes played by the confederate in the theater-system and software prototypes work as complement. Starting with a more open play with design variables and estimation of their effects with the confederate, design options are designed in detail and their effects assessed, until the design can be condensed, realized in software and its effect measured. This loop […] can be iterated as often as necessary.[87]

5. Project Planning

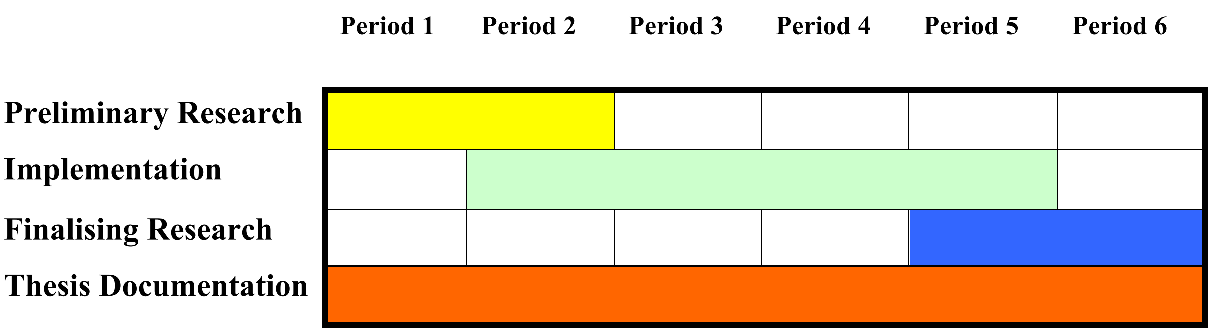

Fig. 15: Initial time plan.

Automotive User Interfaces and Interactive Vehicular Applications, Essen, Germany, 2009. New York: ACM Press, 2009, 44.

[86] Cf. ibid.

[87] Ibid.

The HaM project was composed over a period of four month and divided into two main milestones and iteration phases. Finishing each of the two milestones, it was planned to present the project to the public, to evaluate on the feedback and to continue with the next design phase taking into account the outcomes of the evaluation. Additionally, a plan for the entire master thesis was composed involving three main stages: A preliminary, an implementation and execution stage and a finalising research phase. The project plan will be presented in detail in the following section. Fig. 14 gives an overview of the working process. One period covers a time span of four weeks.

5.1 The Human and Machine Project (HaM)

From the beginning of the HaM project some specific goals targeted were to share and publish the actual state of affairs. The reason for this was that the project itself was deeply connected to the idea of an open source concept and therefore tried to be as accessible as possible in every stage of the design process. Therefore one milestone was to present a first prototype at the *Nordic Larp Talks* in Gothenburg at the beginning of April and a second one including two full time performances at the *Science Festival* in Gothenburg in May 2014. The final prototype was shown at the *Inter Arts Centre* in Malmö.

5.2 Preliminary Research

As the master thesis is set in an interdisciplinary research field and combines a diversity of skill sets, the first step will be to get a good overview over existing projects, literature, technology and delimitations. Similar projects like Guy Hoffman's *On Stage: Robots as Performers* ranging in a very comparable field of research could provide interesting insights in technology and working balance between performing arts and technology. Additionally research will be undertaken to delimit an appropriate technological framework of the thesis. This process will include:

1. Finding state of the art BCI and bio signal technology and devoting time for familiarising with the handling of this technology

2. Finding ways to visualize information of the sensor data
3. Investigating an available robot arm and its kinematics
4. Learning of animation principles and efficient ways to combine and control them within the theatre play
5. Investigating motors to control the robot
6. Exploring the potentials of an interactive ambient stage environment
7. Finding ways in creating a robust software and hardware architecture
8. Researching human-robot interaction principles

The purpose of the preliminary research phase will be to find a starting point and rough outline on how to structure the HaM project. Therefore most of the above points should be answered during the first month of planning. This is all the more important as the overall idea of the project will be shifting constantly. Once a technological direction and aesthetics will be found, the working process of implementing the initial prototype will be continued.

5.3 Implementation and Research

The following three months will be spent for implementing the ideas collected in the pre-study phase and for creating the different prototypes. As a working environment the maker and hacker space *Collaboratory* in Gothenburg was chosen as it provides a creative environment with the necessary equipment and enough room for rehearsing and testing. Firstly, all the relevant components to have a fully working theatre play and a robot equipped with the most important sensors will be collected. Thus the goal of a first iteration phase will be to assemble a small robot arm with ambient expression, EEG and pulse meter sensors and then scaling up in the next iteration. In this way, research can be continued and the project can be accomplished even if unexpected problems will be encountered. The next step then will be to experiment with a bigger stage environment and robot and to add further sensors. In this phase different scenarios of human-robot interaction will be tested and validated within the scope of the corresponding theories. At this point in the project, all timings like cue and beat animations as well as dialogues and the overall storyline will need to be prepared and finalised. In the final iteration, the scenario the robot will be integrated into will be specified and intensified. Afterwards, a concluding presentation with an overall evaluation of the interactive system will take place. The finalising phase will be used for evaluations within the field of human-robot interaction involving audience and actor feedback. Nevertheless the main part of this phase will be devoted to finishing the master thesis report.

6. Execution

6.1 Concept Development

The first step of the project was to meet up with all stakeholders. I was introduced to the topic by Carl and Robert and we set the topical and temporal cornerstones of the master thesis. The time for the development of the robot and the corresponding theatrical performance was delimited to roughly three months until the first complete presentation of the collaborative work. After setting the time plan, an overall concept on how to find appropriate methods, theories and technology as a basis for the project was set up. One important cornerstone were the regular design workshops. During these workshops findings were discussed, deadlines set and ideas and interaction possibilities brainstormed. This can be seen as the core structure of the entire design process as it evolved during the whole project phase.

The workshops were prepared by individual research of the stakeholders. This implied to read literature and investigate similar projects and contemporary technologies. I focused on researching projects like those of Guy Hoffman who had conducted research in a similar field and was thus potentially interesting for the HaM project. Additionally, I researched within the field of theatre and technology so that Robert and I would have a foundation to base our collaborative work on. With the help of the previous research, it was possible to define the scope as well as the limits of the collaborative project. Because of the complexity of merging these two areas it was soon decided to work with a scalable robotic and technological approach that would be adequate for beginning to test and develop the theatre piece but might also be extended beyond that stage. Based on this decision, I continued by searching for theories that would be appropriate within the field of human-robot interaction. A first assessment showed that Csikszentmihalyi’s flow theory, Plutchik's wheel of emotion as well as Maisel’s theory of responsiveness could be suitable for the project and deliver a basic understanding on how human-robot interaction can be successful and how new strategies could be developed.

During this preliminary stage of brainstorming and discussion, a crowd funding campaign to raise some more money for the project was initiated and, as a side effect, other persons who were interested in the project were searched. They were also intended to participate in an ensuing design workshop that was planned to create a persona for the robot.

6.2 First Iteration Phase

6.2.1 Responsiveness of the Robot

The main idea of human-robot interaction is based on the robot's ability to perceive/interpret and respond on/express messages in an appropriate manner.[88] Therefore I searched for projects similar to the HaM project. Cynthia Breazeal's et altera's *Interactive Robot Theatre* and Guy Hoffman's *Robot Responsiveness to Human Disclosure Affects Social Impression and Appea*l gave a vital insight into the topic. As the robot's responsiveness and understanding of the situation would have a direct impact on the overall flow of the interaction it was important to deepen the research in this field. Focussing on related research made within the field of HRI what became clear was that socially interacting robots, like those in a theatre environment, encounter three main problems:[89]

1. Articulation problems
2. Intentionality problems
3. Interpretation problems

The articulation problem refers to the fact that current robots are often limited in their technology and range of motion so that they are unable to express themselves in a similar way like human beings. What becomes clear is that this approach suggests that in the field of human-robot interaction human-like articulation is strived for. If problems are solved in an abstract way, humans are less likely to understand. However, they might still be able to interpret or learn the respective signal.

The intentionality problem highlights that certain robot intentions are often vague or not clear for the respective recipients and thus result in failures of understanding or misunderstandings on the human side.

[88] Cf. BREAZEAL, Cynthia et al. "Interactive Robot Theatre", 80.
[89] Cf. LU, David V., et al. "Human-Robot Interactions as Theatre", 473.

The interpretation problem correlates with the miss-interpretation or lacking understanding of human actions and intentions by the robot. This often leads to inaccurate responses of the robot and thus affects the human robot symbiosis negatively.

Solving these problems is a prerequisite for a successful human-robot interaction and thus needs to be given special attention within the project. Inside the small given time frame until the first presentation it was decided to start with a small six DoF robot arm that provides a certain flexibility and could later easily be modified. Additionally, the idea of putting two RGB LEDs to the robot's end effector emerged so that the impression of two eyes facing an observer could be created. With the LEDs it is possible to express certain emotional and behavioural stages mostly related and coloured after Plutchik's wheel of emotion and thus making it easier for the recipient to interpret certain intentions of the robot.

6.2.2 Shaping the Robot's Awareness

From the beginning of conceptualising the human-robot interaction new ways in making the robot aware of the human's intentions and actions were researched. We wanted to research a solution by which each person interacting with the robot is given the chance of communicating its very individual state of feelings and emotions. One possibility that was discussed was to measure the bio signals the human body provides such as the conductivity of the skin, pulse or brain activity. With the help of this data the robot should be made aware of certain arousal levels of the human physique. A first step here was to look for suitable BCI devices with a high resolution. Two devices were ordered, an OpenBCI, which sadly did not arrive until the end of the project, and a MindWave from NeuroSky. The MindWave is a consumer non-invasive BCI headset that measures the activity of the human brain. It provides two different output modes: One raw output with a sample rate of 512Hz and a 1Hz pre-calculated signal that uses NeuroSky's internal algorithm eSense. The eSense algorithm provides a low noise signal of the different brain waves and three easy to control values: attention, meditation and eyeblinks. The attention level can be seen as an equivalent to concentration while mediation refers to a state of relaxation. When I tried the MindWave for the first time it became clear that some practice would be needed to easily influence both values equally. Additionally it seemed that triggering the attention or meditation level slightly differs from person to person. Next to the MindWave a pulse oximetry was used to measure the vitality of the human body mainly by looking at the real-time heartbeat and pulse. The main idea was to combine the BCI device with the pulse oximetry and therefore create a more precise measurement of the human body's arousal level.

Together with Robert Bolin, I arranged an experimental set-up (fig. 15) in which different arousal/emotional scenarios with the MindWave BCI and the pulse oximetry were recorded non-empirically. Robert Bolin who will later also be the actor in the theatre performance tried to set himself into different emotional stages by adapting certain acting methods. I wrote a program that recorded the data of both sensors and stored them in a file for later evaluation. For the visualisation during the recording and at the first presentation I used the free Processing-Brain-Grapher by Eric Blue,[90] which I later modified to fit the individual needs of the project. This programm will also serve as a control system for the robot and other technology and will therefore be refered to as Multimodal Control System.

Fig. 16: Experimental set-up with *Multimodal Control System*

The following graphs show some of the main measurements that were taken focussing on the heart rate and the MindWave's attention and meditation level. All recordings are made in a one-minute time frame.[91]

[90] The program can be downloaded from GitHub: BLUE, Eric. "Processing-Brain-Grapher." *Homepage GitHub.* Web. 31 Aug. 2014. <https://github.com/ericblue/Processing-Brain-Grapher>.

[91] The following abbreviations are used for describing the graphic representations: HR = heartrate, AT = attention level, ME = meditation level.

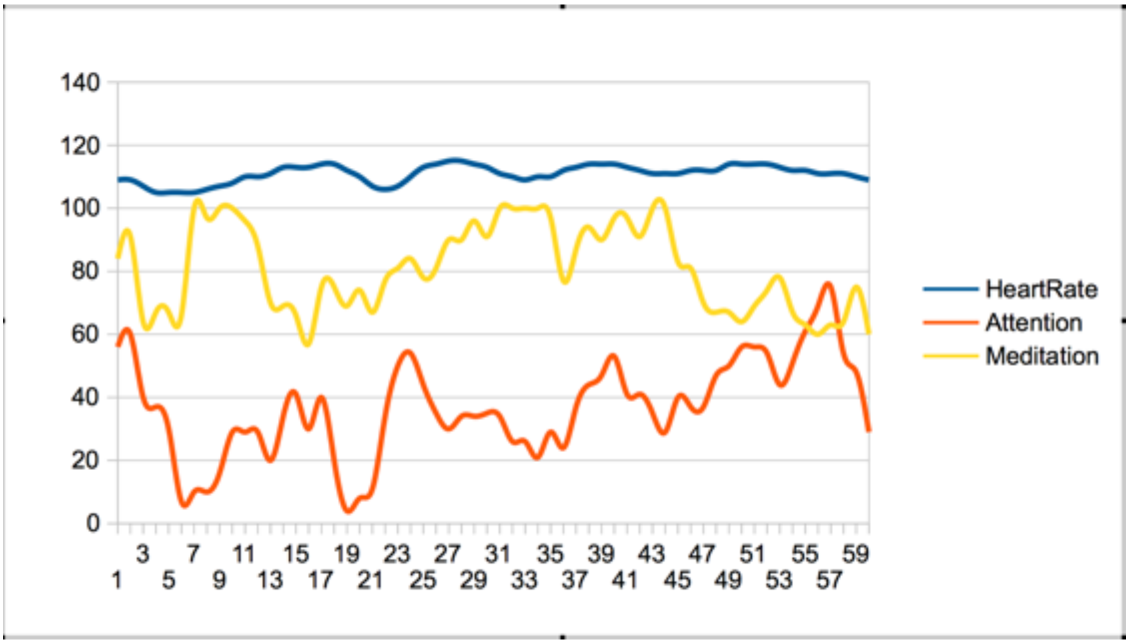

Fig. 17: Neutral mood. Average: HR 110; AT 36,7; ME: 80,75

In fig. 16 one can see that Robert's pulse remains rather stable over the whole measurement period and only minor changes in the amplitude can be recognized. It should be mentioned that Robert generally has a very high pulse rate at rest usually circling around 100 BPM. Additionally one can say that by looking at the meditation and attention level Robert shows a rather high meditation level so that he tends to be relaxed in a neutral state.

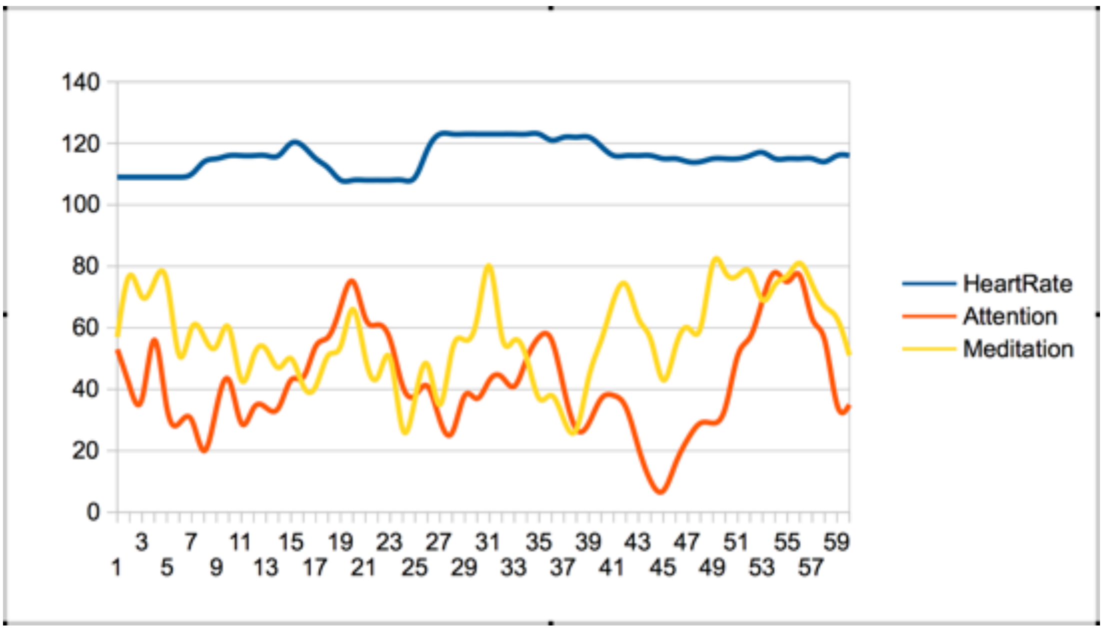

Fig. 18: Anger. Average: HR 115,5; AT 42,35; ME: 57

Fig. 17 shows that once in an angry state the heart rate rises distinctly compared to the neutral state of fig. 16. Furthermore, both meditation and attention level shift a lot and therefore support the general impression of a high arousal level.

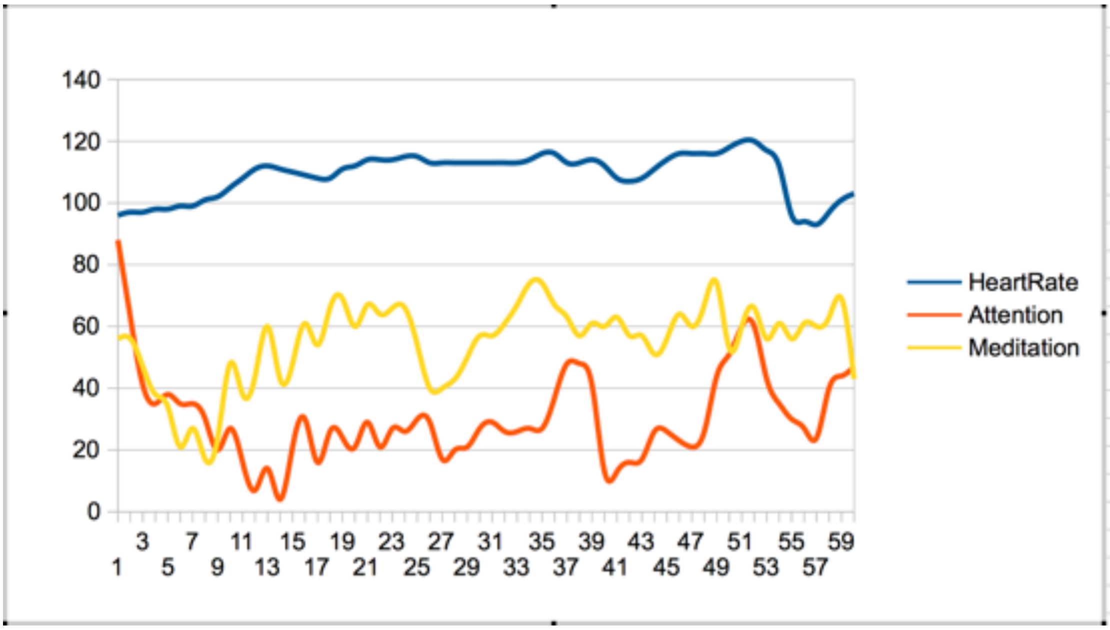

Fig. 19: Happiness. Average: HR 109; AT 30,5; ME 54,9

Considering fig. 18 one can see that in a state of happiness the heart rate rises above the normal level but not as intensely as during anger. While the attention level is rather low the meditation level is obviously more present and reminds of a less intense neutral state. In general, happiness can be seen as a neutral level with a more present arousal level.

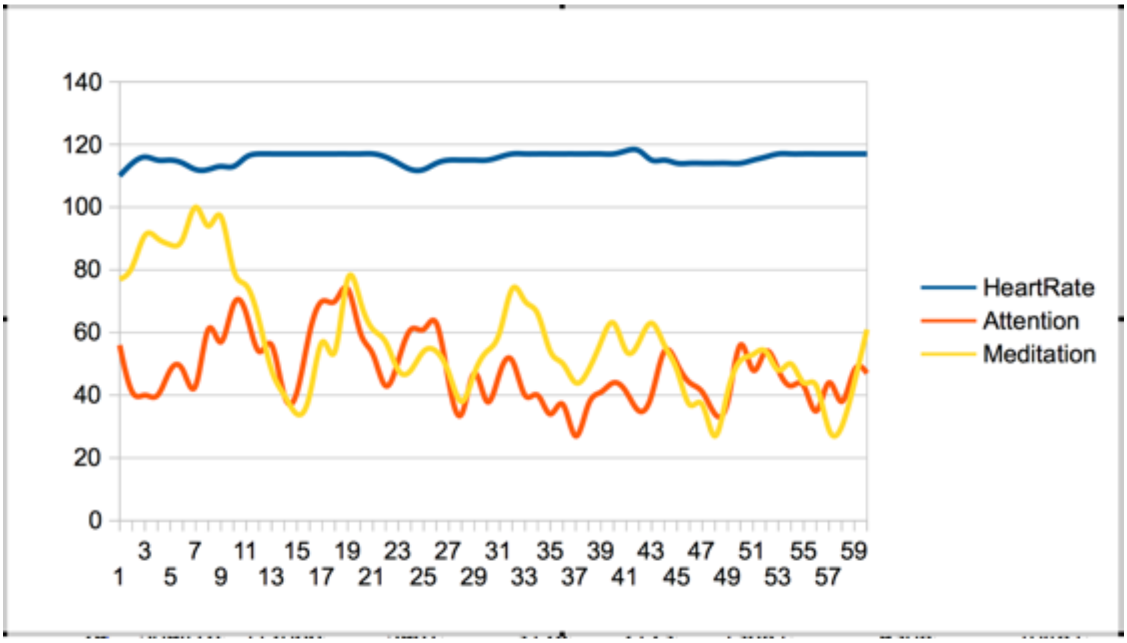

Fig. 20: Sadness. Average: HR 115,5; AT 47,8; ME 57,8

Interpreting fig. 19 it becomes clear that both meditation and attention level noticeably lower over the displayed period. As there cannot be made a direct connection to the state of sadness it should be mentioned that the intensity Robert put into expressing sadness significantly rose over time. In contrast to this the heart rate was constantly on the same level.

When conducting the experiment I was quite sceptical about its outcome, as I was not convinced that the MindWave as a consumer BCI product would really show a difference among the expressed moods. Nevertheless, after evaluating the graphs it became clear that it is possible to at least differentiate between a general arousal level ranging from a relaxing calm state over a neutral up to a high level of excitation. Considering the very detailed information displayed by the graphs one might as well distinguish between the different emotional states. However, when recording the material, Robert had to reduce his body and muscle movements to a minimum. The reason is that any bigger movement as it tends to happen during any intense emotional state influences the measurements and reliability of both the MindWave and the pulse oximetry. The single sensor of the MindWave tends to slip during body movements and face contractions while the pulse oximetry was attached to the finger and therefore sensitive for quick arm movements. With different devices especially a more precise BCI such as the OpenBCI, better results could be reached.

6.2.3 The Robotic System

I assembled the small 6 DoF robot arm and started exploring the general kinematics as well as running a first test on controlling its servomotors. It soon became clear that it would be hard to animate movements and actions without a system that simplifies controlling the different servomotors. The solution was to implement an inverse kinematic system that provided the user with the possibility of setting X, Y and Z values in a Cartesian coordinate system. As a consequence it was possible to measure a designated position to which the robot should move. All the joints used by the IK equation would be exactly aligned by designated servomotors.

A problem that occurred here was that the IK equation as described in the theory section could not be adapted on a one to one basis as the length from elbow to wrist was not the same like the length from shoulder to elbow as the equation assumed. Therefore the equation needed to be changed in the following way:

$$ulnaEven = ulna + (wristOffset * sin(gripAngle))$$

$$zEven = z - (wristOffset * cos(gripAngle))$$

This helped to even out the length differences from elbow to wrist and resulted in a more precise positioning of the robot arm.

After the basic functionality of the robot arm was settled, I started mapping the values from the different sensors into its motion. For the first iteration we aimed at presenting a robot arm that was connected to an actor via the MindWave BCI and the pulse oximetry. The robot should react to the arousal level of the actor and therefore approach him if he is in a relaxed state or on the other hand draw back if not. As described above, for intensifying this behaviour I attached two RGB LED eyes at the front of the robot.

6.2.4 First Performative Evaluation

In this stage of the design process, the first presentation of the project was held at the *Nordic Larp Talks* after nearly two month of preparation and work. Accompanied by a talk by Carl Heath, the first prototype of the robot was shown in front of a larger audience. The robot was mounted to a wooden board and exhibited an oscillating movement from left to right depending on the sensor input and the grade of relaxation the actor provided. During the presentation the MindWave lost connection due to some interferences with other radio frequency devices. From that point on the robot received only data from the pulse oximetry and could not realise its complete range of motion. As Robert, who interacted with the robot in the performance, was not instructed on how to control and affect the robot he did not notice the technical problem and continued normally. This allowed us to finish the presentation and proved that even with only one sensor as input a certain grade of interaction was still possible and the lacking of the second sensor was not necessarily recognizable. All in all, the system should continue working even if one of the sensors stopped temporarily or entirely.

6.3 Second Iteration Phase

6.3.1 Preliminary Considerations

Evaluating the performance at the *Nordic Larp Talks* showed that there were two main aspects that needed to be changed on the robotic system. The first aspect was that according to the problem of articulation the range of motion and expressiveness of the robot itself needed to be increased. This would also become essential for the theatre performance as the robot in its current state was not perceptible enough.

Additionally, it was planned to design a comprehensive persona of the robot's personality. In fact, the conventional method of creating personas was adapted for the design of the robot in the context of the underlying project. It was modified from its original purpose of visualising a typical user description towards a persona that describes the needs and scenario of the robot itself. By this it was intended to firstly develop a more detailed image of the robot so as to be able to build an appropriate interaction of the robot and the actor. Together with two contributors of our crowd funding campaign we arranged a design workshop in which this potential persona of the project's robot was created. The design workshop's outcome was an enhanced and more graspable persona of the robot describing its needs, habits and emotions. Thus the participants imagined the performance robot's persona as OBO, an old painting robot made of spare parts who expresses feeling through simple animated motions. For example when he is happy he dances and swivels, while he crunches and backs-up when he feels intimidated or afraid. Moreover, OBO can speak and control certain parts of its ambient surroundings. The creation of a persona for the robot made it possible to narrow down its actual use in the play and the interaction itself. Based on the persona, general ideas and experiences made at the *Nordic Larp Talks,* a redesign of the robotic system was initiated.

6.3.2 Redesigning the Robotic System

When reconsidering on how to enhance the robotic system the attention was shifted towards the possibility of giving the robot a wider range of motion. First, I thought of replacing the small robot arm with a bigger industrial one. For this goal, an old Mitsubishi Movemaster was acquired at the *Chalmers Robotförening*[92] and the working process of integrating it to the robotic system was started. Due to time constrains and missing spare parts I had to refrain from that idea. Instead, a $2m^3$ truss was built which is equipped with a dolly system that can slide easily in an X and Y direction and contains a mount to which the robot arm is attached upside down (fig. 20). The dolly system is connected to three stepper motors that are fully controlled by the MCS and enable the robot to go to any position within the X and Y coordinate area.

Fig. 21: Dolly system with robot arm

Fig. 22: Illuminated robotic system

To broaden the functionality of the truss, RGB LED strips were attached to each corner and around the robot arm. They illuminate the theatrical scene and can be linked to the robot's actions or might be directly controlled. The wider range of expressivity provided by the truss

[92] Cf. Chalmers Robotförening. *Homepage Chalmers Robotförening*. Web. 30 Aug. 2014. <http://chalmersrobotics.se/?page_id=486>.

system made it possible to explore new correlating sensors and methods. An interesting way to integrate the truss in the performance was the use of motion tracking systems as they provide the system with an exact position of the actor. Thus I experimented with Microsoft's Kinect[93] as it is a promising and easy to handle motion capture system. With the Kinect, the motion of the actor's head was tracked and translated into correlating robot movements. Hall's concept of personal spaces adapts here perfectly: The system needs the accurate position between the robot and the actor for recognising the respective personal space and thus for triggering specific actions of the robot. For realising this, I created an animation pattern by which the robot exhibits his movement according to the position of the actor. In combination with the other sensors a system could be created in which the robot is not only aware of its own personal zones but also of the actor's arousal level. To visualise which signals the robot received during the performances the sensor data was mapped into visual depictions and ambient illuminations for the audience and actor. Therefore I redesigned the interface of the MCS so that it would illustrate the output of all three sensors. This had the purpose of the technician having an overview of the system and being able to check possible malfunctions. Furthermore, this enabled the audience to see and interpret the data from the sensors. Additionally, I created a different way of visualising the pulse oximetry through the stage illumination of the truss. Depending on the real-time heart beat of the actor the lights were pulsating and thus providing an subliminal connection to the physical state of the actor.

6.3.3 Introduction of the Cue and Beat system

After rethinking the robotic system, Robert Bolin and I needed to focus on the actual representation of that system in his theatre performance. It consists of different scenes being again divided into several sequences. These sequences contain cues subdivided into two beats that contain actions, positions and speeches of the robot. The beats might again be distinguished into a) discrete, timed and turn-taking beats like a specific position or action and b) continuous fluent beats which are real-time synchronised with the actor.

I started by implementing a cue and beat sequence into the MCS which could easily be changed and mangaged by an external textfile. Using a specific syntax Robert could devise

[93] Cf. Microsoft. "Kinect for Windows." *Homepage Microsoft.* Web. 31 Aug. 2014. <http://www.microsoft.com/en-us/kinectforwindows/>.

actions and positions for the robot which I implemented into the program. The cues could then easily be controlled within the MCS.

6.3.4 Second Performative Evaluation

The prototypes 0.2 and 0.3 were presented in the *Theatre Jaguar* during the *Vetenskapsfestivalen* in Gothenburg (fig. 22).

Fig. 23: Performance in the *Theatre Jaguar*

Unfortunately mainly because of the limited time frame it was impossible to present a completely finished play and correctly working robot. So we decided to create all the necessary cues to show half of the theatre piece and to skip the movements across the truss as the system was not fully fault-tolerant at that point. The performance was divided into two scopes of activity. Firstly, most of the performance was controlled by cues with a turn-taking beat triggered by me as technician. The timing of these cues had to be apprehended by Robert and me and could not be perfected at the given stage. Secondly, there were cues with a fluent beat. Once one of these cues was prompted the robot was only reacting to the sensors' input and could then trigger different story lines, speeches or positions depending on the actor's arousal level and/or relaxation. Thus it was possible to create a dynamic narrative structure.

6.4 Final Iteration Phase: Refining the System

6.4.1 Preliminary Considerations

The performance was conducted with no rehearsal time at all. Consequently, a lot of problems concerning the representation of the robot as well as technologic failures occurred. It became apparent that after a long running time the sensor technology occasionally emitted some false data that was not handled correctly by the MCS system and thus led to some critical crashes. Additionally, some parts of the ambient LED illumination system were not stable enough to endure the entire theatre play. This resulted in an on and off flickering. As this in fact created an interesting look, we decided to integrate this effect into the performance. One main problem during the performance was clearly that the robot and the actor had no equal standing in the play with regard to bodily movement: According to the feedback of the audience collected in the discussion round at the end of the performance the robot was sometimes not able to convey its full intention mostly because it was constantly stuck at its position and only able to move the robotic arm. Opposed to this, the actor could move freely during the entire performance. This highlighted the possible impact of a working truss for the performance and its effect on the audience. Another feedback given by the audience was that the data visualisation they saw was not understandable enough and the purpose not fully clear. As there was no time for designing the interface in the second iteration stage, the visualisation became too small and too confusing as it e.g. displayed all the output data of the MindWave instead of just the values influencing the robot. A last

6.4.2 Finishing the prototype

After completing the truss and implementing the effect of the flickering lights into the final prototype version, the fixing of the deficiencies of the robotic system which had shown during the second performance at the *Theatre Jaguar* was the most important step in this final iteration. I undertook several test runs examining the overall stability of the system and to clearly define the fault sources of the robotic system. To prevent a lack of performance in the technical devices or the crash of the program during the theatre performance, the different processes related to the task of communication such as moving the truss, animating the robot arm or controlling the lights were put into separate threads. Furthermore, I changed the cue and beat system, which in turn allowed the technician to manually skip an animation even though it was still running. In that way it was possible to adapt to the individual speed of the actor's performance and creating a better flow experience. Establishing more concrete animation principles like eased movements and faded transitions strengthened this approach. For the parts of the play in which the sensors exclusively control the robot I included some light animations that are coherently coloured to mirror emotion states of the robot and support the performed situation.

6.4.3 Third Performative Evaluation

When presenting the play in Malmö we experienced for the first time a continuous flow in certain parts of the performance but also still some uncertainties that showed the individual difference of the fluent beats. When controlled just by sensor data, certain fluent beats are only triggered if a discrete value, e.g. a certain pulse is reached. If this does not happen the play gets stuck until the actor reaches the value. In our case Robert was not able to trigger one of those values thus we had to quit the program, lower a certain threshold and restart from the last cue. In a newer version of the MCS this problem is solved as the technician is allowed to trigger manually even in the middle of fluent beats or to change certain thresholds. All in all, the last performance showed that there is scope for improving animations, timings and in the long run refining the benefit of the sensors for example by adding additional ones.

Considering the time planning aspect it is necessary to mention that due to the complexity of the project I was constantly behind the schedule. This was partly a result of the interdisciplinary work done in the *Interactive Institute* and the HaM project as next to building the robot other related tasks needed to be finished. Therefore it was impossible to finalise the thesis and report within the given time.

7. Result

In the final concept of the HySens system the actor controls the robot, which is divided in two parts, robot arm and truss, by using different sensors measuring the actor's position, heart-rate and brain activity. During the entire theatre performance the HySens system will be controlled by a technician (me) with the exception of individual parts in which the robot reacts and speaks only according to the sensor data. This independent action is based on different interaction strategies. The controls for the technician as well as the sensor data are visualized during the entire performance to give the technician and the actor a visual response but also to enrich the experience for the audience as they get a better impression of what happens on stage. Additionally, an illumination system will be installed at the robot arm and truss to dynamically integrate the stage environment into the performance. The final implementation of the HySens system contains several different parts of software and hardware. These parts are responsible for controlling the robot, the sensors, the stage environment and the cue system. In the following section, a deeper insight into the architecture of the interactive system will be given. Furthermore, the techniques of human-robot interaction used in the performance will be explained and substantiated.

7.1 The Hardware System

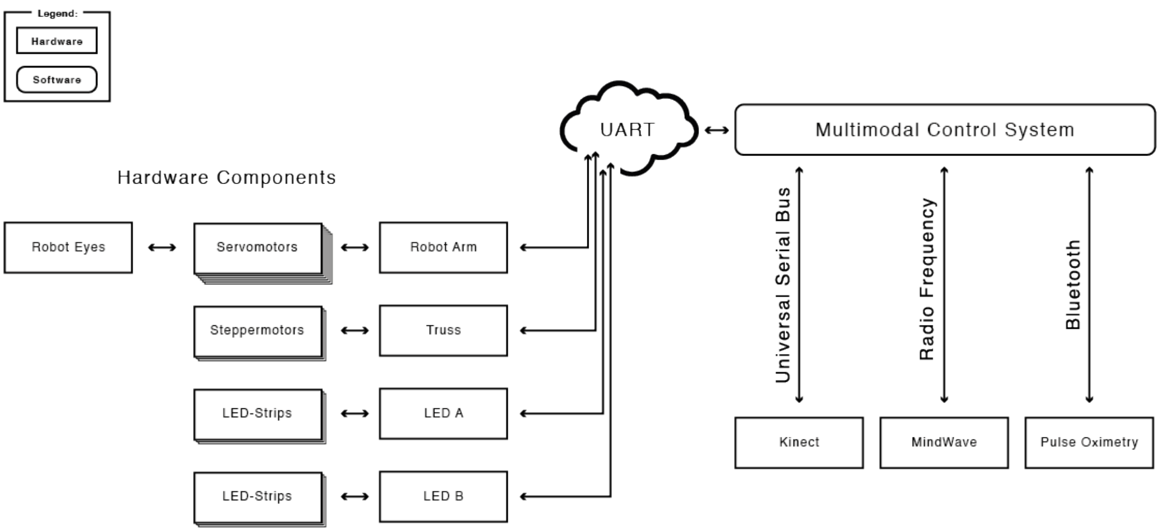

Fig. 24: Scheme of the hardware layout

Considering fig. 23 one can see that the hardware system is separated into several sovereign parts:

1. The robotic system, which in turn is separated into the robotic arm and the truss system
2. The light system divided into a light group A and a light group B
3. The sensor system

The sensor system was ready-made as each of the sensors was already a discrete and fully functional system. The rest of the hardware was completely built and developed during the project and refined step by step in each iteration phase. All hardware systems except the sensors are controlled by microprocessors based on the open source platform Arduino. Each of them runs a program written in C++, which enables the microprocessor to communicate via the serial protocol UART with the MCS. A tailor-made communication protocol allows the MCS to send and receive serial messages, which control the microprocessors and check for its status and functionality.

7.1.1 Robotic System: The Robot Arm

The robotic arm is made of aluminium, has 6 degrees of moving freedom and a servomotor at each joint. The system is controlled by an Arduino Mega 2560, which is connected via serial to the MCS. Depending on the calculations made by the MCS the microcontroller can move the robot arm by sending a specific pulse width of microseconds to the right servomotors. Each motion of the robot arm can be eased so that the movement looks more natural and smooth. Therefore the Arduino is able to calculate a certain resolution of eased positions, which then can be applied to the multiple joints. The resolution of the eased positions can additionally be used to set a general velocity of the animatronic.

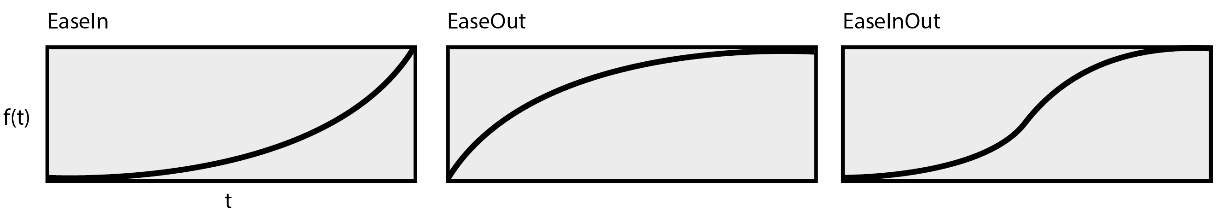

Fig. 25: Cubic ease function

All eased animations are based on the cubic ease function as seen in fig. 24. Two RGB LEDs representing eyes are attached to the robot arm. They are not connected to the rest of the light system and thus controlled separately by the robot arm's microcontroller.

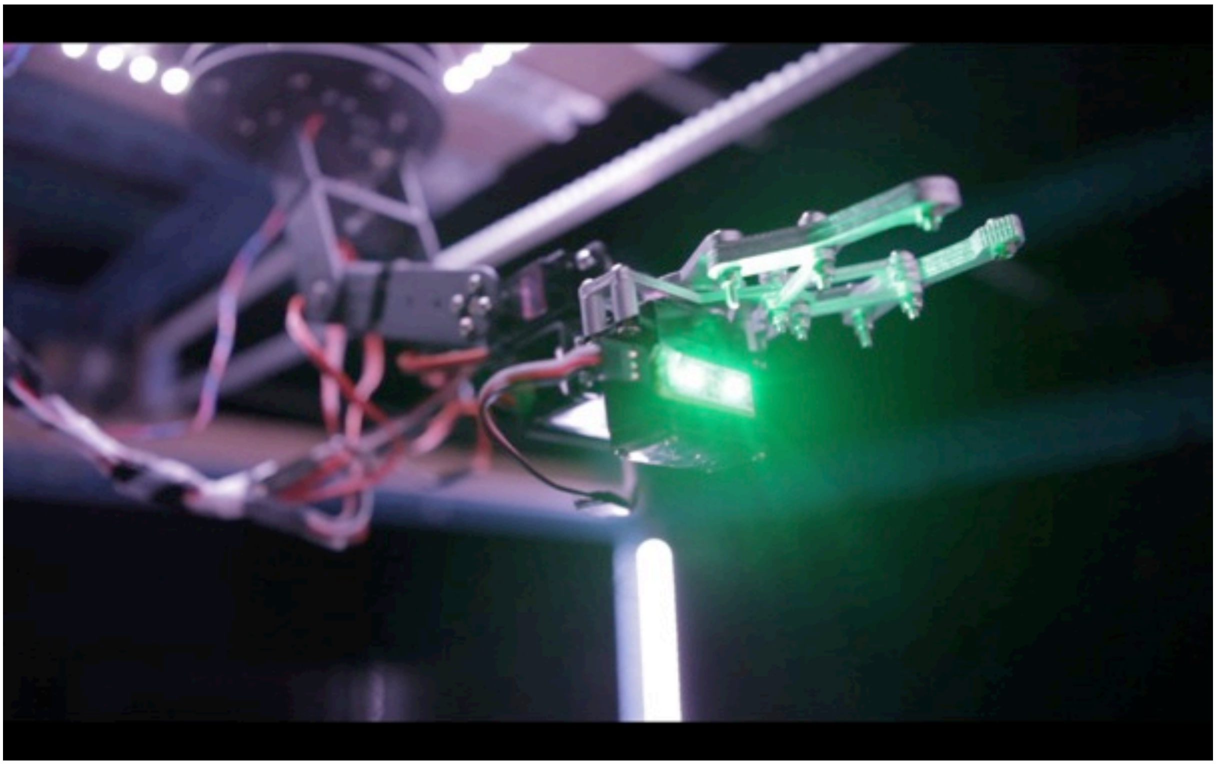

Fig. 26 The robot system

7.1.2 Robotic System: The Truss

The truss is a cubic construction of roughly 2 m^3 made of recycled shelf poles and wood. The dolly construction (cf. fig. 20) is based on the same materials and equipped with skater rolls and a high quality bearing allowing a precise and smooth movement. To move the truss remotely three stepper motors were attached to a custom-made drive belt over a 3D printed gear. The motors are controlled by a Melzi controller board originally used in a RapRap 3D printer and are based on an Arduino Leonardo. This board proved to be ideal for this purpose as it provided a good reliability even under the high electric currents the motors drew. Similar to the robot arm the Melzi controller board communicated serially with the MCS and provided the same functionality as the robot arm's microcontroller. Like the robot arm the truss uses the cubic easing function for all movements. The microcontroller was programmed in such a way that the truss calibrated itself when turned on and during use. To provide this four buttons were attached to each end of the X and Y axis. Whenever the truss had an offset and reached one of the buttons the microcontroller recognised this and reset the counted steps.

7.1.3 Ambient Lighting

The illumination system of the HaM project is grounded on nearly 11 meters of RGB LED strips attached to the corners, rods and dolly of the truss. The 584 RGB LEDs need to be controlled by two Arduinos as the number of LEDs is too high for a single one. Like all the other microcontrollers the LED system is also connected to the MCS and communicates via serial protocol. Through the MCS the illumination system can receive triggers for colours, brightness and light effects. As most of the light effects can only be calculated on the microcontrollers itself it was necessary to code these effects in an efficient way. As the system uses two separate microcontrollers it must be assured that both controllers are synchronised during the performance. Otherwise the light effects would be delayed and jittery.

7.1.4 Sensor Technology

The final prototype made use of the three different sensors, the Microsoft Kinect for motion tracking, the MindWave BCI from Neurosky to measure the brain activity and a pulse oximetry for the heart rate. All three of them are connected to the MCS in different ways. While the Kinect is connected via USB and the pulse oximetry via Bluetooth, the MindWave has an own radio frequency protocol and transmitter with an USB dongle as a receiver. While the Kinect and the pulse oximetry show no connection problems, the MindWave tends to lose connection when surrounded by a lot of wireless signals and devices. This problem was only solvable by a manual reset in the MCS.

7.2 The Software System

The MCS acts as the heart of the interactive system architecture as it connects parts of the stage technology, the robotic hardware and voice playback with the logic system. The system is a necessary intervention point for the technician, an orientation point for the actor, controls the robot and exhibits a direct feedback towards the audience. All parts of the MCS are programmed in JAVA and Processing. In the following, its functionality, structure and use will be described.

7.2.1 Multimodal Control System

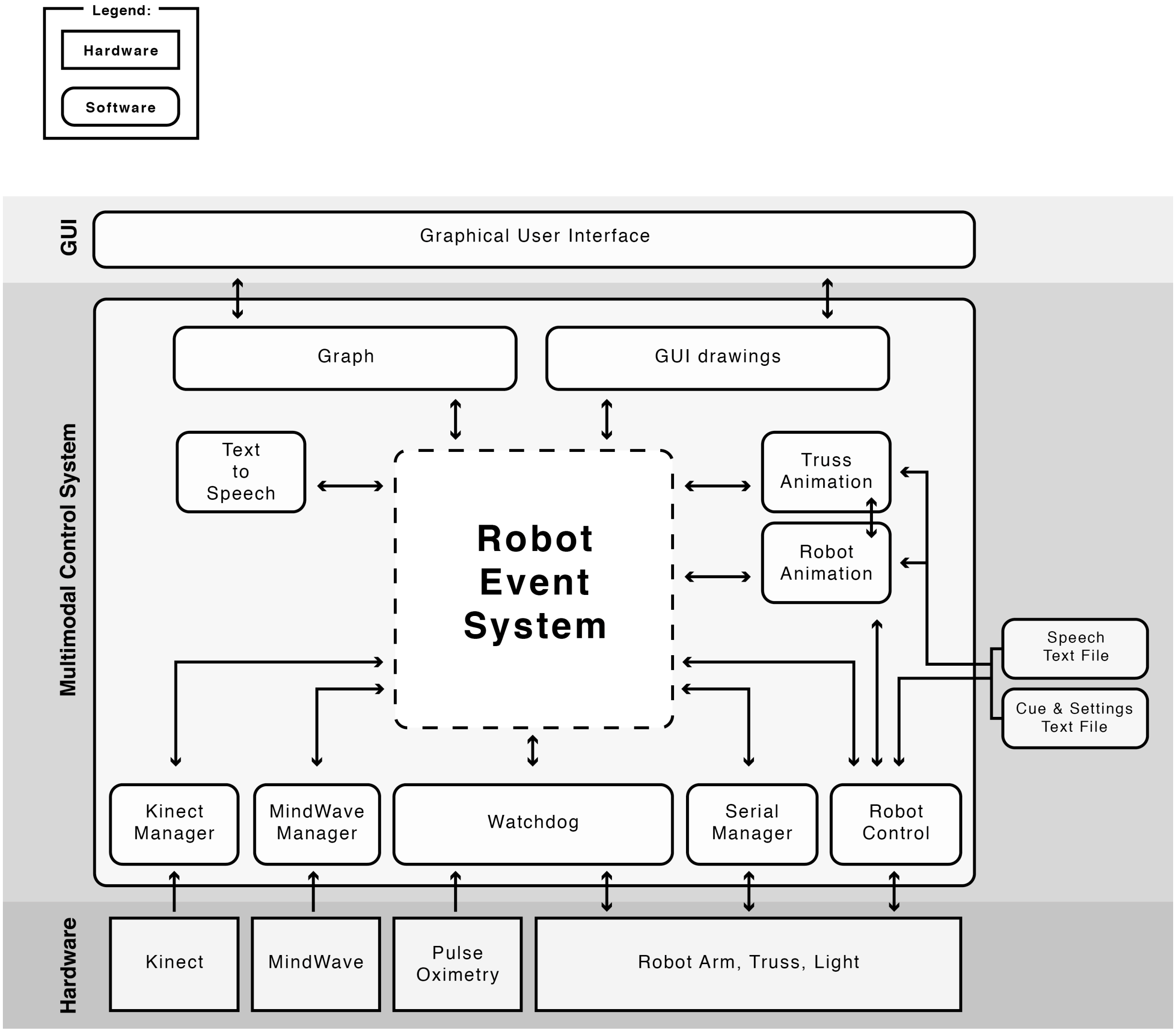

Fig. 27: Architecture of the Multimodal Control System

As seen in fig. 26 the MCS is split into several sub-systems and modules. Each of them is linked to the event loop called robot event system, as it is the heart of the program. It handles and distributes all the messages and events it receives among the sub-systems.

The hardware communication subsystem: All the connected hardware that communicates with a microcontroller like the robot arm, truss and light system is controlled by a system with three modules. First, there is a serial manager receiving incoming serial messages of all microcontrollers including the pulse oximetry. Once it received a serial message it distributes it to all attached systems such as the watchdog.

The watchdog is the second module and responsible for checking the status of each connected microcontroller. This means that the system sends regularly sequenced signals to each controller in short time periods and waits for a response. If it does not get a response from the serial manager it will set the device on a waiting list and try to reconnect to it from time to time. This helps to make the system more fault-tolerant as all devices are dynamically connectable. The third module is the robot control system, which handles the animatronics of the robot arm and the truss. It therefore receives the data from the cue and beat system and forwards it to the hardware microcontrollers. Temporarily, it also sets the ambient illumination of the scene.

The sensor manager: Another sub-system is the sensor manager containing a Kinect manager, a MindWave manager and a pulse oximeter manager. While the Kinect and MindWave manager are independent systems, which just forward their data to the robot event system and the cue and beat system, the pulse oximetry is connected to the watchdog and the serial manager. This is because the pulse oximetry sends its serial data directly via Bluetooth to the MCS while the Kinect and MindWave's data is accessed through external SDKs or libraries.

The collected sensor data is often combined in an equation or used in a way that puts the values in a close relation to each other. In that way the cue and beat system can handle complex scenarios that depend on the position and arousal level of the actor but also on the robot's previous actions.

The cue and beat system: The cue and beat sub-system is responsible for triggering the different cues and managing the turn-taking and fluent beats. A beat can be seen as subcategory of a cue and contains usually several positions and animations (fig. 27).

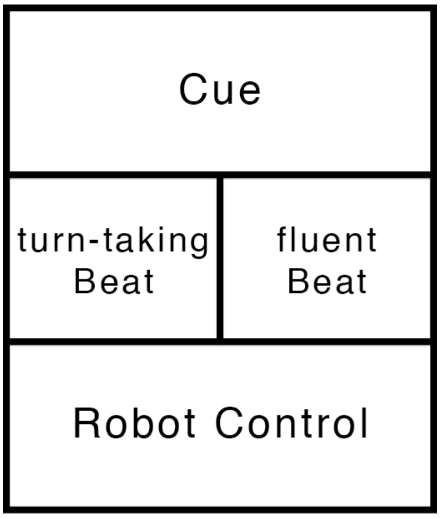

Fig. 28: Layout of the Cue and Beat System

All cues are structured and written down in two text files. One file contains information about the cue's ID, the robot's position, settings and beats while the other one contains the strings of the text to be spoken by the robot. The architecture of the cue and beat system is divided into three main modules. The first one is the robot animation module containing turn-taking beats such as positions or animations controlled by the technician as well as fluent beats which contain a collection of decisions (decision tree) to be individually triggered depending on the sensor input. The fluent beats can be seen as a loop running as long as the actor's sensor input triggers enough decisions to reach the end node of the specific tree. The beat system in the robot animation module furthermore triggers the light system, texts to be spoken by the robot and the truss movements. As light settings can be directly sent via the robot control system to the microcontrollers, the truss animations as well as the conversion of text to speech must be situated in separate modules. The truss animation module therefore contains all animations of the truss linked to the specific cue ID and its beat. As a separate module it has the possibility of acting independently so that the truss can for example move while the robot arm stays in a specific animation. The same accounts for the text to speech module as it needs to be equipped with the possibility of triggering speeches independently from the other modules.

7.2.2 User Interface

A bigger sub-system of the MCS is the interface system, which is responsible for the visual appearance, information visualisation and GUI elements of the MCS's user interface. It contains a GUI drawing module that draws all GUI elements needed for controlling and monitoring the robotic and cue system and a graph module visualising the real-time feedback of MindWave and pulse oximetry. The user interface in fig. 28 shows two main areas displaying the sensor data of the MindWave in the top part and at the bottom the real-time heartbeat of the pulse oximetry. The MindWave sensor output is displayed in a semi transparent shaded graph with the attention level in green colour and the meditation level in blue. All values of the MindWave and the pulse oximetry can also be seen as discrete values on the left side of the interface. At the bottom left corner of the interface one can additionally see the depth picture of the Kinect combined with the tracking result of the actor's head. To monitor the devices' status the interface provides indicator lights at the top right. While green labels show an active and functional device, yellow indicates a short connection or lost or false data while red displays a permanent lose of connection. To control the robotic system and the cues, a robot control area is set on the left side. It contains a number showing the currently active cue and a text field with a coloured label. The label indicates three stages. Red means that a current cue is running and not yet finished, yellow shows that an animation is running but ready for interruption and a green label indicating that a cue is completely finished. The text field can be used to send commands to the robot control system to change certain thresholds or to manually set a position of the robot. As the technician can go back and forth through the cues with keystrokes there is also the possibility to press on the back and forward button displayed under the text field. The current frame rate is displayed at the lower left corner to debug performance problems.

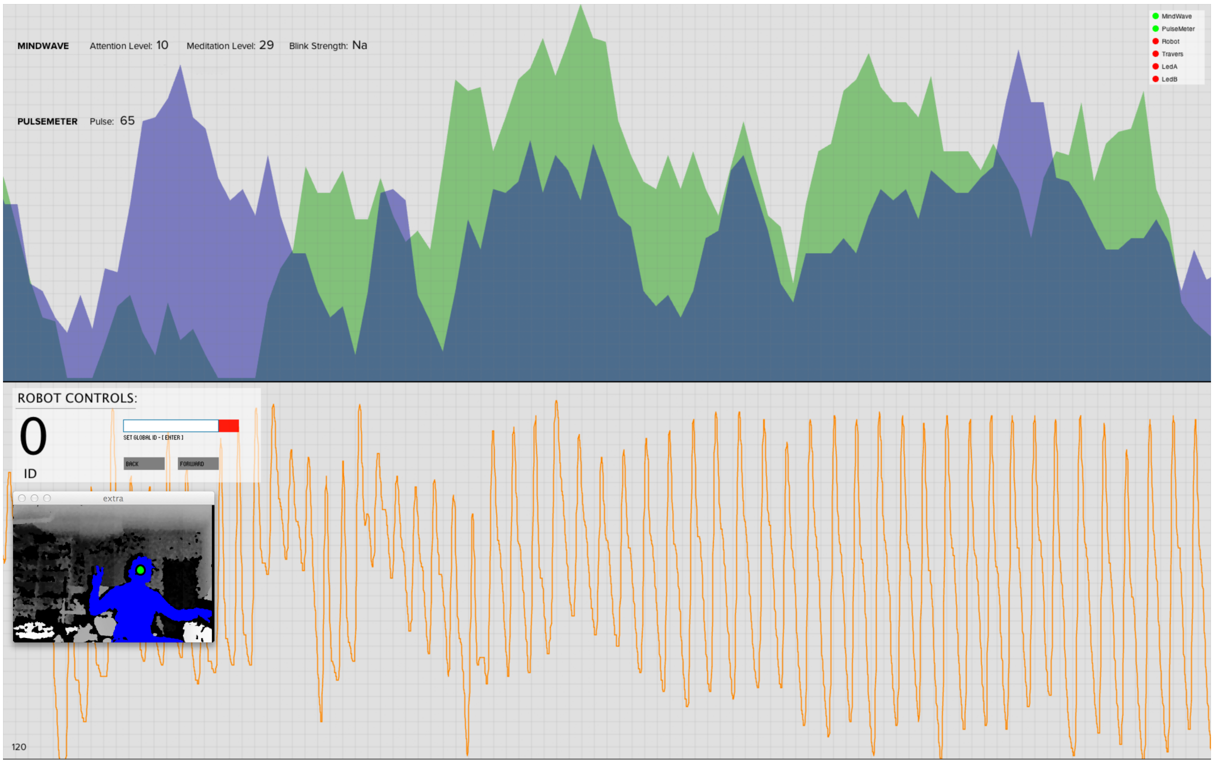

Fig. 29: User interface and information visualisation

7. 3 Techniques of Interaction Design

During the HaM project several different techniques of human-robot interaction were tried out and implemented into the final theatre performance. The premise for a fluent and working interaction between the actor and the robot is based on the difficult task of making the robot understand its opponent and make this visible by an easy interpretable response. One way to achieve this is to apply certain theories and interactive strategies to create a set of interactions that can be used, refined and extended at a later point. In addition, the robot needs to be provided with concrete physical data describing the surroundings and the characteristics of the person he shall react to. The following section shows some of the interactive patterns integrated in the theatre play.

The strategy of personal spaces: Using the Kinect I was able to determine the exact position of the actor on stage and thus calculate the distance between the robot and the human. This distance could then be used to create a set of specific social zones around the robot based on Hall's theory. The interaction with the robot was programmed in such a way that he responds to the actions of the actor in a delayed way. Thus reactions of the robot could be prevented by taking just very small steps as the system ignores those as only minor deviations from the original position. Taking bigger steps and fast movements however resulted in an increased reaction and retreat of the robot as its personal space or intimate zone was violated. This could be boosted by reaction animation patterns in which the robot not only retreated but, on the opposite, started to threaten the actor and to violate his personal space. This made sense in combination with the actor's arousal level as a more aroused and intimate violation of the robot's personal space would result in an equal or more aggressive response from the robot.

The strategy of characterisation: According to Maisel's theory of responsiveness there are three components of responsive behaviour: Understanding, validation and caring.[94] As described in the theory section this concept is based on the research with related couples. The component *caring* reflects the given circumstances of expressing love and care. In my case I intended to create a robot that understands, validates and can give his own characteristic responses. The strategy of characterisation is implemented in such a way that the MCS receives data from the MindWave and Kinect and uses them to control certain decisions and actions in the fluent beat system. The following table shows a simple decision tree as it is used in the theatre performance. Each decision contains a variety of animations, light settings and utterances and can be seen as the main part of the interactive narrative.

Trigger	**Decision**
Relaxed and not close to robot	Decision 1
Relaxed and close to robot	Decision 2
Neutral and not close to robot	Decision 3
Neutral and close to robot	Decision 4
Focused and not close to robot	Decision 5
Focused and close to robot	Decision 6

Depending on the decisions, the robot can respond with different characteristics and actions and thus influence the actor who then again has to evoke a certain state in the robot's behaviour (fig. 29). This creates a bidirectional communication with an immediate feedback similar to that of humans. Certain behaviours trigger certain responses. In this way behaviours and responses of the robot can be specifically adjusted to the individual characteristics of a user and thus become more fluent and interpretable. Taking this approach to the limit the

[94] Cf. MAISEL, Natalya C., et al. "Responsive Behaviors in Good Times and in Bad", 318.

robot could even categorise and finally analyse the human's behaviour and then try to predict his intention. This might again be connected with Dennett's theory of intentional stances.[95]

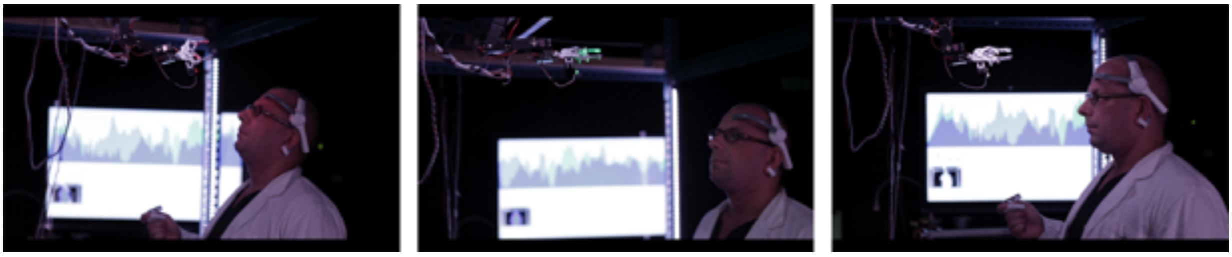

Fig. 30: Various decisions triggered by the actor

The strategy of ambient feedback: A certain merge between awareness and action can be essential and helpful in creating a good human-robot interaction flow. Thus it is sometimes necessary to shift the focus from the directly perceivable human-robot interaction to the more subconscious and neglected communicative elements. In this project, the robot was made aware of the actor's level of arousal by using the pulse oximetry and the MindWave. However, a direct response by the robot can be very straight and awkward and thus lead to a misreading by the actor. So I decided for a subtler approach in which the actor's arousal level is directly merged into the ambient illumination. As seen in fig. 30 the real-time heartbeat was mapped to the LED strips resulting in a pulsating orange flashing of the LEDs at every heartbeat. This might possibly result in a subliminal manipulation of the actor and his decisions and in turn influence the robot's actions.

Fig. 31: Illumination of a single heartbeat

[95] Cf. DENNETT, Daniel C. *The Intentional Stance*, 43-68.

8. Discussion

8.1 Result Discussion

HySens

Considering the initial goals for this master thesis the iterative design process played an important role with regard to the implementation of the HySens system. In fact, no previous outline existed which might have served as a point of orientation illuminating the requirements for building a completely independent robot for a theatre performance. At the first performance at the *Nordic Larp Talks* it became obvious that the robot was too small – the audience could not clearly perceive it and its role in the performance. Consequently, it was of great importance to increase the visibility of the robot and in turn make him an integral part of the theatre performance and more graspable for the audience and thus to potentially create a more profound flow experience for them. This was partly realised with the introduction of the truss. Modelling a frame encircling the stage to which the robot was attached and along which it could move increased its visibility for the audience. Furthermore, this broader range made it possible to use the space of the stage in an enhanced way as the robot could approach and move away from the actor. Referring back to Hall's theory of personal spaces, this use of proximity is of major importance to create different emotional stances such as feeling threatened or comfortable.

Of course it would have been desirable to enlarge the size of the robot itself. Unfortunately this turned out to be a problem because firstly, this would have caused problems with regard to its mass. With the material we had at our disposal it would have become too heavy. In turn, this would have complicated the handling and the dynamic motion along the truss. Secondly, there were no financial resources to rebuild the robot as the project made use of open source material with small budget. This also resulted in a lack of technological reliability in the course of some performances.

Another aspect to be discussed is the initial aim that the robot in its final version was intended to perform with fluent expression. Of course we aimed at the highest possible degree of autonomy of the robot and its actions. In fact this was partly realised. The end product's reactions are only partly triggered by a technician. These instances of controlled intervention mainly relied on an exact timing of corresponding cues and beats triggering a specific performance of the robot. However, as the time for sufficient rehearsing was not given during the project, some triggering failures from the technician occurred which caused a confusion of the actor. We were able to reduce these mistakes with more practice and rehearsing time so that in the last performance they occurred only scarcely.

Thirdly, due to the complexity of the task, we stuck to a limited amount of robotic activity. It would have been doubtlessly interesting, if the robotic animation in general could have been of higher resolution and more detailed expression. Again, this is mainly a time factor as each action of the robot consist of several animations. Of course this would also have been much more expensive. In the end, one has to consider that the developed robot met the needs; a more complex product would have probably gone beyond the scope of the performance project.

Multimodal Control System

The MCS served as a key control centre for the HySens. Furthermore, it delivered a visual response for the actor and audience and fulfilled most of its requirements in controlling and visualizing the technology and its informative output. It is mentionable that especially the possibility to insert small scripts and value changes helped to improve the overall handling of the fluent beats. Regrettably, the implementation happened during the very last iteration phase and thus could only be used once. Moreover, one can mention that a clearer visual response on triggers would have been helpful for the audience to specifically follow the beat-initiations of a sensor. If, for example, a specific value triggered an action of the robot, this could have been visually represented by a flashing spot or even a textual message at the peak before a decrease of the graphs in the diagram (cf. fig. 26).

Animations

Reflecting on the use and handling of animation cues and beats it is possible to state that the general principle that was used had a vast flexibility and was easy to handle. Especially the external text files helped to manage, maintain and change animations quickly. Textual data was used to which specific cues encoding the robot's actions (for example those exhibited by his LED-eyes) were added. These cues could then be directly deciphered by the MCS. However, this was not the case with the general animations of the robot arm. With the current system each position needed to be set by manually clicking through the Cartesian coordinate system and thus moving the robot arm to its designated position. This took quite a lot of time and resulted in a lower animation quality and resolution. A possible solution could be to hack the servomotors of the robot to directly read out the values of its potentiometers. In that way one could move the robot arm by hand to a designated animation point and read out the position of all joints of the robot. This would make the animations quicker and more accurate. However, the success of hacking the servomotors is not granted and takes a decent amount of time.

Sensors

Controlling the robot in coordination with the actor's bodily functions and mind can be seen as an entirely new degree in the interactions between actor and robot providing an additional degree of freedom in the robot's handling. This freedom added a qualitative degree to the perception, consciousness and experience of the actor. Robert Bolin often stated that trying to trigger a certain decision in the robot could be seen as a moment of trance and flow. Even with an easy to handle and comparatively less complex consumer BCI like the MindWave, a certain degree of mental control over the robot could be achieved and perfectly integrated into the theatrical performance. As opposed to visual control movements such as gestures or approximation, the BCI provided more subliminal means of controlling the robot.

In turn referring to the robot, it was partly possible to make him analyse the behaviour of the actor via the various sensors and to use this data to allow for certain predictions of the actor's intention. With this, Dennett's theory of intentional stances accounting for human's relation to and making sense of their surroundings might be partly applied to the robot. Moreover, being triggered by different levels of arousal mirroring the protagonist's embodiment in accordance with the performed narrative, the level of perceived authenticity for the audience was raised. However, as the use of the sensors (BCI, pulse oximetry and motion tracking) was to a certain degree limited in the performance, more investigations and refinements could have been made on interpreting the sensors' data. Especially the use of improved algorithms would have resulted in a promising improvement for the interaction.

Interaction techniques

One of the main aspects of this master thesis was to investigate certain interactive strategies, which could have a potential influence on human-robot interaction. During the iteration phases and the design workshop (with the robot's persona as one of its outcomes) three different strategies could be defined, the strategies of personal spaces, characterisation and ambient feedback.

The strategy of personal spaces can be a powerful way of simulating different interpersonal stages from normal conversation to the violation of intimate spaces. As a descriptive theory reflecting natural human behaviour it consequently holds the potential of being ideally adaptable to the underlying project dealing with human-robot interaction with the aim of mirroring the contact between human beings. In the theatre performance this could be used dramaturgically for creating the impression of a human-like behaviour of the robot. One example is the retreat of the robot in cases he potentially "feels" threatened – though, of course, his retreat could only be realised to a certain degree due to physical constraints i.e. limitations in its spatial motion. If this moment of constraint is reached the robot actually compensates the situation by changing his behaviour. The adaption of this strategy for the theatrical situation was mostly dependent on the use of the Kinect and its calculation of the exact distance between the actor and the robot. While this basically was a quite reliable approach, it sometimes resulted in strange behaviour and false interpretation of the actor's actions by the robot. This was for example the case when the actor went out of the sensor range or turned his body sideways as he could no longer be tracked. This problem was not easily solvable as the Kinect was constrained to a certain area of measurement in which blind spots could not be prevented.

Secondly, the strategy of characterisation was developed, which can be considered as the prime strategy of this research. Characterisation in this case refers to the communicative and situation specific interaction between actor and robot, which means that a specific action or bodily signal encoding different states of arousal caused the robot to individually react to it. This interaction was wrapped around the dramatic structure and thus formed a major part of the performance. To evoke certain decisions and thus responses in the robot the actor needed to be basically familiar with the MindWaves. Gaining practice in the interaction, this resulted in a controlled and continuous triggering of certain decisions. A problem arising here was that certain mental stages were not reached. Consequently, a long time span occurred between different actions to be triggered. This was not as dramatic because the robot was still reacting to the MindWaves data. However, the danger was that it could stretch e.g. a conversation to a length that felt unnatural.

Thirdly, the strategy of ambient feedback was used. This means that the actions of the robot and the physical and mental stages of the actor were subliminally illuminated referring to the colours as identified in Plutchik's wheel of emotion. This resulted in an atmospheric illustration of e.g. the actor's real-time heart rate or arousal level and was thus not only effecting the actor but additionally the participating audience. Another positive effect of illuminating the stage was that common static and non-dynamic stage lights could be nearly completely left out and thus technology and stage became more homogeneous.

8.2 Methods

As the focus of research was not set in a classical field of interaction design the use of methods was limited. Furthermore, if methods were used, they were often taken out of a formerly intended setting and used in a different context. The main focus was set on design workshops following the research through design-method. We established these as a recurring routine to keep the interdisciplinary communication between the different research areas upright and to support the project during all stages of the design process. New ideas were brainstormed and similar projects revisited.

Firstly, the outcomes were mainly concerned with design choices regarding the HySens system as well as the interactive narrative of the theatre play. This was important because the narrative went hand in hand with the technological implementations and limitations and thus needed a constant iteration to look if e.g. a certain idea could be implemented on both sides or not. From workshop to workshop Robert and I developed an increasingly efficient way to translate theatrical choices into actual technical implementations. This resulted to a certain amount in an own language in which Robert wrote parts of the theatre play in a coded syntax, which I could easily integrate into my program.

Secondly, the workshops helped to create a persona, an in-depth vision of the robotic product with the aim of creating an authentic interaction between the two protagonists. We conducted this persona workshop with external people. This had an impact on making design choices regarding the animation patterns of the robot and the overall appearance as new ideas by people who were not part of the project and thus had an entirely independent vision were integrated. All the ideas that seemed to be suitable were subsequently introduced and refined during the different phases.

Next to the design workshops, it was of high value for the development of the robot to present the current prototype to the public during the different iteration phases. This iterative process helped a lot to shape and evaluate on the actual product and went hand in hand with the research through design-method. Only via these performances and in combination with the oral feedback of the audience we became aware of certain aspects that still remained imperceptible or unclear to outside observers and consequently needed to be improved. One such aspect was the size of the robot: Members of the audience hinted at the fact that the robot was barely visible and that the quality of the performance would be seriously improved if we thought about a greater prominence. We consequently implemented this suggestion in our design process.

During the first ideation phases and while starting to create low fidelity prototypes it was soon noticed that certain kinds of features in the prototype might not be realisable until a first testing and evaluation phase due to time constraints and the complexity of the technology. Under these circumstances it made sense to use the interaction design method Wizard of Oz including the presentation of an – though invisibly – unfinished product to a consumer by the unseen researcher, was integrated. In this case this meant that certain parts of the robot appeared to be autonomous and responsive while they factually needed to be controlled by human input and with the help of theatrical cues. The aim here was to gain creatively new impulses for the product's further development.

This method, however, needed to be adapted to the underlying project as there were no real end users for the developed product, but exclusively the audience as a part-time consumer. In our case, we used a derivate of the Wizard of Oz-method, the theatre system technique, which actively integrates the researcher into the performance and aims at integrating the audience as the end user into the action on stage. In the case of the project under discussion this method was used in an adapted version. During the parts of theatre performance, in which the robot did not act autonomously, a technician (me) would control it in accordance with the actions of the actor. Thus in this case the user is not directly involved in the interaction on the stage but rather limited to observation. However, the audience's feedback had been obtained in a final discussion at the end of each performance. This was conducted by having a general discussion round, in which the audience was able to criticize the overall performance. They were also given the chance of triggering specific responses of the robot. Interesting aspects of their feedback were then integrated into the next iteration phase. Changes for the interface inspired by the audience were the display of the data in two big rows instead of small ones as well as an increased highlighting of some sensor data with shaded graphs.

8.3 Generalisability

The outcome, theories and strategies of this master thesis are not necessarily limited to the theatrical purpose as stated in this master thesis: A general use can be derived via the influence on future human machine and robot interaction. Thus the opportunity is given to explore the presented strategies in a more conventional context such as industries or social environments establishing a collaborative workspace between human beings and robots. Making these robots aware of the individual physical and mental states of a human can help to engage in a better symbiosis between the robot and the human and thus e.g. prevent accidents or caution unawareness. Additionally, the bio sensing approach presented in this thesis can go beyond the scope of human-robot interaction. For example, it can help to track the users' bio signals and awareness in the scope of an entertaining activity like videogames in real-time and thus dynamically change the difficulty or narrative of a game if the system for instance recognizes a mental underload and thus a lack of flow in the interaction between the user and the product. All the tested strategies and technologies are scalable and thus adaptable to improved and more precise sensors or expandable with additional technology. This holds rich potential for future research.

8.4 Ethical Aspect

Attributing robots with consciousness as attempted in this project can on the one hand lead to a fluent symbiosis of human-robot interaction with the ideal outcome of an equal standing of both robots and humans in society. Regarding robot futures, Nourbakhsh predicts: "This will be new territory in testing our ability, as humans, to flexibly change interaction modalities as we switch the species we are talking to."[96] At the same time, however, this technical empowerment might result in a clash of the two species. In fact, making robots aware of the individual physical, mental and even emotional state of humans could lead to particular problems ranging from privacy violation to misuses or abuses of the individual personality of a human. This of course is future vision but as artificial intelligence continues to increase in the next decades this scenario will be within grasp sooner or later. To prevent this, one should pay attention to a moderate development of robots by sticking to fixed guidelines such as the three laws, which Isaac Asimo establishes in his novel *iRobot*:

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[96] NOURBAKHSH, Illah Reza. *Robot Futures,* 63.

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey the orders given to it by human beings, except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.[97]

In general, these rules can be considered as being in a symbiotic connection with the approaches stated in my thesis. The first and second rule of Asimo's law of robotics depend intensively on the robot's capability to decipher and understand the human intentions correctly as well as to respond to them in an appropriate way. In the future there will be the essential need of refining and further developing these incipient stages. In which direction developments will be heading, however, depends – as it is the case with all ethical issues – tremendously on the attitude of the people who will have the responsibility of implementing those devices in the near future.

8.5 Future Work

Certain aspects of this thesis need further development or research. Firstly, the current robot is neither of professional construction nor of anthropomorphic appearance, which he might be equipped with to highlight the close proximity to the actor, or respectively the human being. Focussing on the large amount of emerging technology it would be appropriate to test more kinds of sensors and also to implement more professional ones than those used in this thesis. This aspect will especially be interesting considering the constant technological progress. Soon many people will be able to afford buying BCIs, body implants and biosensors that measure a myriad faster and more precise than contemporary technology and will thus help people to create a mirror of their own body and mind. The same will apply for the field of robotics, as it will probably become an integral part of human life within the next decades. In the future, devices such as the BCIs, which are used in the robot developed in the HaM project will certainly be able to produce a more accurate output of the brain-activity and mental state. It's also mentionable that refinements within the HySens core system could provide a better result for the human-machine interaction. Concepts like machine learning, which enables the robot to apprehend certain sensor or behaviour patterns from the specific

[97] ANDERSON, Leigh Susan. "Asimov's "Three Laws of Robotics" and Machine Metaethics." *AI & Society* 22.4 (2007), 477.

human and custom react to those seem to be one of the key elements in future research. Future research might focus on aspects dealt with in this paper to propel the development of human-machine interaction forwards. One such project will be *In a Coded Reality* undertaken by the *Scenlaboratoriet*: A group of participants is connected to BCIs and decides on the interactive narrative of a storytelling depending on their mental state. Although this is of course quite a small project, it propels the idea of a cognition driven future forward as all future research will contribute to the idea of an enhanced human-machine interaction.

9. Conclusion

To arrive at a conclusion, it might be helpful to firstly focus on the different sub-questions as will be done in the following.

How can a robot successfully be built and integrated into an interactive theatre performance in which the robot reacts partly autonomously depending on the actor's physical and mental state?

The building and integration of the HySens system followed the rule of giving the robot as much possibilities to express and articulate itself towards the actor and audience as possible. Therefore it was of profound importance to build the truss dolly system attached to which the robot-arm could be animated freely and on eye height with the actor. This could only be achieved to a certain degree as time and resources limited the construction and technologies used. Furthermore, I connected the robot to various kinds of sensors mounted to or controlled by the actor. These sensors measured the position of the actor, the heart rate and the brain activity state of attention and meditation. Combining the heart rate with the brain activity an overall arousal level of the actor could be specified which ranged from relaxed and calm over neutral to high tension and agitation. Using a combination of these sensor values or isolating discrete ones, a partly autonomous behaviour of the robot could be realised. The actor could trigger different actions and behaviours in an underlying decision tree. Nevertheless the investigation of more sensors and the use of more professional products would have been appropriate to broaden the range of robotic action.

How can the robot be controlled?

The robotic parts and hardware of the HySens are controlled by the MCS. The MCS links all attached hardware systems like sensors, truss, robot-arm and lights and makes it possible to control these devices as well as the animations and actions with the integrated cue and beat system. The MCS furthermore controls and illuminates the stage environment. The interface contains control units for the technician and a visual representation of the sensor data for the audience. Moreover, it reads out and interprets the sensor data so that it can be mapped according to the different developed interaction strategies. The overall system is fault-tolerant and scalable and thus gives the possibility to extend the robotic controls as well as e.g. the number of sensors in future research.

How can information be understandably visualised for the audience?

The MCS decodes the data received by the different sensors and visualizes it in a way that is graspable by the audience. The MindWave data is displayed in a shaded graph showing the two used values, attention and meditation, while the real-time heartbeat is displayed underneath. Additionally, the tracking result of the Kinect can be seen in a small window.

How can the development of a technologized and augmented body-to-machine interaction in the context of cultural products, e.g. a theatrical performance influence the general development of interaction technologies as well as envision and improve future human-machine interaction?

Focusing on the three problems of socially interacting robots, the articulation problem, the intentionality problem and the interpretation problem, a set of interactive strategies was applied reducing or solving the given problem and using the theatrical space as a controlled environment for evaluation. The strategies of personal spaces, characterisation and ambient feedback were developed in this thesis drawing from the categorisation and understanding of the human's body and mind. Only with this basic insight into the human's behaviour, its arousal states and emotions, human-robot interaction can become more fluent, interpretable and responsive for both the robot and the human. The strategy of personal spaces focused on the response the robot gave when the actor entered its intimate space. The strategy of characterisation allowed the actor to trigger different decisions in the narrative to which the robot reacted individually with different actions and animations. All these triggers depended on the mental and physical state of the actor. The last strategy, the strategy of ambient feedback, subliminally represented the physical and mental state of the actor's body and illuminates these. As all these strategies dramatically depended on the usage of the sensors, the right handling of the sensor data is respectively important.

Finding appropriate interaction strategies for the field of human-robot interaction combines a comprehensive merge of different kinds of social, cognitive and interactive approaches. As this tends to be of great complexity the master thesis aimed at finding a way by which multi-facetted interactions in the field of HRI can be tested, developed and evaluated. The chance of developing a technical device in the scope of a performance circling around the interaction between a human being and a robot proved to be a valuable chance. Although the theatrical space provides special surroundings, which deviate from a simple everyday situation and are thus more abstract, it at the same time provides a set of circumstances and scenarios adaptable to human interaction.

Consequently, establishing a theatrical scenario in which an actor is able to control a robot with the conscious and unconscious usage of his body and mind creates a personalisation in robotics that can be essentially used in further future developments. During the performance the actor was able to partly trigger different decisions and responses in the robot depending on his physical and mental state and thus created a simple bidirectional communication similar to humans. This could be improved in future research as the current algorithm does not use the full potential of the sensor data. As mentioned above, it would be appropriate to investigate more reliable and professional sensors. If these will then be further refined in the near future and in addition be combined with machine learning, the creation of social robots which are able to articulate themselves and to read human intention and whose reactions can be easily interpreted by humans will become more substantial.

To sum up, the focus will again be shifted towards the main question:

In the scope of the narrative surroundings of a theatrical performance, how can an actor-controlled human-machine interaction be established by the customized construction of a hybrid motion and biosignal sensing robot?

It was shown that with the help of various sensors and interactive strategies the planned interaction between the actor and the robot could be established. In the scope of the interactive story of the theatrical performance, the HySens system could be linked to the actor's physical and mental state. Biosignals of the actor were measured and recorded in an electronic interface. The robot was programmed in such a way that he deciphered these signals, which in turn triggered specific reactions of the robot again enabling the actor to react. This could be basically confirmed by the audience's feedback. They hinted at the artificial nature of the robot's movement sequences but nevertheless stated that they perceived the robot as an active participator in the interaction between the two protagonists. As the robot exhibited individual actions presenting themselves as reactions to the actor's signals, it might be preliminary characterised as a contiguous communicative counterpart towards the actor being able to transport intentions.

Adopting these basic interactive functions to the general relationship between a human and a machine in contemporary society, this rather natural interaction is much more intuitive and able to transfer a broad range of information even on a person's actual emotional and physical condition. It thus helps to establish the prospect of an increased degree of freedom in the interaction between humans and robots. This is of immediate importance for a seamless integration of sensors supporting the handling of technological devices in daily life. This in turn might lead to a much wider range of possible applications with regard to technological developments. The range of these interactions in turn might also be explored and refined with the developed technologies. Still, there is plenty of space for research to be conducted in the future, e.g. the sensor technique as well as the algorithms which interpret the sensor data might be further refined and improved. These findings then would open up new ways of interaction between humans and machines.

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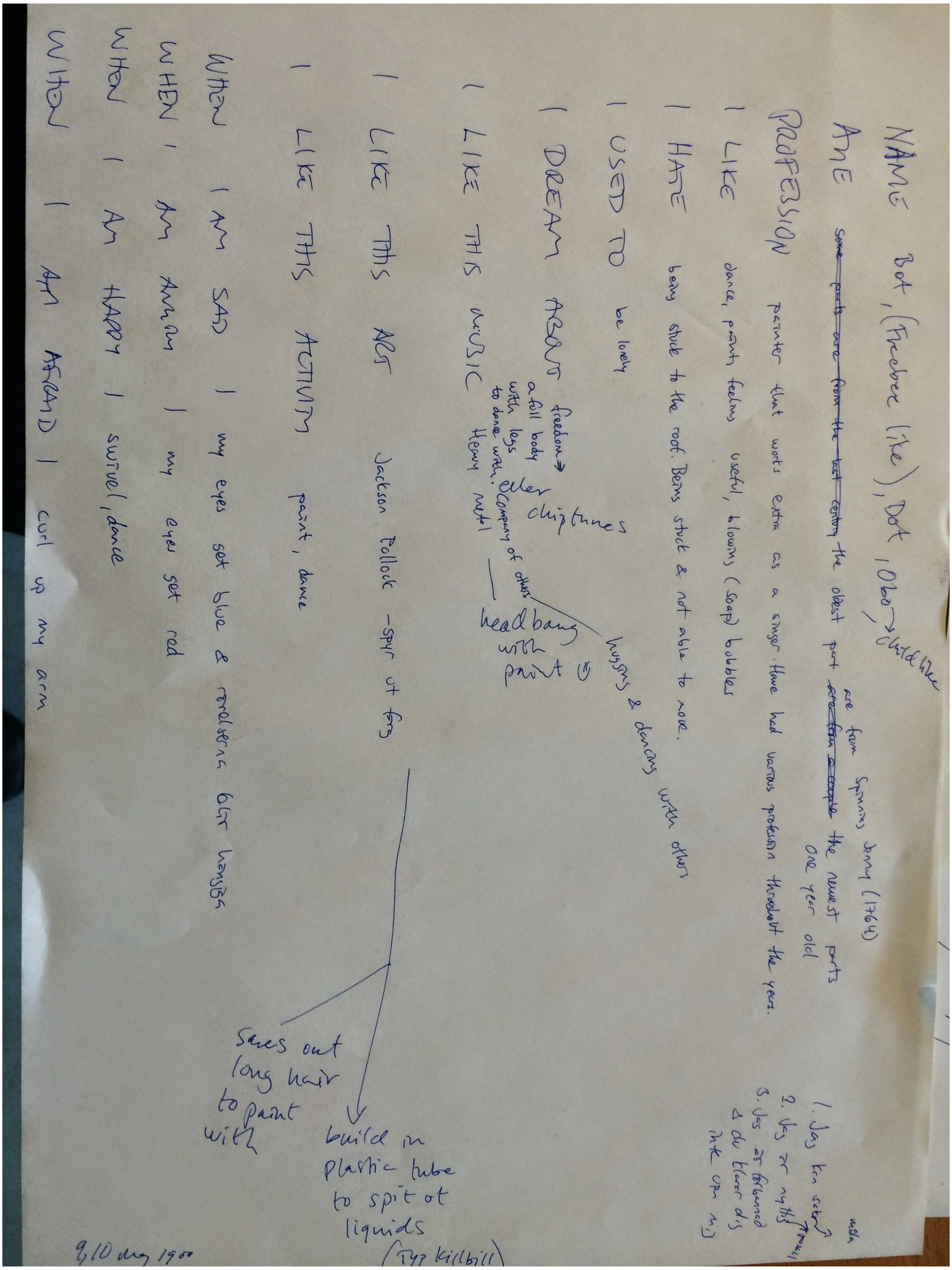
11. Images

[Personal photography of the *Human and Machine* project.]

12. Appendix

Persona


NAME Bot, (Frederic like), Dot, Obo → child like

AGE ~~some parts are from the last century~~ the oldest part are from Spinning Jenny (1764) the newest parts one year old

PROFESSION painter that works extra as a singer. Have had various profession throughout the years.

I LIKE dance, paint feelings useful, blowing (soap) bubbles

I HATE being stuck to the roof. Being stuck & not able to move.

I USED TO be lonely

I DREAM ABOUT freedom → a full body with legs to dance with. Company of others — hugging & dancing with others

I LIKE THIS MUSIC chiptunes eller Heavy metal — head bang with paint

I LIKE THIS ART Jackson Pollock - spur ut färg

I LIKE THIS ACTIVITY paint, dance

WHEN I AM SAD I my eyes get blue &

WHEN I Am Angry I my eyes get red

WHEN I Am HAPPY I swivel, dance

WHEN I Am AFRAID I curl up my arm

Saves out long hair to paint with

build in plastic tube to spit out liquids (Typ Killbill)