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Vlachos, Evgenios

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SUSTAINING EMOTIONAL COMMUNICATION WHEN INTERACTING WITH AN ANDROID ROBOT

BY
EVGENIOS VLACHOS

DISSERTATION SUBMITTED 2015

AALBORG UNIVERSITY
DENMARK

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Evgenios Vlachos

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Dissertation submitted

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PhD supervisor:	Associate Prof. Henrik Schärfe Aalborg University, Denmark
PhD committee:	Prof. Peter Øhrstrøm (chairman) Aalborg University, Denmark Principal Researcher Shuichi Nishio ATR Kyoto, Japan Associate Prof. Anne Gerdes University of Southern Denmark, Denmark
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This thesis has been submitted for assessment in partial fulfillment of the Ph.D. degree. The thesis is based on nine scientific papers; seven published, one accepted for publication, and one submitted for publication. Parts of the papers are used directly, or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication, but only in limited and closed circulation as copyright may not be ensured.

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CV

Evgenios Vlachos holds a M.Sc. in Electronic Automation (2009) from National and Kapodistrian University of Athens, Greece, and a M.A. in Human Centered Informatics (2012) from Aalborg University, Denmark. After his graduation he became a Scientific Assistant at the Department of Communication and Psychology, Aalborg University, and was affiliated with the Geminoid-DK project. Since 2013, he has been a regular reviewer for the International Journal of Social Robotics, and since 2014 he has been a Board Member of the International Conference on Social Computing and Social Media (SCSM) one of the Conferences jointly held under one management and one registration in the context of the International Conference on Human-Computer Interaction (HCII). In 2014, he was also enrolled at the Ph.D. programme in Human Centered Communication and Informatics at Aalborg University where he continued his research on Social Human-Robot Interaction. In the summer of 2015, Evgenios Vlachos engaged in a research stay at Hiroshi Ishiguro Laboratories (HIL) at Advanced Telecommunications Research Institute International (ATR) in Japan. He has until now presented his work in international conferences around the world (China, Denmark, Greece, Italy, Japan, Romania, U.S.A), and has published articles in books, conference proceedings and journals. He has received a Best Paper Award at the Ph.D. Course Writing and Reviewing Scientific Papers (Spring 2, 2015) at Aalborg University, a Best Interactive Presentation Springer Award at the International Conference on Social Robotics (ICSR2012), and three scholarship grants from the Greek State Scholarships Foundation for excellent scholastic performance. His research interests include emotional affordances in human-robot interaction, social robotics, nonverbal behavior, user behavior understanding, maintaining durable interactions with robots, robot-ethics, and societal impacts of social robots.

ENGLISH SUMMARY

The more human-like a robot appears and acts, the more users will have the belief of communicating with a human partner rather than with an artificial entity. However, current robotic technology displays limitations on the design of the facial interface and on the design of believable Human-Robot Interaction (HRI), therefore when directly interacting with such robots discomfort might be created in recognizing either the robotic expression of emotion, and/or the probable following action of the robot. Failure of the roboticist to meet the expectations that rise from the anthropomorphic appearance of an android related to its actions, perception and intelligence, or failure to identify which robot type is qualified to perform a specific task, might lead to disruption of HRI. This study is concerned with the problem of sustaining emotional communication when interacting with an android social robot, and consists of a number of rather diverse contributions to this field of research. These contributions include new results and methods in relation to the perception of robots both prior to and after HRI, the evaluation and assessment of robotic platforms and robot properties in relation to specific tasks, the importance of designing android robotic interfaces after actual humans, and the ethics of such a persuasive technology social robots are. The teleoperated android Geminoid-DK, whose appearance resembles a specific actual human, was used as a robotic platform for the conducted experiments (including user studies, field studies, laboratory studies, online surveys, and pre/post surveys).

In the first part of this dissertation, an overview over the purpose and the goals of this study is given, accompanied by background knowledge of the related fields of knowledge, and a reflection on the theories and methods followed. During this first part, the contribution of the dissertation is summarized, and positioned in relation to the nine research papers that follow in the second part. The second part of this dissertation contains: (a) a classification of robots based on the dimensions of Intelligence (Autonomy-Control), and Perspective (Tool-Medium), (b) connections made between social robots and persuasive technology, and between robots and the user's sense of place attachment, (c) an introduction to the Geminoid Reality including the advances in geminoid technology, (d) a methodology of mapping and evaluating genuine human facial expressions of emotion to androids, (e) a case of designing android faces after specific actual persons who portray facial features that are familiar to the users, and also relevant to the notion of the robotic task, in order to increase the chance of sustaining emotional interaction, (f) an open-ended evaluation method pertaining to the interpretation of Android facial expressions (g) a study on how users' perception and attitude can change after direct interaction with a robot, (h) a study on how androids can maintain the focus of attention during short-term dyadic interactions, and (i) a state-of-the-art report on android hands.

Throughout the dissertation, the main focus has been to understand the underlying problems that could cause disruption in human-robot communication, and to provide meaningful insights on how to prevent them from happening. In conclusion, the eight main steps for sustaining emotional communication with an android robot are: (1) Prior to interactions, evaluate the properties of the robot, (2) Prior to interactions, assess the attitude of the users towards the robot, (3) Prior to interactions, know what tasks the robot can satisfy according to its appearance, morphology, and abilities, (4) Robotic speech, lips synchronization, facial expressions and movements need to be aligned, (5) The robot should avoid abrupt movements towards the user, (6) The robot needs to be as capable as it appears to be, (7) Robot appearance matters less if the situation is engaging, (8) The gender of the robot affects the interactions.

Even though the presented eight recommendations need further investigation, and validation, which will happen soon as more android robots are produced and put into actual use in real life situations, I believe that by following them communication with androids will become more meaningful.

DANSK RESUME[1]

Jo mere menneskelignende en robot fremstår og agerer, jo mere vil brugere opleve at kommunikere med en menneskeligpartner snarere end med en kunstig enhed. Dog er der begrænsninger forbundet med selv de mest avancerede robotsystemer i dag. Det gælder både design af ansigtslignende interfaces og design af troværdig menneske-robot interaktionen (HRI). Derfor kan interaktionen med sådanne robotter give anledning til ubehag enten i mødet med robottens følelsesmæssige udtryk eller gennem robottens handlingsmønstre. Når robotdesigneren ikke lever op til de forventninger, robottens antropomorfe udseende giver anledning til med hensyn til handlinger, perception eller intelligens; eller når designet fejler med hensyn til hvilken type af robot, der egner sig til hvilken opgave, skaber det alvorlige forstyrrelser af menneske- robot interaktionen. Denne undersøgelse beskæftiger sig med problemet om at opretholde emotionel kommunikation når den ene part i samtalen er en android social robot. Undersøgelsen består af en række noget forskelligartede bidrag til denne type forskning. Bidraget indeholder nye resultater og metoder relateret til perceptionen af robotter før og efter HRI, evaluering af platforme for robotinteraktion, og overvejelser vedrørende robottens egenskaber i relation til bestemte opgaver, og vigtigheden af at designe androide robotinterfaces med eksisterende mennesker som forlæg, samt vigtigheden af etiske analyser vedrørende sociale robotter som persuasiv teknologier understreges. Den tele-opererede androide robot, Geminoid-DK, der visuelt ligner et aktuelt menneskeligt individ, er brugt som platform for gennemførelsen af eksperimenter, herunder brugerstudier, feltstudier, laboratoriestudier, online surveys og for/efter interviews.

I afhandlingens første del gives et overblik over formål, hensigt og målsætninger for disse studier, ledsaget af studiernes teoretiske baggrund med tilhørende refleksioner. Endvidere gives afhandlingens hovedpunkter i kort form, og disse positioneres i forhold til de ni forskningsartikler, der følger i afhandlingens anden del. Afhandlingens anden del indeholder: (a) en klassifikation af robotter baseret på dimensionerne Intelligens (autonomy-control), Perspektiv (værktøj-medie), (b) forbindelser mellem sociale robotter og persuasiv teknologi, og mellem robotter og brugerens fornemmelse for sted, (c) en introduktion til "the Geminoid Reality", herunder fremskridt i geminoidteknologien, (d) en metodologi for overførsel af emotionelle udtryk fra mennesker til androider, (e) en case hvor androide ansigter designes med faktiske mennesker som forlæg, mens disse oplever og udviser følelser. Denne case kobles til bestemte opgaver, for at styrke muligheden for vedligeholdelse af den emotionelle interaktion, (f) en åben evalueringsmetode vedrørende fortolkning af androide ansigter, (g) et studie af hvordan brugeres perception af og holdning til robotter kan ændres gennem direkte interaktion med

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[1] The author would like to thank Assoc. Prof. Henrik Schärfe for translating and proofreading this section.

en social robot, (h) et studie af hvordan androider kan fastholde opmærksomhed gennem korte dyadiske interaktioner, og (i) en State-of-the-art rapport om androide hænder.

Hovedfokus for hele arbejdet har været at forstå de underliggende problemer, der potentielt kan forstyrre kommunikationen mellem menneske og robot, samt at tilvejebringe meningsfyldte indsigter om hvordan det kan undgås at sådanne forstyrrelser opstår. I afhandlingens konkluderende afsnit samles disse indsigter i otte nødvendige trin for opretholdelse af emotionel kommunikation med an android robot. Disse trin er: (1) Robottens egenskaber bør evalueres forud for interaktionen, (2) Brugerens holdning til robotter bør klarlægges forud for interaktionen, (3) Robottens handlingsmuligheder med hensyn til morfologi og evne bør klarlægges forud for interaktionen, (4) Robottens tale, læbesynkronisering, ansigtsudtryk og øvrige bevægelser må designes som en helhed, (5) Robotten bør undgå pludselige bevægelser i brugerens retning, (6) Robotten må være ligeså kapabel som den fremstår, (7) Robottens fremtræden betyder mindre når situationen er fængende, og (8) brugerens køn påvirker interaktionen.

Selv om disse otte anbefalinger alle behøver yderligere undersøgelser og validering -hvilket vil ske i takt med at flere androide robotter finder vej til faktisk brug - mener jeg, at opmærksomhed om netop disse anbefalinger vil gøre kommunikationen mellem menneske og androide mere meningsfuld.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor Henrik Schärfe for providing me with the freedom to pursue my research interests, for the trust he showed in my skills, for the numerous enlightening discussions we had, and for his continuous support, and guidance. I extend this gratitude to Peter Øhrstrøm, Ann Bygholm, Ellen Christiansen, and Mikael Vetner for believing in me, and for giving me the opportunity to follow my dream. A special thank you goes to Elizabeth Jochum for sharing with me her secrets on robot dramaturgy through our close collaboration, and exchange of ideas. I would also like to acknowledge Zheng-Hua Tan from Dept. of Electronic Systems, AAU for his support, and our fruitful discussions on user behavior modeling. I never thought I would say this, but I would like to thank all the anonymous reviewers who commented on my work, and eventually made me a better researcher.

My gratitude also goes to everyone at the Advanced Telecommunications Research Institute International (ATR) in Japan for expanding my horizons with their expertise over my stay, and for enhancing my understanding on human-robot interaction. I would further like to address my thanks to everyone at the Aalborg U Robotics for keeping up the good work.

Many thanks go to all my colleagues at the Department of Communication and Psychology, Aalborg University for making it an ideal working environment. I consider myself really fortunate to have been part of such an inspiring research community. More specifically I would like to thank Lykke Brogaard Bertel, and Jens Vilhelm Dinesen Strandbech with whom we share the same passion for robotics, Ulla Lunde Ringtved for enriching my knowledge on learning analytics, Thomas Ryberg for inspiring me to write a paper oh how to design a course, and finally Maria Dolores Castro, Mirna Rivera, Willy Castro Guzman, Farshad Badie and Kinley Kinley for our kitchen sessions. I cannot appreciate enough the assistance of Aase Andersen, Bente Schmidt, Anne Kubel Teilskov, Hanne Porsborg Clausen, Lotte Damborg Mortensen, and of the rest administrative staff for their help, and for tolerating my english.

From the bottom of my heart I thank my Vasiliki for all her love, patience, and encouragement. You are my light when it gets dark. Last, but not least, I would like to thank my Friends (you know who you are), and express my deepest gratitude to my beloved Family for their unconditional love, and endless support.

Evgenios Vlachos
Aalborg, December 2015

To my parents Kostas and Maria, and to my forever little sister Nassia.

THESIS DETAILS

This Ph.D. dissertation is structured in two parts. The first part (I) comprises of an introductory chapter where I analyze the main research questions that initiated this study, describe all relative background work and related research that has been done, reflect on the theories and methodologies I have used, present the Geminoid-DK robotic platform which was used in my experiments, and conclude with a summary of my contribution to the interdisciplinary field of social Human-Robot Interaction (HRI). The second –main- part (II) consists of the following nine articles [A] – [I] in a revised layout. Seven (7) of the articles are already published [A] – [F], [I], one (1) is accepted for publication [H], and one (1) is submitted for publication [G]. I have obtained permission from all the publishers to use their copyrighted material, except for article H where the publisher did not allow the use of material prior to publication.

The articles are not presented in chronological order, but in a way that facilitate the reading process:

A. Vlachos, E., and Schärfe, H. (2012) Interactions between Humans and Robots. In 1st AAU Workshop on Human-Centered Robotics (pp. 29-33). Aalborg University Press.

B. Vlachos, E., and Schärfe, H. (2014). Social robots as persuasive agents. In Social Computing and Social Media (pp. 277-284). Springer International Publishing.

C. Vlachos, E., and Schärfe, H. (2013). The Geminoid Reality. In HCI International 2013-Posters’ Extended Abstracts (pp. 621-625). Springer Berlin Heidelberg.

D. Vlachos, E., and Schärfe, H. (2012). Android emotions revealed. In Social Robotics (pp. 56-65). Springer Berlin Heidelberg.

E. Vlachos, E., and Schärfe, H. (2015). Towards Designing Android Faces After Actual Humans. In Agent and Multi-Agent Systems: Technologies and Applications (pp. 109-119). Springer International Publishing.

F. Vlachos, E., and Schärfe, H. (2015). An Open-Ended Approach to Evaluating Android Faces. In The 24th International Symposium on Robot and Human Interactive Communication (pp. 746-751). IEEE press.

G. Vlachos, E., Jochum, E., and Demers, L-P. (submitted, 2015). Evaluating User Preference and Perception between a Mechanoid and a Humanoid in an Art Context. Submitted to Interaction Studies, John Benjamins Publishing Company.

H. Vlachos, E., Jochum, E., and Schärfe, H. (accepted, 2015). Head Orientation Behavior of Users and Durations in Playful Open-Ended Interactions with an Android Robot. Accepted for publication in Cultural Robotics: Robots as Participants and Creators of Culture (LNAI). Springer Science +Business Media B.V.

I. Vlachos, E., and Schärfe, H. (2014). Android Hands: A State-Of-The-Art Report. In ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis, Paper No. ESDA2014-20564 (pp. V003T17A013-V003T17A013). American Society of Mechanical Engineers.

In addition to the main articles, the following publication has also been made:

J. Vlachos, E. (2012). The Spiral-In Method for Designing and Connecting Learning Objects. In The 4th International Conference on Intelligent Networking and Collaborative Systems (INCoS), (pp. 677-681). IEEE Press

This Ph.D. dissertation was carried out in the period spanning from October 2012 to December 2015 at the Department of Communication and Psychology, Faculty of Humanities at Aalborg University, under the Geminoid - DK project. The work was conducted alongside with obligatory Ph.D. courses equal to 30 ECTS points. Apart from my supervisor, during this period of time I have collaborated with Associate Professor Louis - Philippe Demers from Nanyang Technological University (NTU) in Singapore on a joint experiment, who co-authored one of my publications, and with Assistant Professor Elizabeth Jochum from Aalborg University who co-authored two of my publications. In addition, I had an almost three weeks stay abroad in Japan as a visiting researcher at Advanced Telecommunications Research Institute International (ATR) and Hiroshi Ishiguro Laboratories (HIL).

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PART I

INTRODUCTION

“ΓΝΩΘΙ ΣΑΥΤΟΝ” (English: *Know Thyself*) is an aphorism inscribed into the forecourt of Apollo’s Temple in Delphi almost three thousand years ago [1]. Since then, at least, humanity has been in a constant struggle to understand itself. The advances made in robotics, and specifically social robotics that are designed with the intension to communicate with humans, relate to society and respect social terms [2], indicate that this is the opportune moment to unlock the hidden parts of ourselves provided that we also follow the second inscription of Apollo’s Temple stating “*ΜΗΔΕΝ ΑΓΑΝ*” (English: *Do Nothing in Excess*). Our understanding about what is a human being and what is a robotic entity is constantly changing, as we are still in the process of decoding the former, and exploring the horizons of the latter. I believe that through the process of interaction the above mentioned entities can be approached, since the more a robot is engineered to behave and look like a human, the more we would have penetrated into the inner processes that drive human thought, and action. As we try to understand many different aspects of interacting with the world around us, Human-Robot Interaction (HRI) forms just another tiny fraction of the whole picture. However, it is important to realize that the nature of HRI is related to, but different from the human - human, or human - computer interaction (HCI) paradigms. Interactions with robots can unfold in many different ways, and one of these is with android robots. An android is a robotic system intended to bear resemblance to human form, behavior, intelligence, motion, and communication [3 - 6]. The anthropomorphic appearance of the android is taking advantage of the same brain mechanisms that human beings use to understand other humans, thus, social conventions and expectations are applied automatically, and carelessly to such robots [7, 8].

According to Marvin Minsky, who is one of the co-founders of Massachusetts Institute of Technology's (MIT) Artificial Intelligent (AI) laboratory, “*The question is not whether intelligent machines can have any emotions, but whether machines can be intelligent without emotions*” [9]. Emotional skills are essential for natural communication with humans in order to address multiple concerns in a flexible, intelligent and efficient way, and in order to make sure that the communicated message was understood. However, there is a difference between having emotions and displaying emotions. Robots today may not have, or experience, “real” human emotions, but have the ability to communicate [10]:

- *Indicated emotions,* that the robot operator, or programmer is not aware that the robot is conveying.

- *Displayed emotions,* that the robot operator, or programmer is intending to portray through the robotic interface [11]. However, the receiver of interaction might not recognize them.

- *Signaled emotions,* that the robot operator, or programmer is trying to show to the robot interlocutor via the robot, and intends the interlocutor to recognize them as displayed. This is the category of emotions roboticists are advised to pursue. Signaled emotions can be perceived as real by the robot's interaction partners under certain circumstances

Within the field of HRI and Social Robotics, this Ph.D. dissertation aims to provide a way for sustaining emotional communication when interacting with an android robot by highlighting the underlying problems that could cause disruption in HRI, and by offering an insight on how to prevent them from happening. My attention is mainly concentrated on nonverbal cues, and particularly on the emotions a robotic interface can portray via its facial expressions, how can they be best evaluated, how interlocutors perceive them together with how they respond to them, how to assess the attitude of users and use it in favor of the HRI, and how to overcome technological barriers with smart interaction design.

PROBLEM DESCRIPTION

An android robot can be perceived as an equal interaction partner if it has the appearance of a healthy human, makes balanced movements, has the ability to engage in dialogue, portrays facial expressions of emotion and makes gestures that would make sense to use during communication, and is programmed to process and respond to social cues [12, 13]. Theoretically, the more human-like a robot appears and acts, the more users will have the belief of communicating with a human partner rather than with an artificial entity. However, current robotic technology displays limitations on the design of the facial interface, since it is still struggling to approach the complex system of the human face that uses more than forty four muscles whose activation can produce numerous different facial expressions [14]. Consequently, face-to-face interaction with such robots might create discomfort in recognizing either the facial expression of emotion, and/or the probable following action of the robot. A mismatch between the robots' future action and the anticipated action influences the user's attitude and behavior, and might disrupt the communication. Therefore, the issues that are effortlessly rising are:

- *How can the expectations that rise from the anthropomorphic appearance of an android which are related to its actions, perception and intelligence be met* [3, 15]*?* An android, due to its appearance, transmits similar intentions to that of a human being, which is ability to communicate, understand behaviors and respect social norms.

- *How an android robot can embody emotional facial expressions with respect to the fundamental rules of human affect expression* [16]? When interaction with the user happens in real time, synchronizing the features of nonverbal communication (facial expressions, gestures, body movement and posture, gaze, touch, personal space) of a robot to the flow of the interaction is essential.

- *Which situations give rise to which emotions, and how these emotions influence behavior in a situation* [17]? The process of trying to recognize an emotion usually involves a transformation from low-level physical phenomena/signals (body posture, motion, facial expressions, gestures, pitch and volume change, verbal cues) to high-level abstract concepts (what behavior is typical for the situation, life-tasks, goals). When emotions are portrayed in a robot, the levels of abstraction may vary from low levels, such as a motion sequence of actuators, to high levels of interpretation such as the sentence “She/He looks surprised!”.

These issues have been addressed by the scientific community for almost twenty years starting with Rosalind Picard’s work on Affective Computing [17], and they have been (and still are) fundamental in the course of conducted robotic research. Affective computing involves systems that can accurately identify, interpret, analyze, and simulate human emotions, and affective robotics can be considered as a subcategory of them. These questions addressed earlier continue to be pending, and in my quest towards dealing with them, from a robotic perspective, I have discovered that as science advances responses will always differ. This work summarizes experience accumulated over three and a half years of robotic research focused on human-android interaction, and states my current interpretation of sustaining emotional communication with an android robot.

BACKGROUND AND STATE OF THE ART

Throughout the last thirty years, as technology was progressing following the Moore’s Law exponential curve [18] (stating that almost every two years microprocessors are doubling their performance indicators while decreasing in size), humanity was trying to understand these changes, adjust to the new technological circumstances, and take measures in order to avoid “*non liquet*” situations where there is no applicable law. When the technology-centered perspective was prevailing [19], the concept of human-machine interaction was related to terms like control, automation, navigation, manipulation, and other heavy industry terminology. As humanity entered the post-industrial era, interfaces matured to social processes, and the focus of interaction started to shift away from the machine, and move closer to the user [20, 21]. In the information era, research presented a turn towards understanding human behavior, and reevaluating the role of the machine [22]. Today, researchers examine whether the application of communication and psychology theories can make the robots interact more naturally with their environment, and how the appearance and the abilities of robots affect the way humans communicate with them [23].

For a realistic, and durable HRI, social robots should incorporate human-friendly appearance, communication functions, user behavior modeling techniques, and cognitive skills in the descriptive specifications of an industrial robot, that is accuracy, acceleration, carrying capacity, durability, repeatability, and speed. Building an android is a composite assignment demanding extensive knowledge from dissimilar disciplines like computer science, psychology, mathematics, engineering, neuroscience, communication, materials, biology, and anthropology to name a few. Practically, all the knowledge humanity possesses and has gained about “thyself” needs to be put into use. Universities, institutions, and laboratories from around the world have spent great amount of resources, and have invested heavily in research and design (R&D) to create the “perfect” android, but nevertheless we still have not seen a robot that combines appearance, functionality, mobility, operability, vision/speech/acoustic/tactile abilities, with high cognitive behavior, and intelligence adequate for natural HRI. We have seen robots that excel in one -maybe two- of the aforementioned qualities, but we have not –yet- seen a robot that excels in all of them. In the next decade, major advances in the android science field are likely to be more successful when robot designers acknowledge the need for a combined platform comprised of trends already visible in current day research such as robotic vision and perception, localization and positioning methods, learning algorithms, decision making in dynamic environments, mobility techniques, and finally multi-robot communication, intelligence and coordination [24].

Despite that fact, humanoid and android robots are making an entrance into our daily routines taking up roles related to care, assistance, companionship, wellness, education, and play. There are instances of an android (Geminoid-DK) taking up the role of a university lecturer [25], of another android (Geminoid-F) performing in theatrical plays around the world [26], of a teleoperated humanoid (Telenoid) facilitating communication with elderly people suffering from dementia [27], of a humanoid robot (Kaspar) promoting cooperative dyadic play among children with autism [28], of a teleoperated robot (Rofina) helping children with special needs to understand play behaviors [29], of a child-like humanoid (Zeno) assisting physical therapists treating sensor-motor impairments [30], of the small humanoid robot NAO used in various child-robot interaction tasks [31 -33], of the real size humanoid iSocioBot used in elder care [34], or even of a humanoid robotic nanny that plays with and takes care of a child on its own [35]. Social robots may also have a zoomorphic (animal-like) appearance, like Sony’s robot dog AIBO [36], the MIT’s robotic creature Kismet [37], the AIST’s seal robot Paro [38], the Nabatzag rabbit [39], Fujitsu’s Teddy bear robot [40], the Probo elephant robot [41], or the robotic cats i-Cat [42] and NeCoRo [43], or even a mechanoid (machine-like) form like Cynthia Breazeal's Jibo [44], or the GiraffPlus Video Conferencing Robot [45]. Figure 1 illustrates representative types of social assistive robots.

Considering the European Union's encouraging estimations of the Robots and Artificial Intelligence market over the coming years [46], the recent report from analysts of the investment bank Bank of America Merrill Lynch stating that the total global market for robots and artificial intelligence is expected to rise [47], and Google's spending millions of dollars in robotic research and development by acquiring seven worldwide robotic companies [48], it is evident that we are moving towards a robotic era.

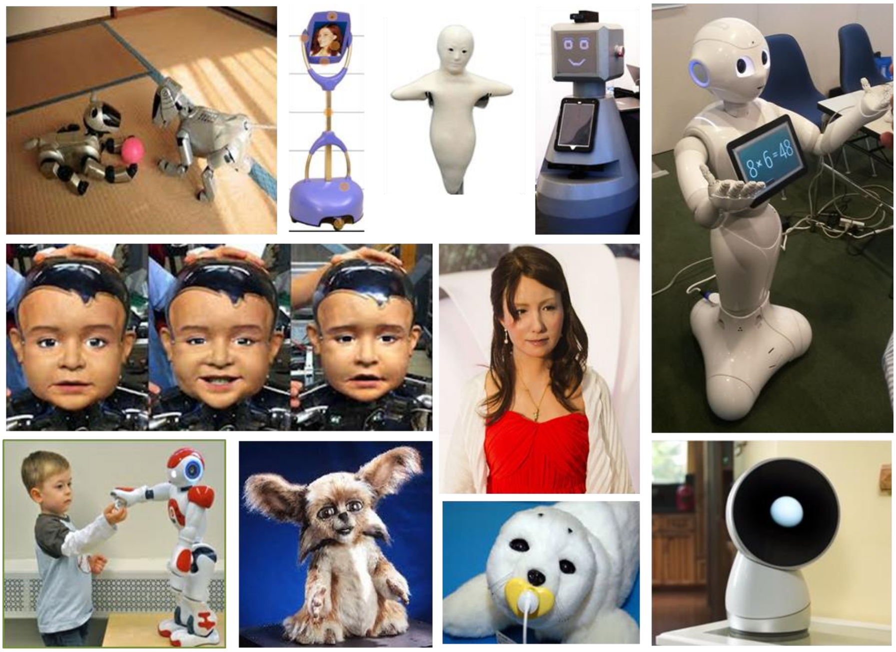

Figure 1 Social Assistive Robots: AIBO / GiraffPlus Video Conferencing Robot / Telenoid / iSocioBot / Pepper (first line), Diego-San / Geminoid-F (second line), NAO / Kismet / Paro/ Jibo (third line).

REFLECTIONS ON THE THEORETICAL APPROACH

EMOTIONS, SOCIAL CONSTRUCTIVISM AND EVOLUTION

Throughout the years, many theories about emotions have come to light (the Darwinian Theory, the Jamesian Theory, the Cognitive Theory and the Social Constructivist) and many definitions of the term emotion have emerged. The most compact one is given by Klaus R. Scherer stating that "*emotion is defined as an episode of interrelated, synchronized changes in the states of all or most of the five organismic (central nervous / neuro-endocrine / autonomic nervous / somatic nervous) subsystems in response to the evaluation of an external or internal stimulus event as relevant to major concerns of the organism*" [49].

As Paul Ekman has stated; "*emotions are viewed as having evolved through their adaptive value in dealing with fundamental life-tasks*" [50]. Trying to explain the role of emotions in our society, we are confronted with the evolutionary theorists who give emphasis on the ancestral history of humanity, as well as the social constructivists who give emphasis on the past history of the individual [51]. Charles Darwin was the first to formulate a scientific argument for the theory of evolution by means of natural selection [52]. Recent research revealed that even before birth, when we have the form of a fetus inside the womb, we learn to develop facial expressions which are associated to specific emotions [53]. Therefore, facial expressions can be considered as an adaptive pattern that prepares our entrance to the society, formulates social attachments and bonds and even helps to negotiate hierarchies [54]. Susskind et al. [55] study provides support for the hypothesis that "*facial expressions are not arbitrary configurations for social communication, but rather, expressions may have originated in altering the sensory interface with the physical world*". In the facial expression of fear, for example, an increase in nasal volume and air velocity during inspiration, and the widening of the eyes are enhancing perception when in danger, whereas the opposite pattern was found for the facial expression of disgust in order to dampen the potential harm [56]. Another use of facial expressions is to maintain aspects of relationships between interaction partners [57]. Societies[2] have memory and when confronted with unfamiliar, or unexpected situations, a mechanism is automatically activated that prompts towards a specific direction which was proven better than others in the past. The automatic appraisal mode indicates that the role of this mechanism is played by emotions, allowing our society to go beyond the information given, and act as if certain things were true now, even if they might be not, just because they were true in the past [58]. Some facial expressions are innate, but others are learned through the past

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[2] Significant agents of socialization that have the power to shape the character of an individual are parents/ family, teachers/school, peers, mass media and institutions that constitute the society the individual lives in [59, 60].

history of the individual and they, in turn, are passed to the next generations. Our affect programs allow for additional input during our life span, enabling us to learn and remember which expressions of emotion relate better to certain situations, thus governing our behavior automatically [61].

Natural selection is the only known cause of adaptation, but not the only known cause of evolution. Social constructivism is closely related to social constructionism in the sense that people are working together to construct artifacts, however, there is an important difference: social constructionism focuses on the artifacts that are created through the social interactions of a group, while social constructivism focuses on an individual's learning that takes place because of their interactions in a group. A person's cognitive development (understand what occurs in society and constructing knowledge based on this understanding) will be influenced by the culture that he or she is involved in, such as the language, history and social context [62 - 64], a perspective related to the developmental theories of Vygotsky, of Bruner, as well as the social cognitive theory of Bandura [65 - 67]. When an emotion is mobilizing the organism to deal quickly with important interpersonal encounters, it is prepared to act according to types of activity that have been adaptive both in the past of the species, and the past of the individual. Therefore, we have to consider equally these two theories.

A convenient way to distinguish emotions is to separate them into “primary” and “secondary” emotions. According to Damasio [68], primary emotions are located in the limbic system, are innate and respond to stimuli before a corresponding cognitive state is activated. Primary emotions can occur with a very rapid onset, through automatic appraisal, with little awareness, and with involuntary changes in expression and physiology, so, we often experience emotions as happening to us. Primary emotions are impulsive, not chosen by us, coming from the past when humanity had to deal with fundamental life tasks, and still appear when we appraise and respond to a current situation [69]. Secondary emotions (or Social Emotions) develop during one’s upbringing through repetitive social interactions, and behaviors causing the creation of relationships between specific persons, spaces, objects, or situations with specific primary emotions. They also activate limbic structures, but prefrontal and somatosensory cortices are also involved [17]. In addition, secondary emotions can be triggered solely by thoughts.

According to Paul Ekman the facial expressions that correspond to the primary emotions, or to the **six basic emotions** of surprise, fear, disgust, anger, happiness and sadness are considered to be psycho-physiological entities universally accepted and firmly established (in terms of how people reveal them, and how people recognize them), although there are cultural differences in when these expressions are shown [70, 71]. These primary prototypical facial expressions reveal emotions that can be understood universally by people worldwide, but by no means has this implied universality in other components of emotion. The secondary emotions are sympathy, embarrassment, shame, guilt, pride, jealousy, envy, gratitude, admiration, indignation, and contempt [72]. Therefore, reaction to a stimulus triggered by a primary emotion could be "by default" installed to the emotional behavior system of a capable and smart android (needs to have the necessary sensors, and processing power) by programming the robot to react to loud sounds, or abrupt movements towards it, and to seem curious when unfamiliar objects appear in its visibility area. Secondary emotions that would be relevant to the notion of a specific task, or to the group of users interacting with the robot could be installed to the robot prior to HRI.

LIFE TASKS

It is widely accepted that different people often have different emotions about the same situations, but most of the time, most people feel practically the same way about most things, meaning that there are physical, biological and social reasons which explain why we are more similar than dissimilar to each other [73]. Experimental results indicate that people reason about the goals of others by using the same mental modes that are used to guide their behavior and form their goals [74]. If the case was not so, all the associative social processes (cooperation, accommodation, assimilation) would be ungovernable within any society. Without plenty of common life-tasks, our society would move to a state of "high entropy" (maximum disorder). The organizing scheme for these social processes and activities of society is provided by the life-tasks which are embedded in the everyday life of the individuals. The life-tasks provide an integrative unit of analysis for understanding the interaction between a person and a situation, and give meaning to his/her actions [75]. They are defined as the tasks which the person is working on, and devoting energy to solving during a specified period in life, and are conceptualized as "desired states that people seek to obtain, maintain, or avoid" [76, 77]. The fundamental life-tasks, according to Johnson-Laird and Oatley, are "*universal human predicaments, such as achievements, losses, frustrations, etc*" [78] that enable individuals to give personal meaning to their lives, to organize personal effort and activities, and to reflect their personal history to the world when progressing towards realizing a goal [79]. In happiness, for instance, the task is to attain or maintain a goal, in sadness the task is connected to failure to attain or maintain a goal, and in fear the task relates to expectation of failure to achieve a goal [80]. These tasks are spread over a wide range of behaviors in a particular life domain, and they may not always be done in conscious awareness by the individual as they often fall under the shadow of more general concerns about achievement, affiliation, power, or personal growth and identity [79]. Life-tasks may also correspond to words, or to complex/indirect events.

The social-intelligence view of personality does not propose that every person at a particular age is engaged in the same life-tasks. Periods of transition are precisely those times where individual differences in life tasks become most apparent. Only by taking into consideration the period of transition, the number of generated dimensions is controllable. During transitions, people tend to be intensely aware of themselves, and of their place in the world. Our society is now experiencing the transition from the information era to the robotic era, and the formation of new age-graded life tasks is needed. The cognitive process of interpreting the life-tasks that are related to communicating with an android, generates a respectful number of dimensions to assess them. In a transition, however, the analysis of the level of shared tasks that all society finds either more, or less compelling as they enter the transition becomes easier [81].

THE IN-GROUP ADVANTAGE AND INTERSUBJECTIVITY

Intersubjectivity is the mutual understanding among members of the same group, whose communication depends on shared interests, rules of language, impressions, social patterns, and expectations that lay the ground for their production of meaning [82, 83]. Production of definitions for terms, and production of knowledge is then acquired through compromises, and discussions within the groups [84, 85]. Consequently, every personal point of view is affected by the intersubjectivity of the group.

A recent study provided critical evidence on the essentiality of personality when designing social robots [86], while another one highlighted the usefulness of tailoring a robot to its users by investigating effects of social category membership on the evaluation of humanoid robots, and by proving that an in-group advantage existed [87]. The in-group advantage states that individuals are more accurate when judging emotional expressions from their own cultural group rather than from foreign cultural groups [88]. The confidence one has in decoding non-verbal emotion signals depends on the person signaling them, and on the degree of familiarity one has with the type of expressions signaled [89]. Individuals brought up in the same group, display different emotions in different situations, so that they may become socially appropriate, and acceptable within their group [90]. Although the in-group advantage in recognizing facial expressions disappears after practicing with feedback (indicating the correct answer) when dealing with “out-group” others [91], however, there is not such research conducted in robotic affective interfaces to my knowledge. Despite that fact, two studies that deal with manifestation of personality in robotics, and bear some similarities with the in-group advantage research are [86], [92]. They both underline the need to select robots according to their personality for being comprehensible to the user, and according to the preferences of the user. Pursuant to the current state of android research, an android can have its facial expressions preprogrammed, and tailored to a specific group of users, but is incapable of altering, or adjusting them in real time for communication with a different group of users. Stepping on the theory of Tomkins and McCarter [91] who stated that emotions differ culturally just like the dialects of a language, introducing the term "*dialects of emotion*", an emotional dialect needs to be pre-built in the affective interface of the robot such that it's expressed emotional displays to match culturally with the perceiver's emotional judgments. HRI based only on facial expressions that stem from the universal emotions might create a communication discomfort due to the subtle differences that exist across different groups.

PRODUCTION OF MEANING

One crucial issue of high importance that could accelerate the integration of robots in the human society is to preserve, and perhaps even extend, one of the fundamental hallmarks of human communication, the production of meaning. In order to lay the ground for this question, thorough investigation is required into modeling the ongoing process of meaning making under the prism of robotics. Following the traditions of semiotics, and the work of C. S. Peirce we may then say that meaning is to be understood as a relational structure emerging from behavioral patterns that emerged due to the interaction of humans with their environment [93]. According to Peirce, meaning is grounded on three categories [94 - 97]:

- *Firstness*: a concept that is understood as a unique (monadic) quality without referring to anything else.

- *Secondness*: a concept that is understood in relation to something else as part of a dyadic relationship, without referring to a third entity.

- *Thirdness*: a concept capable of bonding a second entity with a first one in the same way that it bonds itself with the first, and the second entities.

Let us consider the following example to further understand how roboticists can benefit from semiotics; a smiling face. The firstness is represented by the face, the secondness is connecting the face with a smile because a smile only makes sense in the context of a face, and the thirdness necessitates the need to look for possible interpretations to a smiling face that should be in context with the situation (it could be a friendly greeting, it could be a funny story, it could be a joyful situation). Modern robotic systems can easily detect faces (firstness), and even expressions like smiling or frowning (secondness), but no robotic system is currently able to make accurate guesses (thirdness) as to the reason for a person smiling.

Albert Mehrabian’s Communication Model

Albert Mehrabian’s communication model explains the importance of nonverbal communication, and of the subtle aspects of interpersonal interaction when trying to produce meaning out of spoken dialogue that deals with communicating feelings and attitudes [98, 99]. Meaningful communication, and relationships are based on the effectiveness to convey (when speaking), and interpret (when listening) meaning. The model is described with the following formula:

Total Liking = 7% Verbal Liking + 38% Vocal Liking + 55% Facial Liking [98]

According to which:

- 7% of the meaning of the communicated message is in the words that are spoken.

- 38% of meaning of the communicated message is paralinguistic (the way that the words are said).

- 55% of meaning of the communicated message is in the facial expressions of the one sending the message.

REFLECTIONS ON THE METHODOLOGICAL APPROACH

The work presented was based on results derived from active experimentation and computer assisted analysis including:

- *Laboratory Studies*. I invited subjects to the Geminoid-DK laboratory and monitored/recorded their response to various triggers for obtaining information on how to design meaningful HRI interactions. I was keeping the environmental conditions under control, and focused on the actions and reactions of the subjects. Apart from subject, I also recorded experimented with the facial expressions of the robot (Fig. 2). Prior to the experiments the task of setting the scene up is of great importance for getting valid responses

- *Field Studies*. I took the android out in the public, and run open-ended unscripted interactions, or positioned the android in specific places and attributed to it a specific role (e.g., artifact in an art gallery). Likewise, preparation for the experiment is necessary for valid results, and interactions were also recorded.

- *Online Surveys*. I conducted online surveys and questionnaires with short videos of photographs of the robot as stimuli, and asked users for assessments. Online surveys are important especially at the stage of evaluation of a robotic interface, as they provide a “foretaste” of the attitude of users against the robot. Figure 3 serves as an example.

  Human facial expressions of emotion are conveyed through extremely rapid facial movements called micro-expressions, lasting 1/15 to 1/25 of a second and most people fail to see them, or recognize them at a conscious level [100]. A robot cannot portray micro-expressions as the actuators move quite slow; therefore an emotion stays longer on the face of a robot, and instead of a rapid signal it makes more sense to consider emotional moods when referring to android emotions. That said, videos with still photographs of a robot are considered a valid way to gather data.

- *Judgment-based approach* and *Sign-based approach*. The Judgment-based approach suggests that when viewing a facial expression, emotion can be recognized entirely out of context, with no other information available. This judgment depends on the judges’ past experience of that particular facial expression; either of his/her own face in conjunction with a particular feeling, or someone else’s face in conjunction with other revealing verbal or non-verbal behavior, or in general according to types of activity that have been adaptive in the past of the species [101, 102]. Upon seeing a smiling face, an observer with a judgment-based approach would make a judgment such as “happy,” whereas an observer with a sign-based approach would classify/count the facial expressions and movements in some fashion, and code the face as having an upward, oblique movement of the lip corners, or state that subject A lifted his/her cheeks more times than subject B [103]. The Judgment-based approach was used in Paper D, Paper E, and Paper F, whereas the Sign-based approach in Paper H.

- *Face Analysis* of the operator of the robot via the FACE API software (Fig. 4), that tracks in real-time the position and rotation of the head, and the position of key facial features. I mainly used it when running field studies to give a more natural kinesiology to the head movements of the robot.

- *Face Analysis* of the user (and the robot) via the Noldus Face Reader software, a tool providing emotional assessments (six basic emotions, and the neutral face). Face reading software like the Noldus, might still be in its infancy, and a far cry from the finely tuned ability of man, but it does give us the ability to minutely analyze, and validate assumptions about both natural and artificial faces. This tool was used to analyze the subjects’ facial expressions from the recordings collected after the experiments. See figure 5.

- *Coding Behaviors* and Video Analysis of users with The Noldus Observer software used for collecting, analyzing, and presenting observational data.

- *Statistical Analysis* of the results using the R, SPSS, and Excel platforms in order to examine my hypotheses, to provide valid insights into the relations, and correlations of my examined variables, and to visualize my data.

Figure 2 Laboratory settings for acquiring photographs and videos of the robot.

VIDEO 2 In which situation would you use a facial expression like this? *

Give a small example.

VIDEO 2

Figure 3 Printscreen image from the online survey.

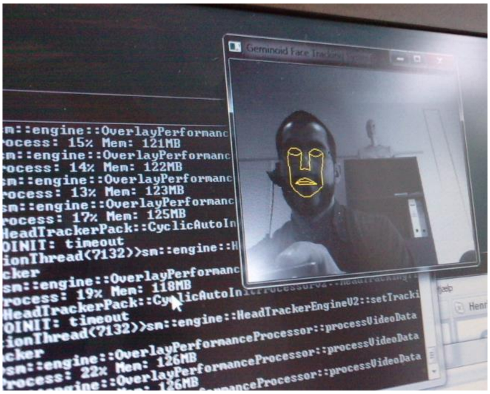

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Figure 4 Printscreen from the FACE API software.

Figure 5 Printscreen from the Noldus Face Reader during emotional assessment of the facial expressions of the Geminoid-DK.

THE ROBOT

The robotic platform that was used for all the conducted experiments (including user studies, field studies, laboratory studies, online surveys, and pre/post surveys) was the Geminoid-DK[3] tele-operated robot that has similar appearance with an original existing person, and is intended to work as the duplicate of that person [23, 104]. The first Geminoid was created in 2005 by Professor Hiroshi Ishiguro of

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[3] The word Geminoid (meaning resembles-a-twin) comes from the Latin word “geminus” for “twin”, and the Greek suffix “-oides” for resembling.

Advanced Telecommunications Research Institute International (ATR), and the Tokyo-based firm, Kokoro Inc. Geminoids were designed as a tool to study the nature of the human presence, and if human presence could be transferred to a remote place. Geminoids are remotely controlled by a human operator through a computer system which uses a motion-capture system that tracks facial expressions and head movements of the operator, but can also be controlled by preprogrammed commands. Geminoid-HI2, Geminoid-HI4, Geminoid-F, and Otonaroid are robots of the Geminoid series. Geminoid-DK, which is the third in the Geminoid series, was created in 2011, and is the first to be modeled after a Caucasian face (Fig. 6). It consists of twelve pneumatic actuators for the movement of Eyebrows Up-Down, Eyebrows Frown-Relax, Eyelid Open-Closed, Eyes Left/Right, Eyes Up/Down, Mouth Open/Closed, Cheeks Up/Down, Left Neck Extension, Right Neck Extension, Head Turn Right/Left, Breath Deep/Low, and Lean Forwards/Backwards.

Figure 6 The Geminoid-DK robot.

CONTRIBUTION

The individual contributions are rather diverse and sometimes only connected by the purpose they all serve; finding and eliminating the reasons that might cause disruption during social interactions with an extremely human-like robot. In this section I will summarize, and reflect on the nine research papers. Paper A, Paper B, Paper C, and Paper I can be considered as theoretical/review papers setting the stage for this work, as well as future work. Paper D, Paper E, and Paper F deal with robotic facial expressions of emotion, how can they be replicated from humans to robots, how can they be evaluated and the advantages of doing so. Paper G, and Paper H deal with user preferences and attitudes towards direct interactions with social robots, analysis of behaviors, gender differences, and attention direction.

PAPER A: Interactions between Humans and Robots

This paper presents a classification of robots based on the dimensions of Intelligence (Control – Autonomy), Perspective (Tool - Medium), Locomotion, and Appearance, and explains the reasons for their selection. The paper also introduces a generic model for comparing and contrasting robots, the Compare – Contrast Model (CCM). This model can be used as a platform for characterizing, comparing, and contrasting robots from all the scientific areas, and purposes with just a single glimpse. The CCM is easy to comprehend, and is targeting the robot designers and developers, as well as the ordinary user. Future work includes research on implementing this model, and its validity, by organizing an experiment where various robotic platforms will be tagged according to the CCM, and then participants only by looking at the tag would “guess” the properties and the abilities of the robot.

PAPER B: Social Robots as Persuasive Agents

I conceived the idea to write this paper when I was invited by Peter Øhrstrøm to give a talk on Robot Ethics during the 1st AAU Workshop on Robot-Ethics, Slettestrand, 30-31 October 2013. Unfortunately, no continuation was given to this promising workshop series. In this paper I state that social robots include in their definition all the three aspects of Fogg’s Functional Triad, namely the notion of media, the notion of tool, and the notion of social actor, therefore they should be considered, and treated as persuasive technology artifacts. Finally, I make an assemblage of robot-ethical issues that need to be addressed prior to HRI.

PAPER C: The Geminoid Reality

This paper could be considered as a review paper for the Geminoid technology. I have collected all the research conducted with Geminoids that could unveil what happens from the user’s side when interacting with a Geminoid. The user experience encompasses traces from both virtual, and augmented reality, but actually the total experience is even greater as the Geminoid Reality adds presence to the real environment. The notion that both the concept of the robot, and the concept of the human was –somehow- united in the Geminoid Reality needs further explanation.

Conceptual Blending is a general theory about cognition put forth by Faucounnier et al. [105]. The core idea is that human thought operates on basis of small pieces of conceptualizations oriented towards actions, and further thought. Such a conceptualization is called a mental space, and the theory of cognitive blending proposes that the mind essentially works by combining such mental spaces through a process of projections. This means that two or more mental spaces can be combined into a blended space where new structures emerge. Sometimes structures emerge that were not available from the input spaces alone. For the purpose of describing the meeting between human and android, presence can then be described as the blend of two kinds of facts that the human is aware of. Both kinds of information are readily available to the mind, but none of them makes up the basis for how to react to the android. Instead, the mind produces a blend of the two inputs, and it is in this blend that reaction forms. The blend is informed by knowledge of how to interact with humans based on general knowledge and previous experiences, as well as it is informed by previous conceptions regarding androids (fact, or media). The newly constructed blended mental space, then determines how the human should react and respond to the robot.

In the case of a meeting a full-size humanoid robot with distinct personal characteristics it would then make sense to assume that some people would begin their exploration of the phenomenon by placing emphasis on the human form in what they see before them. Conversely, others may begin their conceptualization by placing emphasis on the mechanical aspect of the robot. Within a very short span of time, people from both positions would be required to deal with the other aspect as well, blending the two, but it is unlikely that all would reach the same “middle position” between the organic and the mechanic as the blends proceed. If the blend is dominated by the impression of the organic human form, the challenge becomes to reconcile that perception with the fact that indeed this human form is made from steel, wires and silicone. And the other way around: if the blend is profoundly informed by the perception of mechanical engineering, than the task becomes to reconcile this with the fact that this apparatus may require considerations normally reserved for humans. Figure 7 illustrates the map blending of the two types of presence.

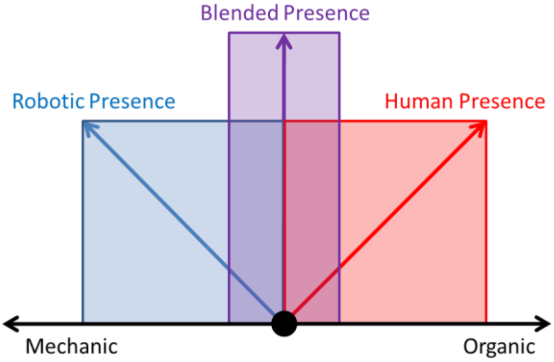

Figure 7 Blending of two types of presence.

PAPER D: Android Emotions Revealed

This paper seeks to find when a Geminoid portrays the six basic emotions more convincingly; when mimicking its Original, or when following a theoretical perspective according to the work of Paul Ekman and Friesen? In order to program the Geminoid after the Original, I had first to extract these emotions from the Original, meaning my supervisor. For this task, I had to come up with various psychological tests, and tricks in order to trigger genuine emotions from him. It's not an easy task. Figure 8 illustrates the laboratory conditions for acquiring the data. I was organizing, monitoring, and recording the session in room 2, while my supervisor was in room 1. The findings indicated that the emotional state of the robot when mimicking the human is equally, or more understandable by observers than when following the theoretical approach of how a facial muscles should be activated to reveal a specific emotion.

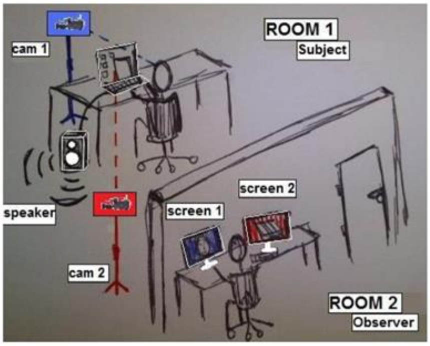

Figure 8 Geminoid Lab Settings for the Original's Photographs.

PAPER E: Towards Designing Android Faces After Actual Humans

Assuming that android robots had personality, it should be a combination of brand personality (the set of human characteristics associated with a brand), and human personality (the pattern of collective character, behavioral, temperamental, emotional and mental traits of an individual that have consistency over time and situation) [106 - 108]. Hardly a product is appealing to everyone, hardly a human is sympathized by all of his/her acquaintances, and hardly a generic anthropomorphic robot would enjoy a universal appeal [109, 110]. Therefore, social robots should be designed for specific user groups, should be embedded with personality traits that match the user's cognitive style, and adapt to the user's needs [111].

PAPER F: An Open-Ended Approach to Evaluating Android Faces

The robot properties, as well as the attitude of users towards the robot need to be evaluated prior to interactions. The properties of an android robot like the Geminoid are the expressiveness via its facial signs, and the attitude of the users pertains to how they decipher these expressions in their minds. Apart from the evaluation method that is thoroughly describe in the paper, a side outcome from the results was a collection of situations highly relevant to the portrayed facial expressions for emotions that could be used from a database system receiving to predict scene sequence, or next possible action of the human. This is related to the thirdness, and the production of meaning, where a robot needs to be able to make accurate guesses as to the reason a person is acting on a certain way.

PAPER G: Evaluating User Preference and Perception between a Mechanoid and a Humanoid in an Art Context

This was a joint research between my supervisor Henrik Scharfe, Elizabeth Jochum and me from Aalborg University, and Associate Professor (and artist) Louis-Philippe Demers from Nanyang Technological University (NTU) of Singapore who brought one of his robotic inventions, the Blind Robot, to Aalborg for an art exhibition. His robot was jointly exhibited with Geminoid-DK in a one-day open for the public art installation, named the UNSEEN on the 4th April, 2014 (Fig. 9, and Fig. 10). In this exhibition, visitors were invited to sit in the front of the robots and engage into a non-verbal dialogue with the Blind Robot, and into verbal dialogue with the Geminoid-DK. The paper analyzes the comparisons of impression that were made based on pre/post questionnaires, material, touch, and speech. The main message to take home is that a user's perception can change based on an actual interaction with a robot, even if the HRI is brief, and unscripted. Additionally, we confirmed that field studies in open environments like art exhibitions, or galleries where users can choose their level of engagement with the robot- are useful testbeds for identifying key factors in HRI research.

Figure 9 The Geminoid-DK setup during the UNSEEN experiment.

Figure 10 The Blind Robot setup during the UNSEEN experiment.

PAPER H: Head Orientations Behavior of Users and Durations in Playful Open-ended Interactions with an Android Robot

This paper is connected with the previous one, as all the data were retrieved from the same experiment (the Unseen). The difference here is that I focus only on the Geminoid-DK interactions, and analyze the head orientation behavior of users, as well as the duration of the interactions to investigate if visitors that approached the robot in groups would show increased rates of head turning behavior in contrast to those who approached the robot alone. The main goal is to examine if attention is shared when interacting with a robot while surrounded by others, and if the gender of the robot (as well as the gender of the participant) affects the attention span during dyadic HRIs.

PAPER I: Android Hands: A State-Of-The-Art Report

A review paper focused only on five finger robotic hands that highlighted the importance of the five fingers in future android robots was missing from the bibliography. Since, humanity has adjusted everything in accordance with its abilities, and limitations, an anthropomorphic robot should also adjust its properties within these predetermined boundaries. In this paper I present the anatomy, and the key functionalities of the human hand followed by the state of the art on android/humanoid hands for grasping and manipulating objects. The four prerequisites each robotic hands should possess in order to be presented in the study was to have size similar to human hand, five fingers, almost equal number of joints and degrees-of-freedom (DoF), and almost equal dexterity and grasping. The paper was written as future work when considering equipping the Geminoid-DK with articulated arms, and hands in order to expand its nonverbal expressions with hand gestures, and make it more interactive.

SUMMARY OF CONTRIBUTION

Considering the experience accumulated over the last three and a half years, all the discussions I have made, all the presentations and conferences I have attended, all the nine research papers I have written, and all the effort put behind them to understand the theories, to get a grasp of all previously conducted research, to formulate critical questions, to select the right methodologies, to set-up the experiments, to produce high-quality data, to analyze the results, and to reflect on the findings, I present you bellow *the eight main steps for sustaining emotional communication with an android robot*:

i) *Prior to interactions, you (the roboticist, the designer, the programmer, the engineer, the operator) have to evaluate the properties of the robot.* If it is a robotic arm, for example, then you have to measure how fast it moves, or how precise it is in order to know what to expect during the interactions. If it is an android robot designed for social interaction, then for instance you have to evaluate beforehand its facial expressions, or its dialogue system (Paper D, Paper F, and Paper I support this statement).

ii) *Prior to interactions, you have to assess the attitude of the users towards the robot.* You need to know your users, envision the HRI from their perspective, and you need to meet their expectations towards the robot. By assessing the attitude of the users, you gather information about both the robot, and the users, that will assist you in designing more natural HRI (Paper D, Paper F, and Paper G support this statement).

iii) *Prior to interactions, you need to know what tasks the robot can satisfy according to its appearance, morphology, and abilities*. This phrase can also be stated as: Prior to interactions, you need to know what type of robot can satisfy the tasks you need to resolve. Not all robots are capable of, or qualified for dealing with all sorts of tasks. You cannot expect an android robot to be better than a vacuum cleaning robot (e.g. Roomba) for cleaning the floor (Paper A, Paper E, Paper F, Paper G, and Paper I support this statement).

iv) *Robotic speech, lips synchronization, facial expressions and movements need to be coordinated.* Natural flow of communication (including verbal and nonverbal cues) is essential in sustaining durable interaction with a robot, especially when the interlocutor is in close proximity to the robot, and when the robot is intended to be used as a companion (experience gathered from all the Papers).

v) *The robot should avoid abrupt movements towards the user.* The majority of people have not encountered an actual robot before, not to mention an extremely anthropomorphic one, and relatively big in size (human size). The robot represents something strange and unknown to them, and they neither know what to expect from the robot, nor how to behave towards it. Therefore, communication can easily be disrupted due to fear, or due to uncanny feelings (Paper G, and Paper H support this statement).

vi) *The robot needs to be as capable as it appears to be.* This is something that you cannot do much about it if you are not in the robot’s production team, but you need to have it in mind as the “owner” of the robot. Users build very high expectations when the robot appears very human-like, as they assume that it will also behave and act very human-like, but most of the times it’s not the case (Paper B, Paper G, and Paper I support this statement).

vii) *Robot appearance matters less if the situation is engaging.* If it makes sense to use a robot in a specific situation, and the scenario of interaction is well designed, then robot appearance matters less. With an engaging scenario users react emotionally to the robot as if it was a human, and do not lose focus of attention by faults in the appearance, lack of expressions, or technical drawbacks. On the contrary, if the situation is less engaging then even the least significant imperfection of the robot might affect negatively the interaction (experience gathered from all the Papers).

viii) *The gender of the robot affects the interactions.* If the robot has a profound gender, or you decide to assign a gender to it, you have to expect different reactions from users. Users tend to engage more with robots of the opposite sex (Paper G, and Paper H support this statement).

These eight steps may be regarded as the culmination of my current interpretation of sustaining emotional communication with an android robot, but I claim neither that they form the only right interpretation, nor that they will withstand the test of time. Android Science is a very recent field of research, hence extensive in depth investigation on android robots and on human-android interaction has mostly occurred in research facilities, and laboratories (apart from very few exceptions like the Henn-na Hotel in Japan that is staffed with robots [112]). The presented results need further investigation, and validation, which will happen soon as more android robots are produced and put into actual use in real life situations.

The danger of the past was that men became slaves. The danger of the future is that men become robots.

Erich Fromm

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PART II

PAPER A. INTERACTIONS BETWEEN HUMANS AND ROBOTS

Evgenios Vlachos, and Henrik Schärfe

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The layout has been revised.

ABSTRACT

Combining multiple scientific disciplines, robotic technology has made significant progress the last decade, and so did the interactions between humans and robots. This article updates the agenda for robotic research by highlighting the factors that affect Human – Robot Interaction (HRI), and explains the relationships and dependencies that exist between them. The four main factors that define the properties of a robot, and therefore the interaction, are distributed in two dimensions: (1) Intelligence (Control - Autonomy), and (2) Perspective (Tool - Medium). Based on these factors, we introduce a generic model for comparing and contrasting robots (CCM), aiming to provide a common platform for robot designers, developers and users. The framework for HRI we propose stems mainly from the vagueness and the lack of clarity that has been observed in the definitions of both Direct and Indirect HRI.

Keywords— human - robot interaction; robot properties; interactions; operator; autonomy; control; tool; medium

1. INTRODUCTION

The emerging field of Human-Robot Interaction (HRI), which has recently received global scientific attention [1], is a multidisciplinary area that not only encloses the fields of Humanities, Social Sciences, Computer Science and Engineering, but also expands towards directions connected to Education, Medicine and the Life Sciences [2 - 4]. A shift towards a more human-centered design of HRI has been observed, including issues such as perceptions of robots, robot behavior, believability of interaction, and meeting people’s expectations [6, 7]. This human-centered perspective does not imply that the constant technical challenges that arise are of trivial importance. On the contrary, they continue to be taken into serious consideration.

Nevertheless, we still have difficulties in unlocking the mechanisms that steer human thought and action, and we still cannot provide a solid well-formulated definition of what a robot is, as the field of robotics is evolving following the Moore’s Law exponential curve [5]. Humans and Robots are two entities that our knowledge about them keeps constantly expanding; we are on the process of understanding the former, and exploring the boundaries of the latter. We believe that through the process of interaction we can approach all the above mentioned issues. However, it is important to realize that the nature of HRI is related to, but is different from human – human, or human - computer interaction.

This study proposes a model that allows comparisons and contrasts among robots from all the scientific fields, by exploiting the four main factors that affect the properties of a robot: Control, Autonomy, Tool, and Medium. In the next sections we will justify the reason why we have chosen these four factors, the relationships and dependencies that exist between them, and present a platform for comparing robots with the Compare-Contrast Model (CCM).

2. INTERACTIONS

Interactions between humans and robots that pertain to the flow of information and control can be separated into two main discrete categories (even though the human-robot communication may take several forms) according to their proximity [1, 8].

- *Direct or Proximate Interaction,* where humans and robots are co-located (physical interaction).
- *Indirect or Remote Interaction,* where humans and robots are dislocated, and are separated spatially, or even temporally (teleoperation / supervisory control / telemanipulation).

With the rise of Human - Centered Robotics, the role of the human started to claim its own space within the area of HRI, and issues like the types of interaction in HRI, which until now looked well established, started to be questioned. A special kind of mediation is required depending on the position and location of the operator of the robot, and the robot itself, in accordance to the surrounding environment. Most of the definitions about Direct Interaction are referring to the communication **between the robot and its surrounding environment** (composed of humans/ other robots/ objects/ nature), while in the Indirect Interaction are referring to the communication **between the robot and its operator** [8]. Until now we have approached the matter of Direct and Indirect Interaction by comparing two different entities. Even in the -so far accepted as- “Indirect” interaction, the communication between the robot and its surrounding environment is still direct. We firmly believe that there should be a distinction between the flow of information, and the flow of control. Fig. 1 depicts schematically the flow of information for these interactions, when on the other hand, the flow of control is strictly limited to the interaction between the operator and the robot, with a direction from the operator towards the robot.

According to the degrees of freedom the operator has, the robot can be more or less controlled, and consequently less or more autonomous. Autonomy refers to a robot’s ability to accommodate variations in its environment, and is a determining factor of HRI with regards to the tasks a robot can perform, and the level at which the interaction takes place [8]. Control, which is the inversely proportional quantity of autonomy, is added to the factors affecting the HRI.

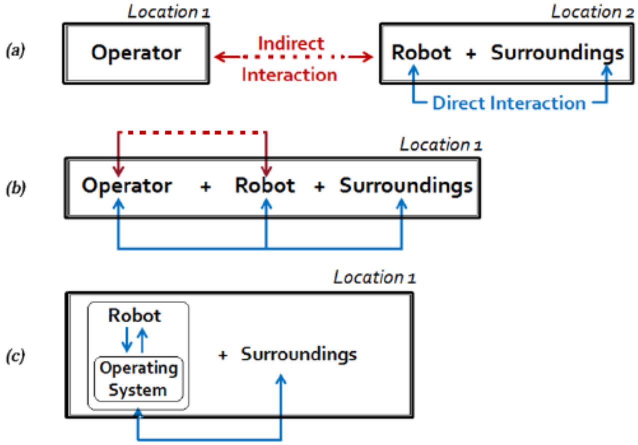

Figure 1 Flow of information in Human-Robot Direct and Indirect Interaction: (a) Operator and Robot Dislocated, (b) Operator and Robot Co-located (operator part of the surroundings), (c) Operator and Robot Co-located (operator part of the robot).

Figure 1 reveals also another factor that affects interactions, the one of location. This is indeed a critical factor, because when the operator and the robot are co-located, the operator is either part of the surroundings, or part of the robot (meaning the operating system). Further research towards that direction may reveal to what extent the presence, or absence of the operator affects interactions between humans and robots. Due to the insufficiency of information on the location factor at this point of research, we decided not to consider it as one of the critical factors for our model.

INTERACTION PARADIGMS

The three primary interaction paradigms are *computer-as-tool* (addressed mainly by the research community of Human-Computer Interaction), *computer-as-partner* (addressed mainly by the research community of Artificial Intelligence), and *computer-as-medium* (addressed mainly by the research community of Computer-Supported Cooperative Work) [9]. The computer-as-tool paradigm extends human capabilities through a tool, the computer-as-partner paradigm embodies anthropomorphic means of communication in the computer, and the computer-as-medium paradigm allows technology to serve as a mediator of communication between geographically distributed environments [10].

In the field of robotics, Artificial Intelligence is spread over almost all its applications, meaning that there are robots serving both as tools [11], and as mediums [12] that can be characterized as partners. Hence, we can consider *Tool* and *Medium* as our next two key factors that affect the HRI. Again, the factors Tool and Medium are inversely proportional, just like a robot built for industrial use, and a robot intended for social interaction. In most of the cases, we will not choose to design our robotic tools with social relational personas [13].

3. CLASSIFICATION OF ROBOTS

The best way to describe the notion of robotics is to look into the different types of robots that exist. Under the prism of Autonomy, Control, Tool, and Medium, we make an attempt to shed some light on the various applications, and fields of practice a robot can be engaged in. We separate these four factors in the dimensions of Intelligence (Autonomy-Control), and Perspective (Tool-Medium).

INTELLIGENCE

The degrees of freedom an operator has, makes the robot more or less *controlled*, and consequently less or more *autonomous*. It is highly likely to find a robot that combines elements from both of these sub-categories [23-29].

1) Control

- *Teleoperated,* is a remotely controlled robot guided by a human operator who views, and senses the environment through the robot sensors. Such robots are used mainly as mediums for communication (e.g., the Geminoid series [12]).

- *Telepresence,* is a robot that provides a two way audio, and video communication for embodied video conferencing using wireless connections (e.g., the Anybots' Virtual Presence Systems [32]).

- *Manually controlled,* is a robotic interface contolled in a non-autonomous manner. For example, a hand-operated tool used in surgical operations [33], a gaze-controlled robot [35], a gesture, or voice control robot [36], fall under this sub-category.

- *Brain controlled,* is a robot operated through a system that picks up electrical signals stemming from the brain, and translates them into commands [34].

2) Autonomy

- *Autonomous*, is a robot able to fulfill the given tasks by obtaining information solely from its surrounding environment without human intervention [27]. The human operator is substituted by an operating system located inside the robot. An *Epigenetic,* or a *Developmental Robot* can fall under this category since it uses metaphors from neural development and developmental psychology to develop the mind for autonomous robots [16]. It’s a type of robot inspired by the fact that most complex and intelligent biological organisms (as opposed to artificial ones) undergo an extended period of development before reaching their adult form and adult abilities.

- *Semi-autonomous* is a robot acting as an autonomous one, except for the occasions that a human operator interrupts its routine, and is involved so as to handle an event, or add perceptual input/ feedback.

- Neuro controlled, is a robotic system coupled with a network of living neurons coming from the cortex of a vertebrate [37].

PERSPECTIVE

1) Tool, aiming to extend the human capabilities, with Industrial Robots to be the most characteristic example. According to the ISO 8373 definition they are “…automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications” [31].

2) Medium, indicating communicative activity mediated via robots. Within this category fall Social Robots which are embodied agents, part of a heterogeneous group (including humans and other robots), and are able to recognize the members of its group, engage in social interaction, communicate within the social and cultural structure, and also learn [17, 28]. Embodiment means establishing a basis for structural coupling by creating the potential for mutual perturbation between system and environment [17]. Social robots are described as relational artifacts that convey intentionality, presenting themselves as having “states of mind” [18, 19]. There are two classes of social robots; the utilitarian robot, and the affective social robot, both assisting humans in achieving better physical, mental and emotional health [19]. Utilitarian robots, or domestic robots, or service robots, are designed to interact with humans mainly for instrumental, or functional purposes, helping them with their tasks. Affective social robots on the other hand, are robots designed to interact with humans on an emotional level, and are used as entertainment, therapeutic companions.

LOCOMOTION AND APPEARANCE

Two of the features that all the above factors share are Locomotion, and Appearance. *Locomotion* does not constitute a dimension since it has a binary value, either static or mobile, forbidding us to define the degree to which its measurement extends. Consequently, it is not considered as a critical factor, yet we analyze bellow briefly its components.

- *Static Robot,* which usually performs with precision dangerous difficult, or dull repetitive tasks like lifting objects, picking and placing, handling chemicals, or performing assembly work. The term static is interwoven with heavy industrious work, but today exist static robots that perform socially related tasks. One of them is the iCAT platform from Phillips Research [38].

- *Mobile Robot,* which can move and navigate in the real world and can be either autonomous, or controlled. The type of the mobile robot movement varies from floating, swimming, and flying to rolling, crawling, or walking [27].

Maybe the interface is the most important component of a robot because it uncovers immediately the purpose that it serves, and sets the interaction rules. Nevertheless, *appearance* is also not a dimension, and will also not be considered among the critical factors, because its components cannot be valued in one direction. A summary of the available interfaces follows.

- *Mechanoid:* A robot with a machine-like appearance which has no overtly human like features and bears no resemblance to a living creature [20].

- *Zoomorphic:* A robot built to imitate living creatures. For this kind of robots, a zoomorphic embodiment is important for establishing human–creature relationships. Usually their objective is to create robotic “companions” [21].

- *Anthropomorphic (anthrobots):* Anthropomorphism is a term coming from the Greek term “anthropos” for man and “morphe” for form, and is attributing human characteristics to robots aiming to rationalize their actions [30].

- *Humanoid:* A robot which is not realistically human-like in appearance, but possesses some human-like features, which are usually stylized, simplified or cartoon-like versions of the human equivalents, including some or all of the following: a head, facial features, eyes, ears, eyebrows, arms, hands, legs.

- *Android:* A robot which is built to mimic humans both in appearance, and behavior. Androids have a broad range of applications and can sometimes combine the features of various types of robots [20], [22].

- *Caricatured:* The principle of exaggeration is at the heart of caricature. It involves amplifying the distinct features that identify the kinetic display in order to make the content of the behavior more convincing. This involves isolating the features that uniquely identify the content of the expression [14].

- *Virtual:* These robots act like virtual simulators in order to test the software of a robot while the real robot is still at the stage of development. It predicts the result of a command before the command is send to the remote robot [39].

4. THE COMPARE - CONTRAST MODEL

As we have discussed in the previous sections, autonomy and control are two inversely proportional quantities, meaning that the more autonomy a robot has, the less controlled it is. In that case, the Robot Properties are depending on the Control and Autonomy Properties the robot encloses. The line tangent to the function Autonomy = 1/Control (Fig. 2a) is the hypotenuse of the (always) right triangle that is formed, and represents the Robot Properties. Likewise, tool and medium are also two inversely proportional quantities (Tool = 1/Medium) that define the Robot Properties, and a second right triangle is formed (Fig. 2b).

The reasoning process described so far, leads to the following four extreme situations that can characterize a robot: (1) totally Medium - totally Controlled, (2) totally Medium - totally Autonomous, (3) totally Tool - totally Autonomous, and (4) totally Tool - totally Controlled. Before we proceed further, we should note that our study is taking into consideration not only the existing robotic technology, but also future scenarios where robots may be a naturally integrated part of human life, or even act independently of humans.

- *To be totally a Medium and totally Controlled.* This is the usual scenario for most of the teleoperated and telepresence robots. The Giraff “caregiving” robot is a characteristic example [15].

- To be totally a Medium and totally Autonomous. If a robot is used as a medium, then it cannot take decisions automatically. It is built to communicate messages from one person to another. For instance, an “autonomous” virtual agent with a set of pre-programmed responses, or with the ability of adjusting its behavior to the user via fuzzy logic algorithms, can be described only as a medium and will never obtain total autonomy since it will always be serving its programmer. We can safely state that the Medium factor, and the Autonomous factor are two inversely proportional quantities (Medium = 1/Autonomy).

- To be totally a Tool and totally Autonomous. An industrial robot (e.g., a robotic arm) is the perfect example of this scenario.

- To be totally a Tool and totally Controlled. When a robot is totally controlled, all and only the intentionality and the capabilities of the operator are transferred to the robot, and mediated to the surrounding environment. On the contrary, a robot as a tool is extending the capabilities of the human, in this case the capabilities of the operator. The robot needs to have at least a very small percentage of automation embedded inside in order to fulfill the expectations of a tool. A robot functioning as a tool cannot be totally controlled. Therefore, Tool is inversely proportional to Control (Tool = 1/Control).

Fig. 3a visualizes all the above relationships into the generalized Compare – Contrast Model (CCM) for robots, where the Robot Properties are depending on the Control, Autonomy, Tool, and Medium features that every robot possesses. The model suggests neither that the fluctuation rate of Control is exactly the same as the fluctuation rate of Medium, nor the fluctuation rate of Autonomy is the same with the fluctuation rate of Tool. The model implies only that their relations are proportional; if one of them increases, then the other one will increase too, but not to the same degree.

The purpose of CCM is to provide a common ground of communication -a baseline- where robot designers, developers and even users can share a mutual understanding of the potentialities, and the limitations of every robot. Thus, comparisons and contrasts between different types of robots are possible. Our interaction model has descriptive power (ability to describe a significant range of existing robots), evaluative power (ability to help assess robots), and generative power (the ability to help designers develop new robots). A tag on each robot with a schematic diagram that illustrates these relationships can reveal very easily its purpose, and its characteristics with just a glimpse.

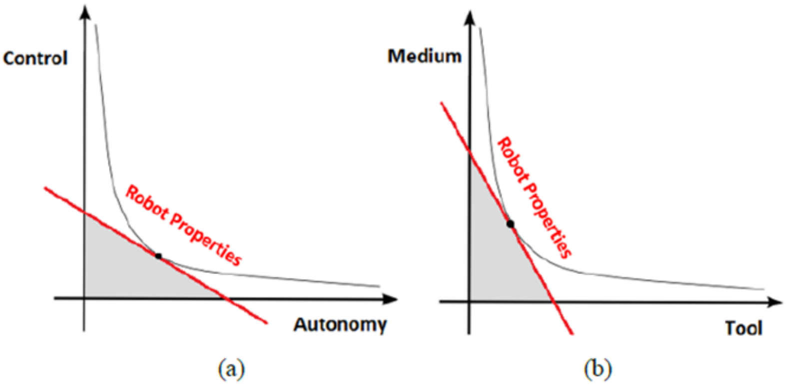

Figure 2 The hypotenuse of each right triangle depicts the Robot Properties for the (a) Intelligence dimension (Control and Autonomy), and the (b) Perspective dimension (Medium and Tool).

5. CONCLUSION

We made an attempt to present all the possible ways that could define the properties of a robot, and consequently the interactions. The expectations towards a robot functioning as a tool, are completely different from the expectations established if the robot is used as a medium of communication. The starting point for this study was a limitation the theory of HRI presented, by not having explicitly defined the notions of Direct and Indirect Interaction. Based on our observations we showcased the four main factors that affect the robot properties and the HRI, namely Control, Autonomy, Tool, and Media. The selected factors were justified by presenting a classification of robots according to them, and by explaining the reasons why we excluded the three, also important, factors of Location, Locomotion, and Appearance. Finally, we analyzed the relationships between these factors and presented the theory, the concept, the architecture, and the objectives behind the Compare-Contrast Model for robots. The proposed model aims to be used as a platform for characterizing, comparing, and contrasting robots from all the scientific areas and purposes. The CCM is easy to comprehend, and is targeting the robot designers and developers, as well as the ordinary user. Future work includes research on finding all the possible attributes of the presented factors, in order to finalize our model with a formula for the Robot Properties that would fully describe the characteristics of each robot.

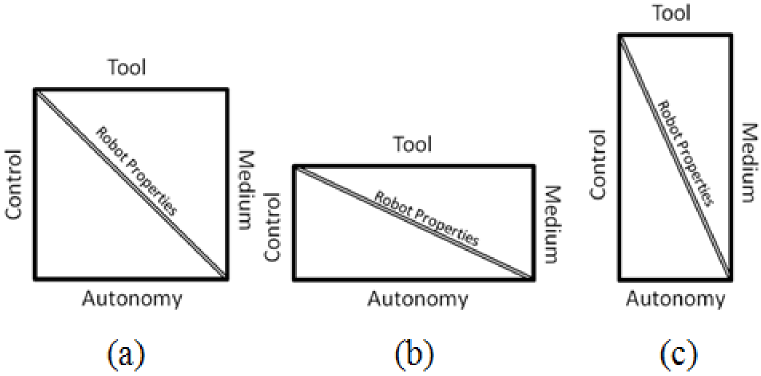

Figure 3 (a) Schematic diagram for the Compare-Contrast Model (CCM). (b) A robot that is more Autonomous and less Controlled, or more of a Tool than a Medium, (c) A robot that is less Autonomous and more Controlled, or more of a Medium than a Tool.

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PAPER B. SOCIAL ROBOTS AS PERSUASIVE AGENTS

Evgenios Vlachos, and Henrik Schärfe

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ABSTRACT

The topic of human robot interaction (HRI) is an important part of human computer interaction (HCI). Robots are more and more used in a social context, and in this paper we try to formulate a research agenda concerning ethical issues around social HRI in order to be prepared for future scenarios where robots may be a naturally integrated part of human society. We outline different paradigms to describe the role of social robots in communication processes with humans, and connect HRI with the topic of persuasive technology in health care, to critically reflect the potential benefits of using social robots as persuasive agents. The ability of a robotic system to conform to the demands (behaviors, understanding, roles, and tasks) that arise from the place the robot is designed to perform, affect the user and his/er sense of place attachment. Places are constantly changing, and so do interactions, thus robotic systems should continually adjust to change by modifying their behavior accordingly.

Keywords: human-robot interaction, persuasive agent, social robots, ethics, place attachment.

1. INTRODUCTION

Until very recently, robots were limited to industrial environments, and research facilities. Only lately did they migrate to our daily life, and became more social, user friendly, communicative, and interactive. In most of the cases of social HRI the user is not able to distinguish clearly the entities that are embodied within the robot when interacting with it. Is the robot completely autonomous and self-oriented, or is it semi-autonomous? Is the robot controlled by a human, by a team of humans, or by other robots? What kind of information is the robot storing? Why and for what purpose? Does it share information with third parties, and who are they? A precondition needed for establishing a trusting relationship between the user, and the robotic system prior to interaction, is to have an answer for each of the risen questions above, meaning that the robotic system should be completely overt. For that reason, HRI could borrow the Code of Ethics from Information and Communication Technology (ICT) called PAPA, acronym of privacy, accuracy, intellectual property, and access [1]. Indeed, HRI and ICT share a plethora of common ethical issues; however, a robot’s physical representation is a decisive factor in the argument in favor of determining new ethics for robots, the robo-ethics.

The majority of the published research findings in HRI deal with the target group of children and elderly people. On the one hand, there is a growing body of research presenting fruitful interactions between children and robots in the home, and in the classroom, specifically when the subject matter is related to science and engineering [2, 3]. Robots have also been shown to have a positive outcome in therapeutic applications for children [4]. On the other hand, according to the Population Division of the United Nations the population ageing is considered unprecedented, pervasive, enduring, and has profound implications for many facets of human life [5]. Moreover, space and staff shortages at health care facilities are already an issue, therefore ageing population is expected to need extensive physical and cognitive assistance. Assistive robotic systems and companion robots for the elderly could be a solution provided that technologies are capable of being commanded through natural communication (e.g., facial expressions, speech, non-verbal communication, gestures), of grasping and lifting items, and of assisting with daily chores and tasks (e.g., navigation, moving, feeding) if they are to improve the physiological and psychological health of the ageing population.

In the following sections we will discuss the notion of social robotics, present the key principles of persuasive technology, explain how the displayed behavior of a robot can affect the requirements for place attachment, and finally investigate the relationships between a user, a robot, and the robot's operator in a HRI scenario tak-ing place in a health facility.

2. SOCIAL ROBOTICS

Robots that are able to interact and communicate with humans in a human-like manner, but also with other robots, as well as with their environment, respecting the existing social, and cultural norms are called social robots [6]. When interacting with such robots we apply social rules, and act on inherited behavioral guidelines, expecting that the robots will have the ability to understand, and follow them. Notable instances of social robots around us are the Geminoid-DK android when it took up the role of a university lecturer, or the role of a business man making financial proposals in an office [7], the Geminoid-F android when it performed in theatrical plays around the world [8], the Telenoid teleoperated humanoid when used for facilitating communication with elderly people suffering from dementia [9], the Kaspar humanoid robot when fostering cooperative dyadic play among children with autism [10], the Rofina teleoperated robot when it helped children with special needs to understand play behaviors [11], and the Zeno child-like humanoid when it assisted physical therapists to treat sensor-motor impairments [12]. Several researchers have also explored interactions with zoomorphic robots like the robot dog AIBO that uses body language and simple musical melodies to communicate with people [13], the robotic creature Kismet that engages physically, affectively, and socially with humans so as to learn from them [14], the seal robot Paro when used to improve the lives of elderly dementia patients [15], the Nabatzag rabbit that augments audio messages with display of non-verbal expressions [16], or the robotic cat NeCoRo whose behavior depends on the history of its interactions and can recognize its name [17].

Robots were not initially created to deceive, but to be trusted. After all, the term robot comes from the Czech word “robota” which means forced labor, or servitude and firstly appeared in the play R.U.R. (Rossum’s Universal Robots) by the author Karel Čapek in 1921 [18]. Their purpose was, and still is, to serve the human either by handling situations, data, or by dealing with various tasks.

3. PERSUASIVE TECHNOLOGY

If we assume that social robots bare strong similarities to traditional media, they should be defined as a medium that connects users to a source of a message. Under the view of computer-as-medium paradigm [19], the robot is the mediator of communication between the users, and the robot programmer or/and the robot operator. Therefore, HRI can be considered as human-human interaction. On the contrary, paraphrasing the computer-as-source unmediated perspective users respond to social robots as a source of information by following unintentionally the Media Equation formula (convenience to perceive robots as humans) [20]. There is strong evidence that in HCI users communicate directly with the computer, and not with a vague persona of a programmer behind it. If we apply these results to the area of HRI, then users should relate directly to the social robot, and not to the person behind it, either this person holds the position of a programmer, a designer, an operator, or embodies a whole organization, or a brand. But, is that the case? Ambient intelligence, multi-Intelligence (draw on multiple sources of intelligence, including big data, cloud and crowd resources), and networked robotics (share sensory input, solutions and problems across many locations and application areas), are three popular research topics among roboticists that enable robots to be more than mediating artifacts. Hence, robots include in their definition and the other two aspects of Fogg’s Functional Triad [21] namely the notion of social actor, and the notion of tool. Robots, and especially social robots, encompass much more qualities than a computer does, and since they are a relatively new field of technology, people have not yet conceptualized their full range of abilities. In order to minimize the amount of false information such robots transmit, either intentionally for the greater good of the mixed initiative team comprised of the user, the robot and its operator, or unintentionally due to the effects of the Media Equation formula, the user should in advance be informed of what the robotic system is capable of doing, and equally important of not doing.

According to the Greek philosopher Aristotle persuasion was the art of convincing people to accept something, or do something they would normally not otherwise. The three modes of persuasion introduced by Aristotle are Ethos (ethical character of the source of information), Pathos (emotional state of the receiver), and Logos (argument) [22]. For a persuasive message a blend of all three is needed. The definition of persuasive technology (PT) includes robotic systems that are “designed to change people’s attitudes or behaviors or both without using coercion or deception” [21]. Gass et al. [23] proposed that “persuasion involves one or more persons who are engaged in the activity of creating, reinforcing, modifying, or extinguishing beliefs, attitudes, intentions, motivations, and/or behaviors within the constraints of a given communication context". The ultimate goal of PT is to promote wellbeing, health, quality of life, and a more sustainable lifestyle, but requires awareness of the user that it is an intentional act, and at all times he/she has the choice to decline. Trust in robotic systems directly influences both the interactions, and the overall acceptance of robotic agents. A user's trust, or distrust, towards a robot is expanded towards the entities that are embodied in the robot, which might be the programmer, the operator, the organization, or company the robot is located in, and even the brand of the robot (e.g., Honda Motor Co. in the case of Asimo, Kokoro Co. ltd in the case of the Geminoids, and Hanson Robotics in the case of Zeno).

What nearly all of the social robots have in common is the –most of the times- false message they transmit concerning two features that make their character being perceived more believable, and encourage interaction; the freedom of their actions, and their degree of autonomy. In [24], due to false attribution of robot capabilities, the children were expecting the robot to play along with them, while researchers were expecting the children to play along with the robot. Hiding or showing false infor-mation can be regarded as manipulation of the truth. This kind of deceit takes unintentional advantage of the effects of the Media Equation [20] and tricks the human mind by letting it treat machines in the same way as towards other people.

4. PLACE ATTACHMENT

"*The structure of the space around us moulds and guides our actions and interactions*", S. Harrison and P. Dourish [25]. The place a user is located frames his/er behavior, and automatically creates a mental icon concerning both the properties of the robotic system, and the type of HRI that would take place in case a robot was present. Therefore, even before real time HRI occurs, the user might have already categorized the expected-to-be-there robot by following unintentionally a robotic version of the HCI Paradigms; robot categorized as a tool (extending the abilities, strength, competence, intelligence of the human), robot categorized as a medium -or avatar [6]- (being a mediator of interpersonal communication and intentionality), robot categorized as a partner (embodying anthropomorphic features, humanlike properties, behavioral characteristics, and emotional/mental states) [26-28]. It seems that the HCI paradigms are identical to the Fogg's Functional Triad that was discussed in the previous section.

Places are constantly changing as they are continuously enacted by people [29]. Being part of the material topography of a place, the robotic system should be readjusted according to these changes either by being reprogrammed manually, or by being able to detect them through its sensory input and modify its behavior. The character of HRI can only be understood, and thereafter evaluated, if linked to a place. Thus, the evaluation criteria for a competent robotic system are limited to only one; how well it conforms to the user's perspective, meaning how well it fits the place. This criterion can be subdivided into smaller segments that represent each task, and each task can also be decomposed to smaller components in relation to the objectives of the task.

While place plays an essential role in human life, it is equally important in robotics, and often takes precedence over all other aspects of HRI. Place attachment is defined as the bond a person develops for a place that "evolves from specifiable conditions of place and characteristics of people" [30]. Extending that definition towards the field of HRI we suggest that robotic behavior should be added to the key factors that affect place attachment. Social robots are structurally coupled with their operational environment, and are connected to it with channels of mutual perturbation [31].

Hence, negative attitudes toward a robot, might lead to negative attitudes toward the people, the organization, the brand, or the company the robot embodies. We hope our statement to stimulate further research in order to avoid being confronted with the phenomenon of place aversion (including brand, company, and organization aversion) due to prejudice against interacting with robots in the near future.

5. ETHICAL CONCERNS IN A HRI SCENARIO

Let us consider the scenario where a hospital makes use of a toy-robot companion for hospitalized children to play with. The robot is monitoring the child, observing every move, collecting personal information and, sending them to a system supervised by an operator. Figure 1 depicts the interactions between the user, the robot, and the robot's operator. The default situation would be the autonomous circle, where the robotic system supervises/communicates-with the user without the intervention of an opera-tor. The operator would only override the autonomous circle in case of an emergency, and take control of the robot. We believe that a human operator should always be engaged in HRIs not only for safety reasons, but also to maintain the human presence vivid and the communication expressive if the automation fails to do so in some cases. The toy-robot holds three roles; (i) is the mediator of communication between the operator (the doctors, and the hospital;) and the hospitalized child, (ii) is a tool measuring temperature, pulse rate, blood pressure, and whatever else is needed according to the situation, and (iii) serves as a companion partner to the child, where the child is speaking to, sharing personal stories, and maybe information that even his/her parents are not aware of. The toy-robot exhibits all of the persuasive characteristics in Fogg's Functinal Triad, but the cognitive and/or mental state of the child might not be sufficient to understand the roles of the involved stakeholders, including that of the robot. Is a consensus between the parents and the hospital about using a toy-robot enough? The toy-robot should neither be used as a justification for leaving the child on its own for longer time since it could lead to malformed development and emotional problems [2], nor as an excuse to migrate the responsibility from humans to robots [32]. One can imagine the same scenario with people suffering from dementia.

Another ethical concern is the liability of the robotic system. In case of a malfunction we have to be consistent with where to place responsibility. It could be the ethics of the operator, the ethics of the designer, the embedded ethical system of the robot, or the ethics of the user. According to [33], the wisest decision is to either avoid blaming anyone, or blame everyone. To prevent such a dramatic turn of events from happening, the stakeholders (user, operator, organization) should form a mixed initia-tive team having one common goal aligned and oriented towards one direction; to protect the user, and secure his/er interests.

6. CONCLUSION

Throughout this paper we focused on ethical concerns raised when humans communicate with robots. We posed questions regarding the privacy, accuracy, intellectual property, access, and liability of a robotic system aiming to formulate an ethical research agenda for issues related to human robot social interaction. In a brief overview we have linked the notion of social robotics to that of persuasive agents, and proposed that social robots could be more than just mediating artifacts. Social robots could also act as tools, and social actors, and thus have all the characteristics in Fogg’s Functional Triad. The ability of a robotic system to adjust

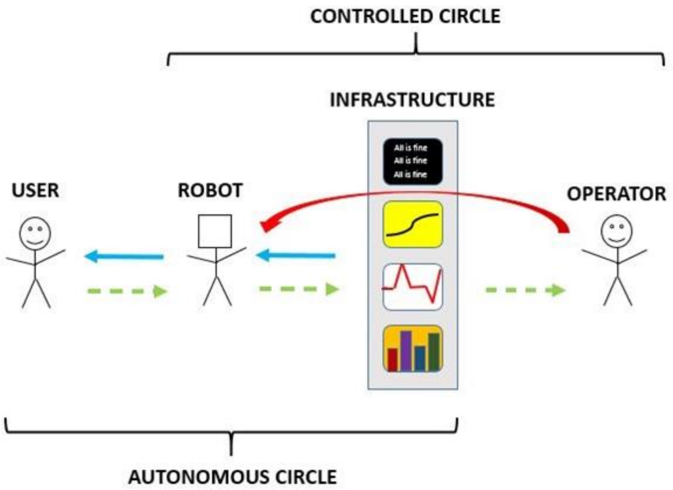

Figure 1 Interactions between the user, the robot, and the operator featuring the Autonomous Circle (operator does not intervene in the HRI) and the Controlled Circle (operator intervenes in the HRI)

to the behaviors, understanding, roles, and tasks that arise from the place the robot is designed to perform, affects the user and his/er degree of place attachment, the bond a person develops for a place.

An aligned perspective among the stakeholders of HRIs through the formation of a mixed initiative team could be the first step towards ensuring that robots do actually benefit, and protect the users, and are not just designed to alleviate guilt from parental personalities, or reduce operational costs of an organization. In spite of the fact that robotic systems are designed by humans, and have more human values inherited than expected, the engagement of a human operator is a reassuring act indicating that robots are not here to substitute us, but to assist us.

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PAPER C. THE GEMINOID REALITY

Evgenios Vlachos, and Henrik Schärfe

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ABSTRACT

Our society is on the borderline of information era, experiencing atransition towards a robotic one. Humanoid and android robots are entering with a steady pace into our everyday lives taking up roles related to companionship, partnership, wellness, healthcare, and education among others. The fusion of information technology, ubiquitous computing, robotics, and android science has generated the Geminoid Reality. The Geminoid is a teleoperated, connected to a computer network, android robot that works as a duplicate of an existing person. A motion-capture system tracks facial expressions, and head movements of the operator, and transmits them to the robot, overriding at run-time the preprogrammed configurations of the robots actuators. The Geminoid Reality is combining the Visual Reality (users' and robot's point of view) with an Augmented one (operator's point of view) into a new kind of mixed reality involving physical embodiment, and representation, causing the ownership transfer, and blended presence phenomena.

Keywords: geminoid, android, human-robot interaction, reality, presence, teleoperation.

1. GEMINOID ANDROID ROBOTS

Androids, due to their anthropomorphic design, are used to facilitate social interaction, and to study the human nature, while geminoids are used as research tools to examine how the presence, the appearance, the behavior, and the personality traits of a robot affects the communication with human partners [1]. The geminoid, coined from the term "geminus" meaning "twin" or "double", and the suffix "-oides" which indicates similarity, is an android robot designed, and developed to resemble an existing person (the Original), envisioned and manufactured by Prof. Hiroshi Ishiguro,ATR Intelligent Robotics, and Kokoro Inc. [1-2]. A geminoid is mimicking the external appearance (the artificial body is of similar proportion), and the facial characteristics of its Original (Fig. 1). Facial characteristics include permanent wrinkles, skin texture, skin coloration, skin pigmentation, bone structure, facial hair, hair coloration, and hair style. It is remotely controlled, with no intelligence of its own, but able to execute pre-programmed sequences of movements (subtle expressed motions such as breathing, blinking emulating the human autonomous system to maintain naturalbehavior), overridden at run-time by the conscious behavior controller driven by a motion-capture system that tracks the facial expressions, and head movements of the operator [3-4]. Movement is executed by means of pneumatic actuators inside the robot in all the geminoid versions (HI-1, HI-2, F, DK) [5]. The speech of the operator is also transmitted through the computer network of the geminoid to a speaker located either inside, or around the robot.

Figure 1 The Geminoid|DK (left side) with its Original (right side).

2. ENTERING THE REALM OF GEMINOID REALITY

While Augmented Reality refers to a real-time direct, or indirect view of a physical real-world environment enhanced with virtual computer-generated sensory [6], and Visual Reality to a constructive process formulated by evolution to guide adaptive behavior [7], the Geminoid Reality (GR) is combining them into a new kind of mixed reality that encompasses physical embodiment, and representation (Fig.2). Being present means readiness to engage, cope, and deal with the surrounding environment, but also ability to witness subjects, objects, and actions, while keeping a record of the witnessed events [8]. In GR, all the intentionality from the surrounding environment is being directed towards the android, but witnessed by the operator through a telepresence system. As long as the GR is in effect, the geminoid with its operator form a symbiont unity which creates a situation akin to mirror-touch synesthesia; a tactile hallucination triggered by observing touch to another person which enables the observer to simulate another's experience by activating the same brain areas [9 – 11]. The illusion of body *ownership transfer* felt by the operator, occurs due to the synchronization between the operation of the robot, and the visual feedback of seeing the geminoid’s motion [12].

Apart from the operator, interactions with a geminoid affect also the users. The anthropomorphic appearance of the geminoid tricks the human mind by taking advantage of the same brain mechanisms that human beings use to understand other humans [13]. This conflict inside the human mind describes the notion of the *blended presence*, where the brain fails to categorize an agent that appears human, but moves mechanically. The selectivity of the human action perception system for the appearance and/or motion of a perceived agent was explored using functional magnetic resonance imaging repetition suppression, confirming the blended presence phenomenon [14].

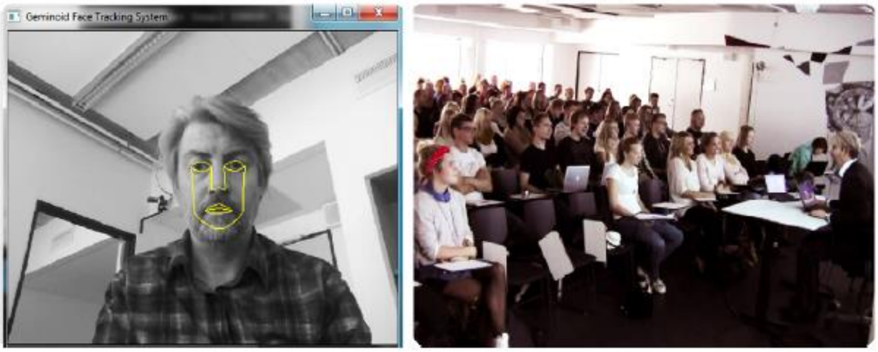

Figure 2 Left: Augmented Reality (part of the operator's point of view). Right: Visual Reality (users' experience).

3. INTERACTION SCENARIOS AND REPORT EVALUTION RESULTS

Despite the fact that the GR has been studied mainly inside laboratories, and research environments, its scope is to be gradually integrated into a form of Ubiquitous Intelligence, where technology is deployed in such way that it becomes an invisible part of the fabric of everyday life [15]. Placement of geminoids in real life scenarios enriches our knowledge on human-robot communication, our experience on practical implications, our database on recorded reactions of interaction partners, and our understanding on how the robot is perceived. Extending the use of GR in the real world, an observational field study on unscripted interactions between humans and the Geminoid HI – 1 was conducted in a public café in Linz, Austria, where 43 participants (out of 98), either mistook the robot for a human, or did not notice it at all, as it seemed to appear human-like [16]. Another instance, is when the Geminoid-F was used as an actor in a play, performing live on stage in theatres around the world [17]. The results indicated that androids might be better poetry reciting agents than humans, and that they can span their usage beyond a practical media interface. An experiment on how touch can be used as a way of inducing trust when interacting with an android was conducted in a typical office room, where the Geminoid|DK (in business attire dress code) was proposing a business deal to the participants [18]. Trust towards the robot was increasing when subjects were touching it before the business proposal. The Geminoid|DK also took up the role of a university lecturer and delivered a 45 minute lecture in front of 150 students at Aalborg University [19]. Overall, the robot was accepted as a lecturer, but during the lecture a change of perception regarding the geminoid has been observed. There were strong indicators that females had higher expectation concerning the geminoid's communication skills, raising an issue on the role of the gender of the robot. A noticeable detail was that several students constructed the impression that the lecturer was human, and maintained it till the end of the lecture.

A fact that all experiments share, is that at first sight, and from a distance it is difficult to tell the Original, and the geminoid apart [20]. In a questionnaire for the evaluation of Geminoid HI-1 and its Original, participants were able to distinguish between the human, and the android stimuli, but the ratings for likeability were not significantly different [21]. Additionally, a web-based survey for rating robots (40 robots-151 participants), claimed that the Geminoid|DK was considered to be among the highly likeable and less threatening ones [22].

Different geminoid versions present different limitations in expressing/ mimicking/revealing emotions through their affective interface. The Geminoid-F was found to successfully produce facial expressions of Happiness, Sadness, and Neutral Face, but failed in expressing Surprise, Anger, and Fear [20]. Alike, the Geminoid|DK reproduced all six basic emotions, but Fear and Disgust [9]. Geminoid developers should cater to accommodate the need for more actuators around the areas of the nose, the mouth, and the eyes in future geminoid versions, for a more natural, and believable interaction.

3. CONCLUSION

The Geminoid Reality is a very recently conceived reality, with no formulated and pre-determined boundaries, still under development, since both the field of robotics is expanding, and we -as humans- have not yet unlocked the brain mechanisms that steer our thought, and action. To sum up, the main properties of the GR could be structured around the following two distinct phases towards the robot; ownership transfer from the perspective of the operator, and blended presence from the perspective of the interaction partner.

Whether, or not, the scenarios discussed in this paper will become applications is a matter left to be discovered in the imminent future. The teleoperated, semiautonomous, portable facility of geminoids, paves the way for many potential uses, making them possible substitutes for clerks, for instance, that can be controlled by one human operator only when non-typical responses are required [2]. Today, we count very few geminoid robots, located in very few research laboratories around the world, scattered in different continents, facts that impose a very slow pace in the GR research in contrast to other kinds of reality.

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PAPER D. ANDROID EMOTIONS REVEALED

Evgenios Vlachos, and Henrik Schärfe

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ABSTRACT

This work presents a method for designing facial interfaces for sociable android robots with respect to the fundamental rules of human affect expression. Extending the work of Paul Ekman towards a robotic direction, we follow the judgment-based approach for evaluating facial expressions to test in which case an android robot like the Geminoid|DK –a duplicate of an Original person- reveals emotions convincingly; when following an empirical perspective, or when following a theoretical one. The methodology includes the processes of acquiring the empirical data, and gathering feedback on them. Our findings are based on the results derived from a number of judgments, and suggest that before programming the facial expressions of a Geminoid, the Original should pass through the proposed procedure. According to our recommendations, the facial expressions of an android should be tested by judges, even in cases that no Original is engaged in the android face creation.

Keywords: Social robotics; Geminoid; androids; emotions; facial expressions; emotional health.

1 . INTRODUCTION

Before the transition from an industrial to a post-industrial society, when the technology-centered view was dominating [1], the words human – computer interaction automatically generated a tag cloud of terms like navigation, manipulation, automation and control. During the post-industrial society, the focus of interaction started to move from the physical machine to the users' world and the interfaces evolved from hardware to social processes [2], [3]. A turn towards human-robot interaction (HRI) has been observed. Henceforth, during the information era, studies presented a shift of focus towards designing social robots, understanding human behavior and rethinking the role of the machine [4]. Communication theories and cognitive psychology principles were applied to the field of robotics in order to produce as natural interaction as possible and to examine whether the responses from humans were affected by the abilities and the appearance of the robots [5].

The Media Equation communication theory [6] states that human-machine interaction is inherently natural and social, and that the rules of human-human interaction apply also to human-machine interaction. The popularity of the above mentioned theory can be justified easily when realizing that people are used to rely on social and mental models to deconstruct complex behaviors into more familiar, understandable and intuitive forms with which to interact [7]. Despite that fact, following the human perspective to address such issues may not be the most efficient one. Humans are the best known example of emotional interaction, but duplicating human emotional abilities in machines does ensure neither reliability, nor performativity [8].

In the context of social robotics, when interaction with the user happens in real time, synchronizing the facial gestures and expressions of a robot to the flow of the interaction is essential. For the acceptance of a sociable robot as an equal communication partner, progress is needed in at least one of the following areas; physical appearance, balanced movements/motions/gestures, expression and/or perception of emotions, engagement in conversation, responsiveness to users, and ability to process social cues in face to face communication [22], [24]. The more believable and competent the robot appears, the more users will have the impression of interacting with a human partner rather than with just a moving manikin. Even slight improvements to the robots' interface can add credits to the ease of HRI [21].

An issue that is effortlessly rising is "How an android robot can embody emotional facial expressions with respect to the fundamental rules of human affect expression?" [35]. To address this issue, we used the Geminoid|DK android robot [5], [23] which is a teleoperated duplicate of an existing person, the facial expressions of which can be programmed or evaluated by referring to the Original person. Reliance only to the facial characteristics of the Original might prove inadequate. In this study, the Geminoid will be tested on the following hypothesis: **The emotional state of the Geminoid|DK when mimicking the Original is equally or more understandable by observers than when following the theoretical approach of Ekman and Friesen in [13].**

We have already presented the train of thought behind this study and in the next sections we will introduce the Geminoid Reality, explain the judgment-based approach for studying facial expressions, describe the research design methodology for acquiring the empirical data, analyze our findings, validate or not our hypothesis and finally conclude with a discussion about our findings.

2. GEMINOIDS AND RELATED RESEARCH

In the last decades, as technology was progressing following the Moore's Law exponential curve [39] and microprocessors were improving in speed and/or performance while decreasing in size, societies were struggling to adapt to these abrupt changes. One after-effect of that fierce technological explosion was the fact that humanity suddenly gained the power to receive and process at the same time, almost parallel to real time, more information than they could physically sense with the natural human sensors. Humanity had the power to build systems, programs, and algorithms that could predict the effects of various changes in the environment, simulate these changes to virtual environments, and be ready to take action in reality. Both the sensors and the results of this enhanced sensing -either of the environment or thyself- could be available on small portable devices. A complex system that encapsulates the same or similar attributes with the one described above, formulates a different kind of reality and is perceived as a different one. Enriching the already known visual reality and objective reality, terms like virtual reality, augmented reality and mixed reality were introduced [11], [18], [26], [28], [30], [36].

THE GEMINOID REALITY

Hiroshi Ishiguro, the inventor of the first Geminoid android robot, strongly believes that society today is on the verge of the robotic age, a period of time that will allow us to comprehend the essential natures of humans and society [38], while Schärfe already speaks of an Android Reality.

While virtual reality replaces the real world with a simulated one and augmented reality enhances the real environment with additional virtual information, Geminoid Reality is going one step further. It combines the real environment (robots point of view) with an augmented environment (robots operator point of view) into a new kind of mixed reality with blurry boundaries that is challenging even our perception on visual reality.

In order to be present in the world, it is vital to be ready to engage, to cope and to deal with the world and also to witness events, people and things that are available [27]. Witnessing also requires a record or representation of what has been witnessed. In the Geminoid Reality, the operator of the robot is engaging and coping with the world, dealing with the world and witnessing events, people and things without being physically situated there. His/her presence is substituted by the Geminoid. The operator and the Geminoid form a symbient unity which creates a situation akin to *mirror-touch synesthesia*; a tactile hallucination triggered by observing touch to another person which enables the observer to simulate another's experience by activating the same brain areas that are active when the observer experiences the same emotion or state [12], [15].

The truth about the Geminoid Reality is that it can only be studied in relation to the available technology [20]. Since the field of robotics is still progressing, so the boundaries of Geminoid Reality will keep changing.

RELATED RESEARCH

Distributed over different kinds of reality, a variety of robotic research has placed emphasis on different aspects of facial expressions, demonstrating the potential in a natural, human like interface. Zoomorphic robots with humanoid facial expression capabilities include MIT’s *Leonardo* [9] and the *iCat* from Philips [10]. In both cases, expression of a range of human emotions is obtained through actuation of the face, often with surprisingly empathic results. Besides the Geminoid series dealt with in this paper, androids with emphasis on facial expressions include the android heads of David Hanson [19] and the *Kansei* head from Meiji University [37]. While the former two robots are often used to obtain and process input from a user as basis for generating an appropriate response, the latter two rely on databases linking emotional expressions to words and phrases.

3. ARCHITECTURE OF DESIGN

THE JUDGMENT-BASED APPROACH

The judgment-based approach suggests that when viewing a facial expression, emotion can be recognized entirely out of context, with no other information available. This judgment depends on the judges' past experience of that particular facial expression; either of his/her own face in conjunction with a particular feeling, or someone else's face in conjunction with other revealing verbal or non-verbal behavior, or in general according to types of activity that have been adaptive in the ancestral past of the species [14], [17].

There are two conceptual types of measurement that focus on different phenomena for studying nonverbal behavior involving observers; the judgment-based approach where judgments about messages are measured, and the sign-vehicle based approach which measures the sign-vehicles that convey the message. In the message judgment approach the observer is asked to judge whether each subject, who is depicted in a visual input (image or video sequence), is for instance happy or sad, according to the facial expressions that the subject showed. These messages are best represented as dimensions or categories. Observers make inferences about the emotions that underlie the subjects' behavior and for that reason they are referred to as "judges". In the sign-vehicles approach, some or all of the facial expressions and movements would be classified or counted in some fashion, for instance happy subjects lift their cheeks more than the other subjects. Observers describe the surface of behavior by counting how many times the face moves, or how long a movement lasts and are referred to as "coders". As an example, upon seeing a smiling face, an observer with a judgment-based approach would make judgments such as "happy," whereas an observer with a sign-based approach would code the face as having an upward, oblique movement of the lip corners [33].

EMPIRICAL STUDY

We need three sets of photographs depicting the facial expressions of the Geminoid|DK that correspond to the six basic universally accepted emotions of surprise, fear, disgust, anger, happiness and sadness. In total, we need eighteen photographs separated in three equal sets. The first set will be composed of photographs of the Original (O) while expressing the six basic emotions, the second set will be composed of empirically driven (ED) photographs, where the Geminoid will be mimicking the Original, and the third set will be composed of theoretically driven (TD) photographs, following the standards of Ekman and Friesen [13].

A dataset of photographs consisting of facial frames of the Original when posing to the camera would only reveal feigned emotions which present significant differences from the prototypical natural ones [25]. In order to depict genuine facial expressions from the Original, all of the six basic emotions had to be triggered. The triggering had to happen naturally; otherwise the reliability of the whole outcome could be questioned. In order to have clear and unambiguous photographs, we decided to subject the Original to a multimodal test on his laptop. The test consisted of a variety of different applications, programs, media, and videos, either online or installed to the laptop of the Original. Each of these was intended to trigger a different emotion. The test was accompanied by a set of instructions explaining the execution order.

The Original was placed in front of his laptop and had one camera pointing at his face, recording the facial expressions, and another one pointing at the screen of the laptop, keeping track of the actions. The next step was to analyze carefully the 44,600 micro-expressions (frames) from the first camera (High Definition - recording 50 frames per second), assign emotions to each of them and finally select six that according to [13] correspond to some universally accepted facial expressions of emotion. The selected photographs depicted one of the many facial expressions that correspond to an emotion. Due to the fact that the triggering was done through a laptop, the eyes of the Original tend to look a bit down (at the screen). Fortunately, this did not affect the outcome of the experiment. Some properties that every photograph shares are that they show the full face under sufficient lighting, are in focus and they are about the same size.

In the figures bellow (Fig.1, Fig.2 and Fig.3), follows a comparison/juxtaposition of the three sets of photographs with the facial blueprints of emotions as they are presented in [13]. For the sake of briefness, the figures illustrate only three of the six emotions; Anger, Happiness, and Sadness.

MEASURING EMOTIONS

As Picard says, even though one has better access to his/her innermost feelings than anyone else, it is still difficult to “recognize” or label the feeling [35]. Through the years, many procedures have been developed for measuring emotions which can be separated into two main categories; the free response measurement and the forced choice response measurement. We can partition off the latter into two sub-categories; the dimensional approach and the discrete emotions approach [16], [17].

Figure 1 All facial blueprints for the emotion of Anger (representing Controlled Anger). From left to right: Unmasking the Face (UTF) – TD – ED – O. [reprinted with permission]

Figure 2 All facial blueprints for the emotion of Happiness (representing Full Face Happiness or Intense Happiness). From left to right: UTF – TD – ED – O. [reprinted with permission]

Figure 3 All facial blueprints for the emotion of Sadness (representing the Lips Down Sad Mouth). From left to right: UTF – TD – ED – O [reprinted with permission]

When emotions are shown as discrete systems, usually the respondents are asked to assess their emotions by a selection from a list of pre-determined emotions or provide feedback on the intensity of an emotion [16]. Following the theories developed by Ekman, we need to be able to select among six different emotions. The research on facial emotions has shown the utility and efficiency of conceiving emotions in discrete states, rather than in dimensions [34]. Dimensional measurements may be most productively applied to emotional experience aggregated across time and to the study of the moods [17]. There appear to be discrete boundaries between the facial expressions of emotion, much as there are perceived boundaries between hues of sound. Facial expressions are perceived categorically, and there is accumulating evidence supporting the claim that a discrete system is better applied to momentary experiences of emotion.

RESEARCH METHOD

We decided to launch an online questionnaire in order to collect feedback from observers. In total we projected 13 videos, each one illustrating a selected facial expression of the Geminoid|DK; 6 with the ED photographs, 6 with the TD photographs and one more video (the first one) that was used as a trial demo.

This questionnaire should not be considered as a test. We don’t intend to train the subjects into recognizing emotions, therefore there is no need to force them view each stimulus only once, or for a fraction of a second [31], [32]. After all, the facial movements of the Geminoid are mechanical and the change of facial status takes more time than a micro-expression. This questionnaire should also not be considered as a survey, since there is no need to specify a sampling frame, or to ensure sample coverage. According to Ekman, the facial expressions that correspond to the six basic emotions of surprise, fear, disgust, anger, happiness and sadness are considered to be psycho-physiological entities universally accepted [13], [17]. These primary prototypical facial expressions reveal emotions that can be understood universally by people regardless of their gender, nationality, social or economic status, and age (except for infants). The questionnaire is following the judgment-based approach and it can only be described as a judgment. Consequently, the subjects who respond to the questionnaire can be characterized as judges. Judges should fulfill two criteria; read and understand the English language, and be at least aware of the android technology in order to avoid “disorientated” results. Those who follow the Geminoid on the Facebook social networking service formulate an acceptable and considerable large group of people that are familiar at least with the Geminoid technology, have access to a computer with internet connection, and know how to communicate in English. An online questionnaire can provide honest answers, as respondents feel that their privacy is not violated [29]. Due to the medium that the questionnaire was launched, and due to time/cost constraints, the judges were random non-expert respondents who had access to the link, representing a group that resembles real world end-users but, admittedly, also introducing the risk of noisy answers.

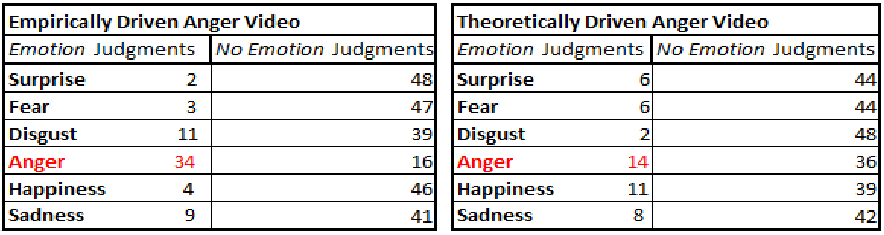
Instead of using static photographs as stimuli, we decided to use videos. Displaying a short video that reminds the blinking of an eye was considered to be a more reliable option, as most facial expressions of emotions during a conversation last between 500ms and 2.5s [32]. Our videos would last seven seconds. During the 5th and 7th second the videos would be blank, and during the 6th second they would display the frame of the facial expression. The first frame (4 seconds) would warn viewers about the briefness of the video. Judges could view the videos as many times as they wanted, and they were prompted to answer the question "*What emotion do you think the face in the video is showing?*" by selecting from a list with the pre-determined six basic emotions on a two-point intensity scale; either the emotion existed, or not.

4. ANALYSIS OF THE RESULTS

The online questionnaire was reached by 678 unique visitors worldwide, but only 50 of them (34 females and 16 males) actually filled and submitted it. The overrepresentation of female respondents was anticipated [29]. The judges were located mainly in Europe, except for two coming from America, and belonged mainly to the age group of 21-30 years old (one was less than 15, nine belonged to the group of 16-21, thirty belonged to the group of 21-30, eight belonged to the group of 31-40, one to the group of 41-50 and one belonged to the group 51-60).
The results for the *Surprise* videos indicated that the strong majority of the judges named the emotion of Surprise as the dominant one, understanding our intention. The judgments for the Surprise emotion in the emotionally driven videos (EDV) outnumber the ones of the theoretically driven videos (TDV) (45 and 39 respectively), validating our hypothesis. The second most dominant emotion for the EDV was Happiness with 24 votes and for the TDV was Anger with 24 votes. In the *Fear* videos, the judgments favored another emotion than the one we intended to show. Instead of Fear, both videos revealed mainly the emotion of Surprise (49 judgments for the EDV and 44 for the TDV). This outcome suggests that the Geminoid is a substitute expressor for Fear. The emotion of Surprise is quite pronounced, coloring the whole facial expression. However, the emotion of Fear was better understood in the EDV than in the TDV (32 against 26 judgments), so the hypothesis is satisfied. For the *Disgust* videos, there was no agreement among the judges about an emotion. No more than a third of the judges gave any one judgment**,** excluding only the emotion of sadness (28 judgments) for the EDV and happiness for the TDV (17 judgments). This result suggests that the Geminoid|DK might be a withholder. The Disgust judgments were equally distributed (5 each), validating again the hypothesis. Both of the *Anger* videos were judged as we indented to (34 judgments for the EDV and 14 for the TDV), fact that confirms our hypothesis. The emotion that came second in the judgments was Disgust with 11votes (EDV) and Happiness with also 11 votes (TDV), as shown in Table 1. The

Happiness videos were also understood (45 judgments for the EDV and 44 for the TDV), but the judges distinguished also the emotion of Surprise (28 judgments for the EDV and 30 for the TDV). This outcome suggests that the Geminoid|DK is a substitute expressor to a slight degree that is not so evident. One more time the hypothesis was confirmed. Results for the *Sadness* videos revealed that there was almost an even split between the intended emotion of Sadness and another emotion – that of Anger. This outcome suggests that the Geminoid|DK might be an Anger-for-Sadness substitute expressor, as Anger was the second most dominant emotion at the EDV with 9 judgments and the most dominant at the TDV with 19. Observers' judgments matched with what we were expecting only in the EDV (24 judgments in the EDV against 12 in the TDV); therefore the hypothesis is confirmed.

Table 1 Table form depicting the experimental results for the Anger videos.



Empirically Driven Anger Video		
Emotion Judgments		*No Emotion* Judgments
Surprise	2	48
Fear	3	47
Disgust	11	39
Anger	34	16
Happiness	4	46
Sadness	9	41

Theoretically Driven Anger Video		
Emotion Judgments		*No Emotion* Judgments
Surprise	6	44
Fear	6	44
Disgust	2	48
Anger	14	36
Happiness	11	39
Sadness	8	42

5. CONCLUSION

We have presented the current status of the Geminoid technology and what it needs to become Geminoid Reality. Apart from an adaptive interface able to communicate with the surrounding environment, it also needs to have believable characteristics and be able to actively engage in interaction. The process of finding the ways a Geminoid can embody emotional facial expressions with respect to the fundamental rules of human affect expression was based on a robotic perspective of the work of Ekman.

The results of the questionnaire revealed an incapability of the Geminoid to reproduce the emotions of Fear and Disgust. Our proposal here concerns the next version of the Geminoid series. We believe that an installation of actuators to the facial areas of the *levator labii superioris /alaeque nasi* (nose wrinkle), *levator labii superioris/caput infraorbitalis* (upper lip raiser), *depressor anguli oris (triangularis)* (lip corner depressor), *incisivii labii superioris* and *incisivii labii inferioris* (lip puckerer) and *orbicularis oris* (lip tightener) will ease the HRI. Another addition that would reveal even more natural facial expressions could be to make the already installed actuators operate independently (i.e., to lift just one eye-brow).

Lastly, we have proven that the emotional state of the Geminoid|DK is equally or more understandable when mimicking the Original than when following the theoretical approach of [13]. This finding suggests that before programming the facial expressions of a Geminoid, the Original should pass through a similar procedure. In cases that no particular Original is engaged in the android's face creation, the facial expressions of the android should be tested by judges in a similar way. Following our recommendations, a believable facial communication is within reach.

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PAPER E. TOWARDS DESIGNING ANDROID FACES AFTER ACTUAL HUMANS

Evgenios Vlachos, and Henrik Schärfe

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ABSTRACT

Using their face as their prior affective interface, android robots and other agents embody emotional facial expressions, and convey messages on their identity, gender, age, race, and attractiveness. We are examining whether androids can convey emotionally relevant information via their static facial signals, just as humans do. Based on the fact that social information can be accurately identified from still images of nonexpressive unknown faces, a judgment paradigm was employed to discover, and compare the style of facial expressions of the Geminoid-DK android (modeled after an actual human) and its' Original (the actual human). The emotional judgments were achieved through an online survey with video-stimuli and questionnaires, following a forced-choice design. Analysis of the results indicated that the emotional judgments for the Geminoid-DK highly depend on the emotional judgments initially made for the Original, suggesting that androids inherit the same style of facial expression as their originals. Our findings support the case of designing android faces after specific actual persons who portray facial features that are familiar to the users, and also relevant to the notion of the robotic task, in order to increase the chance of sustaining a more emotional interaction.

Keywords: Android Robot · Facial Expression · Emotion · Static Signals · Social Perception · Human-Agent Interaction.

1. INTRODUCTION

How a face appears to be is a combined result of genetic factors, environmental and cultural moderations, and individual choices [1]. Faces convey messages via their four types of signals; *the static signals* which include the permanent aspects of the face, such as skin pigmentation, morphological/bone structure (i.e., jaw size), cartilage, fatty deposits, and size/shape/location of the facial features (mouth, nose, eyes, brows), *the slow signals* which include changes in the facial appearance due to ageing, for instance permanent wrinkles, or changes in muscle tone, *the artificial signals* such as cosmetics and plastic surgery, and *the rapid signals* which are temporary changes in facial appearance produced by momentary movement of facial muscles (also known as microexpressions) [2]. This paper is focused on the messages transmitted by the static and slow signals of an android robot, an artificial system designed with the goal of mimicking humans in their external appearance/shape, featuring human-like characteristics in its behavior, regarding motion, intelligence and interaction/communication patterns [3-6]. Androids take advantage of their anthropomorphic design to facilitate social interaction, and elicit social responses [7]. Using their face as their prior affective interface, and as an identification provider, androids and other agents embody emotional facial expressions, and convey messages on their identity, gender, age, race, and attractiveness through their static and slow facial signals [2, 8]. Related research on the rapid signals can be found in [9] and [10].

Central ideas of P. Ekman and W. V. Friesen [2] were used to examine whether androids can convey emotionally relevant information via their static facial signals, just like humans. Considering the fact that socially relevant information (i.e., personality, sociosexuality, aggression, trust-worthiness) can be identified with accuracy in human faces from visible cues in neutral static images alone, as well as the fact that a large number of functional neuroimaging studies have used neutral faces as a baseline condition for comparing facial expressions, we resorted to using neutral images for our study [11-21]. A judgment paradigm at zero acquaintance ("*perceivers are given no opportunity to interact with targets who are strangers to them*" [22]) was employed to discover, and compare the style of facial expressions of the Geminoid-DK android (modeled after an actual human) and its' Original (the actual human). We want to discover the relation between the emotional judgments for the Geminoid-DK, and the emotional judgments initially made for the Original. *We hypothesize that the emotional judgments for the Geminoid-DK will depend on the emotional judgments initially made for the Original*. Our purpose is to persuade researchers to model android and agent faces after specific actual persons who portray facial features that are relevant to the notion of the robotic task, and also familiar to the users, in order to increase the chance of sustaining a more emotional Human-Agent Interaction (HAI). Hardly a product is appealing to everyone, hardly a human is sympathized by all of his/her acquaintances, and thus hardly a generic anthropomorphic agent would achieve a broad appeal.

Mimicking the facial characteristics of a real person is a typical approach when designing android robots today. However, most androids in the scientific literature are built for research purposes without anyone giving consideration to their faces matching any specific function. Notable instances are: Albert HUBO modeled after Albert Einstein, PKD-A after the novelist Philip K. Dick, Android Twin after the roboticist Zou Ren Ti, Repliee R1 after a five year old Japanese girl, "Rex, the bionic man" after the psychologist Bertolt Meyer, FACE android is based on a real subject, Bina48 after the co-founder of the Terasem Movement Foundation, Face Robot after the death mask of a human, EveR-2 is based on a Korean female, Geminoid-HI is built after its creator Prof. H. Ishiguro, and Geminoid-DK after Prof. H. Scharfe [23-32].

2. FACIAL EXPRESSIONS

Facial expressions signal information related not only to the emotional states, but also to the disposition, and the behavioral intention of the interaction partners predicting their future actions [33-35]. Research on personality judgments from facial images indicates that a core accuracy indeed exists in social perception of faces [36], while in [37] it is showcased how a social outcome, such as an electoral success, can be accurately predicted through the brains ability to automatically categorize faces. The evaluation of novel faces possibly influencing the likelihood of social engagement with unfamiliar conspecifics is performed by the primate amygdala [38]. Even though the frontiers of Artificial Intelligence are constantly expanding, simulating the way this subcortical brain region works, and applying it to robots is not yet feasible.

STYLES OF FACIAL EXPRESSIONS

Emotions can exist without facial expressions, and facial expressions can exist without congruent underlying emotional states, as they can be modified by voluntary muscle movements [39]. The individual’s culture, gender, or family background imposes different unwritten codes governing the manner emotions are expressed [40]. The underlying reason for the phenomenon of attributing specific facial expressions to specific social contexts has been observed to be the intention to reveal less negative emotions, leading eventually to tighter bonds within the group [41, 42].

The need to control one’s behavior through managing the appearance of a particular emotional expression appropriate for a particular situation in a certain context is described by societally defined rules called display rules [43]. Deeply ingrained habits about managing facial expressions, idiosyncratic to an individual, are developed and learned during childhood, or through a particular experience [44], resulting in a particular cast to someone’s facial expressions leading to eight characteristic *styles* of *facial expressions* [2]: *the Withholders* have an unexpressive face, and rarely reveal any emotion, *the Revealers* are the opposite of the withholders, and cannot modulate their facial expressions - emotions are “written” all over their faces, *the Unwitting expressors* do not know what emotion their face is showing, *the Blanked expressors* whose faces look blank when they think they are showing an emotion, *the substitute expressors* substitute the appearance of an emotion for another without knowing that this is happening, *the frozen-affect expressors* always show a trace of one of the emotions in some part of the face when actually not feeling any emotion at all, *the ever-ready expressors* characteristically show one of the emotions at their first response to almost any event, and situation, and *the flooded-affect expressors* show one, or two emotions in a fairly definite way almost all the time -there is never a time when they are feeling neutral.

3. THE EXPERIMENT

STIMULI

A Geminoid is a teleoperated robot built after an existing person, and developed as a communication medium to address several telepresence, and self-representation issues [32]. The facial expressions of the Geminoid can be programmed and evaluated by reference to the Original person [9]. Following the recommendations of P. Ekman and W. V. Friesen, the style of facial expression can be extracted through 5 judgments on neutral pictures [2]. We selected a facial expression from our database were the Original looked neutral, not experiencing any emotion, and looking calm/relaxed (Fig. 1/left). Then, we adjusted the values of the 12 pneumatic actuators of the Geminoid-DK to mimic that expression (Fig. 1/right). The stimuli was composed of two videos, each one depicting one of the selected neutral expressions of Fig. 1 in between two black frames, resembling the blinking of the eye. Each video lasted 7 seconds; the first 4 seconds informed the viewers about the briefness of the video, the 5th one was left blank, the 6th projected the image and the last one was left blank again. We also projected one more video in the beginning of the survey depicting the Original when surprised (having the answer already noted), serving as an example of the questionnaire process. The recognition rate of emotional expressions might be higher, and have less ambiguity when dynamic sequences are shown rather than still pictures [45], but we wanted to simulate a behavior analogous to interacting with the robot in real life. The movements of the Geminoid are mechanical, abrupt and the change of facial status takes a lot more than a micro-expression. The emotions revealed have almost zero onset and offset time, and are depicted in a position around the peak of the emotional display. Communication partners of the android cannot tell if the emotion is emerging, or if it is dissipating.

DESIGN

According to the judgment-based approach, emotion can be recognized entirely out of context, while the judgments depend on the judges' past experience of that particular facial expression, either of his own face or of someone else's in conjunction with a revealing behavior [9, 46]. We launched an online questionnaire with video stimuli in order to attract judges. It was a within-subjects design (every user judged both videos) on zero acquaintance (any impact of the stimulus target can be attributed primarily to the physical features of the target). For further validation, the stimuli were tested against the Noldus Face Reader 5, a tool providing emotional assessments (six basic emotions, and the neutral one). Face reading software gives the ability to minutely analyze, and validate assumptions about both natural and artificial faces.

PROCEDURE

Judges were prompted to answer the forced-choice type question "*What emotion do you think the face in the video is showing?*" by selecting from a list with the pre-determined six basic emotions (disgust, sadness, happiness, fear, anger, surprise) on a 2-point intensity scale; either the emotion existed, or not. The neutral choice was not included as people have a tendency to pick this answer when they are uncertain of a facial expression [2]. Judges could re-view the videos since our goal was not to test them whether they can recognize emotions, or train them to do so.

Figure 1 Facial blueprints for the Neutral Face of the Original (left), and the Geminoid-DK (right).

PARTICIPANTS

The judges were non - expert respondents, representing a group of people that resembled real world end-users. P. Ekman and W. V. Friesen state that with the assistance of five judges the results will be sound. All responses were anonymous, providing comfort to the judges to freely select an emotion from the predetermined list. We attracted the attention of 50 participants (34 females, and 16 males), who belonged mainly to the 21-30 years old age group.

4. RESULTS AND STATISTICAL ANALYSIS

RESULTS

The results illustrated at Fig. 2 indicate that the strong majority of the judges (half, or more) named the emotion of Anger as the dominant one for the Original, with 36 judgments. There was little agreement upon the judgment for the Geminoid; almost every emotion term was used by one, or another judge. The 23 Sadness judgments as well as the 24 Anger judgments are less than the half (25), but still significantly high.

The Noldus Face Reader 5 software tool provides results independent of human judgments. We loaded the same facial blueprints to the Face Reader, after having assigned a calibration to each participant; one to the Original, and one to the Geminoid-DK. By using the individual calibration method, the Face Reader can correct person specific biases towards a certain emotional facial expression. The calibration consists of a few seconds video with the participant maintaining a neutral mode while making mild facial expressions of emotion. As depicted in Fig. 3, both images were classified as Neutral (long horizontal bar in the Expression Intensity module), but the emotion of Anger was predominantly present (short horizontal bar) while the rest of the emotions remained on a zero level.

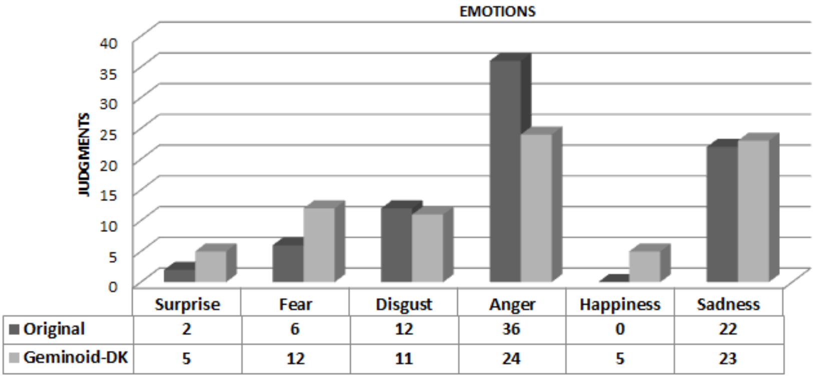


Figure 2 Emotion judgments for the Neutral Faces.

Figure 3 Printscreens from the Noldus Face Reader 5 System featuring the Analysis Visualization (left), and the Expression Intensity (right) modules for the Neutral faces of the Original (up), and the Geminoid-DK (bottom).

STATISTICAL ANALYSIS

Regression analysis showed that the R value, which represents the Pearson Correlation (how strong the linear relationship is), is 0.939. This value indicates a very high degree of correlation between the emotion values of the Original and the Geminoid. The R-squared value, representing the coefficient of determination, equals to 0.882, indicating that the dependent variable "Geminoid-DK" can be explained to a high degree by the independent variable "Original”. In other words, **the emotional judgments for the Geminoid-DK highly depend on the emotional judgments for the Original**, **thus our hypothesis is true**. The statistical significance of the regression model that was applied is 0.005 (p-value), less than 0.05, indicating that the model applied can statistically significantly predict the outcome variable. Details for the ANOVA and Regression Coefficients are depicted in Table 1. The residuals that are illustrated in Table 2 show the difference between the observed value of the dependent variable (Original) and the predicted value (Geminoid). The residual plot seems to have a fairly random pattern (values range around zero and seem normally distributed) which dictates that a linear model provides a decent fit to the data.

5. DISCUSSION

The results indicated that the strong majority of the judges named the emotion of Anger as the dominant one for the Original (36 judgments). *This outcome suggests that Anger is an emotion often revealed through the face of the Original, and he could be regarded as a frozen-affect expressor for the emotion of Anger,* either because he maintains some element of that emotion in his face due to not totally relaxing his muscles when not feeling any emotion, or due to his static signals, and the morphology of his face (deep set eyes, and a low eyebrow). Differences in facial morphology could be the outcome of life long differences in expressiveness, but they could also be attributed to the fact that masculinity and anger expressions share perceptual space such that masculine faces tend to be perceived as angrier than non-masculine faces. Research by D. Vaughn Becker et al. shows that the “Spontaneous generation of a mental image of an emotional expression is likely to summon an associated gender: Angry faces are visualized as male.” [47]. The same study reveals that neutral male faces, relative to neutral female ones, were more likely to be misidentified as angry and less likely to be identified as happy. The zero Happiness judgments for the Original support this case. The 23 Sadness judgments for the Geminoid are justified, as Sadness is a frequent response to a neutral face [2]. However, the 24 Anger judgments combined with the results of the Face Reader software (Fig. 3) which indicate that Anger is an emotion predominantly present in the Geminoid, suggest that the Geminoid-DK has a frozen- affect for the emotion of Anger to a slight degree. The overall results, thus, conclude in stating that the style of facial expressions of the Original, and part of his personal display rules have passed to the android robot. On the occasion where indeed the judges misidentified the human model (connecting anger with masculinity), then they will act similarly when judging the robot by making the same “mistakes”, and by repositing the same misconceptions, and impressions to the robot, as the statistical analysis indicated. In that case, our study is not affected at all. On the contrary, it would enhance our argument that it is possible to copy the style of facial expressions of a real human into a robot.

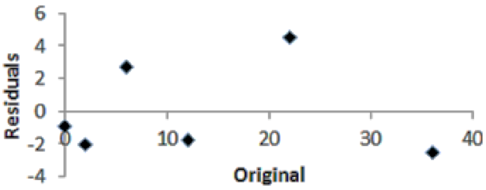
Table 1 ANOVA and Regression Coefficients tables.

ANOVA					
	df	*SS*	*MS*	*F (Ftest)*	*Significance F (Pvalue)*
Regression	1	311,5115789	311,51158	29,794214	0,005476
Residual	4	41,82175439	10,455439		
Total	5	353,3333333			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	5,889122807	1,898035984	3,102746	0,036125	0,61933	11,15892
X Variable 1	0,572631579	0,104908173	5,458408	0,005476	0,28136	0,863903

Table 1. Residual Output and Residual Plot for the Original.

Observation	*Predicted Geminoid-DK*	*Residuals*
1	7,034385965	-2,03439
2	9,324912281	2,675088
3	12,76070175	-1,7607
4	26,50385965	-2,50386
5	5,889122807	-0,88912
6	18,48701754	4,512982



6. CONCLUSION

We (the humans) have adjusted our space, actions, and performed tasks according to our morphology, abilities, and limitations. Thus, the properties of a social agent should fit within these predetermined boundaries. For a successful HAI, the agent should meet the expectations of its interaction partners, satisfy the goals of the task, match its appearance, and behavior to the given situation, and, lastly, be overt. Agents should let their users know about what they are capable of doing, as well as of not doing, prior to HAI in order to avoid deceit, or attribution of false capabilities respectively [48]. We do not propose embodiment of anthropomorphic cues to all types of agents, not even to all the social ones. However, *if a certain task can be best accommodated by an android, then by modeling the androids' face after a specific human who portrays facial features that are familiar to the users, and relevant to the notion of the task the chances for prolonged and more meaningful HAI will probably be increased.* That, of course, still remains to be tested. By showing that the emotional judgments for the Geminoid-DK highly depend on the emotional judgments initially made for its Original, we suggest that androids inherit the same style of facial expression as the humans they are modeled after. This study is only a step towards designing android faces after actual humans. Future research plans include experimentation with more androids that are modeled after humans.

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PAPER F. AN OPEN-ENDED APPROACH TO EVALUATING ANDROID FACES

Evgenios Vlachos, and Henrik Schärfe

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ABSTRACT

Expectation and intention understanding through nonverbal behavior is a key topic of interest in socially embedded robots. This study presents the results of an open-ended evaluation method pertaining to the interpretation of Android facial expressions by adult subjects through an online survey with video stimuli. An open-ended question yields more spontaneous answers regarding the situation that can be associated with the synthetic emotional displays of an Android face. The robot used was the Geminoid-DK, while communicating the six basic emotions. The filtered results revealed situations highly relevant to the portrayed facial expressions for the emotions of Surprise, Fear, Anger, and Happiness, and less relevant for the emotions of Disgust, and Sadness. Statistical analysis indicated the existence of a moderate degree of correlation between the emotions of Fear-Surprise, and a high degree of correlation between the pair Disgust-Sadness. With a set of validated facial expressions prior to nonverbal emotional communication, androids and other humanoids can convey more accurate messages to their interaction partners, and overcome the limitations of their current limited affective interface.

1. INTRODUCTION

An android robot built for social interaction should embody emotional facial expressions in a respectful way towards the fundamental rules of human affect expression for achieving natural communication [1]. One of the features of emotions is to provide information about the inner-self of an individual (plans, thoughts, memories, changes in physiology), about the action which preceded that facial expression of emotion (antecedents) and about the action that is most likely to occur after the facial expression (immediate consequences, regulatory attempts, coping) [2]. Therefore, an android robot capable of making facial expressions of emotion provides information to its surrounding environment about its most probable following action. Other types of nonverbal behavior namely posture, gestures, gaze, and orientation of the interactants are of equal importance, but will not be examined in this study.

Humans and robots forming a mixed initiative team working jointly together on common tasks is one of the visions the field of Human–Robot Interaction (HRI) has. However, robotic technology presents significant limitations on the design of the facial interface, since it is still struggling to approach the complex system of the human face [3]. Despite that fact, various android and humanoid robots equipped with the ability to express emotion are slowly, but steadily, entering into our lives. Experimentation with socially embedded robots includes studies in locations varying from universities, conference venues, and auditoriums, to field studies on unscripted interactions in shopping malls, exhibition centers, and even coffee spots. There are instances of androids and humanoids teaching in universities [4], playing theatrical roles [5], communicating with elderly people [6], playing with children with autism [7], helping children with special needs [8], and assisting therapists in sensor-motor impairments treatments [9]. Thus, interaction with people coming from various backgrounds takes place, whose expectations are really high when communicating with an android. Meeting users' expectations is one of the most important issues in HRI today. Consequently, face-to-face interaction with such robots might create discomfort in recognizing either the facial expression of emotion, and/or the probable following action of the robot. A mismatch between the robots' future action and the anticipated action influences the user's attitude and behavior, and might disrupt the communication. Limitations in flexibility, coloration and plasticity of skin material, and in sensor/actuator technology android interfaces present today, combined with difficulties in coordinated actions between software programmers, neuroscientists, engineers, and social/cognitive psychologists, advance the topic of expectation and intention understanding as a key concept in social robotics. As Beale and Creed [10] conclude in their study on how emotional agents affect users, one major issue is that the emotional expressions of agents and robots are not validated prior to an experiment, raising doubt whether the subjects perceived correctly the emotions researchers expected.

Goetz et al. [11] have stated that people expect a robot to look and act appropriately for different tasks. Acting on existing behavioral guidelines, while respecting the socially accepted norms, androids should be equipped with a database of suitable validated facial expressions to pose on every occasion. *By using videos depicting android facial expressions of emotion as a stimulus, we trigger responses on how users interpret, and connect with them*. A facial expression is not solely made to trigger events and reactions; however in this paper we will examine only this aspect of HRI. The outcome of this triggering would be an assemblage of situations, of real life actions, which would assist the robot designer when programming the face of the android with the provision of appropriate facial expressions according to the nature of the interaction. In the next sections we will describe our methodology, present our results and their statistical analysis, and conclude with a general discussion of our findings.

2. METHODOLOGY

We seek to find the situations that relate with the facial expressions of the Geminoid-DK, when portraying the six basic emotions of surprise, fear, disgust, anger, happiness, and sadness, which -according to Paul Ekman- are considered to be psycho-physiological entities universally accepted [12], [13]. These primary prototypical facial expressions reveal emotions that can be understood universally by people regardless of their gender, nationality, social/economic status, and age (except for infants). Research on facial emotions has shown that there appear to be discrete boundaries between the facial expressions of emotion, much as there are perceived boundaries between hues of sound. Facial expressions are perceived categorically, and a discrete system is better applied to momentary experiences of emotion, whereas receiving emotions as dimensions may be most productively applied to emotional experience aggregated across time, and for studying moods [13]. We are aware of other theories with alternative views in approaching emotions which propose different numbers, and kinds of emotions like Izard who uses ten emotions [14], Tomkins who uses nine [15], Fehr and Russel who use five [16], and Panksepp who uses four [17]. However, Bassili also uses the six basic emotions

[18], and for the evaluation of the EveR-4 [19], the Geminoid-DK [20], and the FACE androids, the six basic emotions were used again [21].

STIMULI

One of the few android robots that can mimic facial expressions of emotion on a satisfactory and sufficient level for the purposes of our study is the Geminoid-DK, which works as a duplicate of an existing person (the Original). The Geminoid is teleoperated through a computer system which uses motion-capture software to track the facial expressions and head movements of the operator, but can also perform pre-programmed loops without any aid, and respond to manual controls [22]. The facial expressions of the Geminoid, which were used in this experiment, can be programmed and evaluated by reference to the Original person.

We used a set of six photographs from our database where the Geminoid-DK android was mimicking its Original when depicting the six basic emotions (Surprise, Fear, Disgust, Anger, Happiness, and Sadness) as illustrated in Fig. 1 [20]. The Original was subjected to a multimodal test in order to reveal genuine facial emotions, and then the pneumatic actuators of the android were adjusted accordingly to match the facial expressions of the Original. The face-to-face experiment for clarifying the special characteristics of the android's face is described in [20]. The stimuli was composed of seven videos; six videos depicting facial expressions of the Geminoid-DK android with the basic emotions, and one more (the first one) which was used as a trial demo for respondents to familiarize themselves with the process of answering the questionnaire. The trial demo included a video of the Original when surprised (not the one depicted in Fig. 2a) and had an answer pre-noted. Instead of using static photographs as stimuli, we used videos displaying the photograph of the facial expression in between two black frames (a procedure similar to the blinking of the eye). The first four seconds of the video informed the viewers about its briefness, the fifth one was left blank, the sixth projected the image and the last one was left blank again.

We are aware of the fact that recognition rate of expressions of emotions is higher and has less ambiguity when dynamic sequences are shown rather than still pictures, but we wanted to simulate a behavior analogous to interacting with the robot in real life. The facial movements of the Geminoid are mechanical, causing changes in the facial status to be significantly slower than microexpressions on the human face. Robotic emotions have zero onset and offset time, and are depicted in a position around the peak of the emotional display. Communication partners of the android cannot tell if the emotion is emerging, or if it is dissipating.

Figure 1 The Geminoid-DK (left) depicting the six basic emotions when mimicking its Original (right); (a) Surprise (Lower Face), (b) Fear (Horror), (c) Disgust (Contempt), (d) Anger (Contreolled), (e) Happiness (Intense), and (f) Sadness (Lips Down).

DESIGN

The videos had to be exposed to randomly selected people in order to gather information on how they perceived the selected facial expressions, and how they connected with them. Therefore, we launched an online questionnaire with video stimuli to collect feedback from such responders. It was a within-subjects design on zero acquaintance, since every subject had to view all the videos, answer all the questions, and was not given the chance to interact with the robot beforehand [23]. Invitations for participation via private mailing lists were sent, but whoever had the link could also share it. An online questionnaire allows addressing questions to people with different social background, thus, not only students, or people related to a certain research field can be reached, forming a group that resembles real world end-users. Moreover, it provides honest responds, and as a method it cannot influence the subjects' answers (The American Statistical Association).

PROCEDURE

The subjects were asked to answer the open-ended question: *"In which situation would you use a facial expression like this?"*, and were prompted to give a small example. Subjects were left free to respond as they saw fit. The risk of conducting a questionnaire with completely unstructured open-ended questions allows for a probability of receiving irrelevant answers. Nevertheless, it was a risk worth taking, as this is the only way for a subject to act with spontaneity and write down a situation that would result from a natural impulse. Spontaneity, which means acting outside of conscious awareness, is increasing the possibilities of a deep penetration into the physical character and the inner reality of the individual [24]. Subjects could re-view the videos since our goal was not to test them whether they can recognize emotions, or train them to do so.

PARTICIPANTS

The online questionnaire was filled and submitted by 89 adult subjects (37 males - 52 females). All of the respondents were anonymous, above 18 years of age, and located in Europe, except for six of them who were located in the continent of America (the questionnaire did not provide options for North/Central/ South). All the received responses were written in the English language.

3. RESULTS AND STATISTICAL ANALYSIS

RESULTS

Open-ended questions call for a variety of answers. The results ranged from one-word answers to small paragraphs. From the 534 received responses (6 videos, 89 participants), 500 of them were valid, and 34 of them where discarded; 12 videos did not reproduce because of poor internet connection, or other technical problems, 7 subjects stated that could not relate to the projected facial expression, and 15 answers were invalid. Invalid results included responses that did not describe a situation, for instance, “bla bla bla”, or “as above/same”, and responses like “mixed feelings”, or “a weird happy face” decoding only the expression of the android. The discarded responses were 3 for Surprise, 9 for Disgust, 3 for Happiness, 6 for Fear, 6 for Anger, and 7 for Sadness.

We investigated a broad taxonomy of situations which respondents indicated to be relevant to interacting with an android. Based on the themes that recurred in the data, responses were grouped together under more generic descriptions, when and if possible, by one coder manually. “When being polite” and “When pretending to be polite” were grouped together under “Be polite/ pretend to”, “See a lion” and “Been chased by a Rottweiler dog” were grouped together under “See or been chased by a huge animal (lion/ dog/ Rottweiler)”, are two typical examples of how grouping occurred. After the grouping we ended up with 140 unique situations. Table 1 showcases the most representative situations for every emotion sorted out from highest to lowest quantity (due to lack of space, we present the top-10 situations for every emotion). It was observed that different respondents quite often described the same situation under different emotions. For instance, the situation of an “Unpleasant sight” was both present under the emotion of Fear and the emotion of Anger. Therefore, we have gathered all the situations that corresponded to more than one emotion in Table 2.

The situations amassing the most responses for the emotion of Surprise (Fig. 1a) was *"Surprise/when surprised"* and "*Unexpected event happens*" with 14 and 12 responses respectively. For the emotion of Fear (Fig. 1b) the most representative situation was when an "Unpleasant unexpected event (something came out/ popped)" happened with 17 responses, while the second described situation was "Surprise/when surprised" with 10 responses. The facial expression of Disgust in Fig. 1c was related with the situation of being *"In a funeral/Missing someone"* with 9 responses, and *"Thinking/Focused"* with 8 responses. The emotion of Anger (Fig. 1d) was mostly represented by the situation when *"Speaking to someone who is annoying you and builds up your anger/ready to explode"* with 9 responses, followed by a situation where one is *"Bored/lost to apathy/not amuses/ignore"* with 6 responses. The dominant situation for the emotion of Happiness (Fig. 1e) is when *"Something funny is going on because of a joke/funny story"* with 20 responses, followed by *"When happy/bit happy"* with 8 responses. Last, but not least, the main situation for the emotion of Sadness (Fig. 1f) was *"Thinking/Focused"* with 16 responses, and *"When I'm sad/unhappy"* with 8 responses.

STATISTICAL ANALYSIS

The Correlation Coefficient Matrix illustrated at Table 3, measures the extent to which each pair of the emotion variables tend to "vary" together (140 unique situations distributed to 6 emotional categories). Many respondents have attributed the same situation to different emotions either because they misunderstood them, or because they decided it was relevant according to their experience. The critical remarks that can be made are the positive -moderate- correlation of 0.446 between Fear and Surprise, the positive correlation of 0.713 between Disgust and Sadness implying a strong connection between them, and the very weak correlation (0.201) between Surprise and Happiness.

4. DISCUSSION

According to the results, for the emotional expressions of Surprise, Fear, Anger, and Happiness the subjects responded with relevant situations, meaning that they understood the emotional face of the android. The positive -moderate- correlation of 0.446 between Surprise and Fear justifies the few shared common situations. This confusion is attributed to the fact that the expressions of Surprise and Fear share similar facial actions as reported by Ekman and Friesen [12]. Once a situation is evaluated, it is not unexpected, or misexpected any more, hence the individual is no longer surprised and moves into another emotion which, according to Table 3, is usually Fear. Our results are consistent with a previous survey designed to evaluate the facial displays of The Geminoid-F, where expressions intended to convey Surprise and Fear were also confused [25].

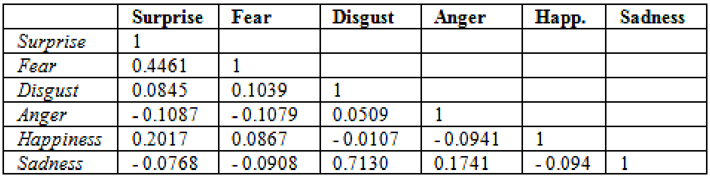
Table 1 Description of the situations that correspond to each emotion.

Situations for SURPRISE (34 in total)	**Quantity**
Surprise/when surprised	14
Unexpected event happens	12
Surprise Party/Receive a present	7
Interesting/impressive information	7
Shocking news	5
Something strange, out of character is happening	5
When you see a bug (spider/cockroach) in rotten food or approaching you	4
Discover something unknown/lost	2
When you say WOW	2
Good news	2
Situations for DISGUST (39 in total)	**Quantity**
In a funeral/missing someone	9
Thinking/Focused	8
When I'm sad/unhappy	7
Disappointed	6
A bit apologetic, feeling guilty/morally wrong	5
Desperate	3
Interesting/impressive information	3
Unpleasant unexpected event (something came out/popped)	3
Bored/lost to apathy/not amused/ignore	2
In doubt	2
Situations for HAPPINESS (33 in total)	**Quantity**
Something funny is going on because of a joke/funny story	20
When happy/bit happy	8
Being with friends	7
Just talking	7
Be polite/pretend to	6
Surprise/when surprised	6
When I have free/good time	2
Good news	2
Interesting/impressive information	2
Situations for FEAR (33 in total)	**Quantity**
Unpleasant unexpected event (something came out/popped)	17
Surprise/when surprised	10
Witness a car accident	8
A bit afraid/fear/scared	4
See or been chased by a huge animal(lion/dog/Rottweiler)	3
Stunned in a negative way	3
When you see a bug (spider/cockroach) in rotten food or approaching you	3
Unpleasant sight	3
Watch a horror film	3
Situations for ANGER (41 in total)	**Quantity**
Speaking to someone who is annoying you and builds up your anger/ready to explode	9
Bored/lost to apathy/not amused/ignore	6
Anger/bit angry	6
In serious conversation/situation	4
Evaluating a situation	4
Flirting	4
Disagree with someone/something	4
Robert DeNiro “Are you talking to me?”	3
Someone taking my food/dropped food	2
Situations for SADNESS (36 in total)	**Quantity**
Thinking/Focused	16
When I'm sad/unhappy	8
Bored/lost to apathy/not amused/ignore	7
In a funeral/missing someone	7
Depressed/melancholic	6
Sad and bad news	4
Bad grade in exams	2
Anger/bit angry	2
Content	2
Disappointed	2

Table 2 Descriptions of situations that correspond to combined emotions.

Situations	Quantity	Emotions
In serious conversation/ situation	4+1	anger+sadness
When what I want to wear is dirty	1+1	anger+happiness
Confident	1+1	anger+happiness
Mad at a teacher/somebody	2+1	anger+sadness
Shocking news	5+1+1	surprise+fear+happiness
Unexpected event happens	12+3+1+1	surprise+fear+disgust+happiness
Confirming a rumor/ satisfying expectation	1+1	surprise+fear
Good grade in exams	1+1	surprise+anger
When offended by someone	1+2	surprise+anger
Not feeling good	1+1	disgust+sadness
Something funny is going on because of a joke/funny story	1+1+1+20	surprise+fear+disgust+happiness
Be polite/pretend to	2+6	anger+happiness
Thinking/ Focused	8+1+16	disgust+anger+sadness
Stepping on dog's shit	1+1	fear+sadness
Bored/lost to apathy/ not amused/ ignore	2+6+7	disgust+anger+sadness
Disappointed	1+6+2+2	surprise+disgust+anger+sadness
Desperate	3+1	disgust+sadness
In doubt	2+1+1	disgust+anger+sadness
Sad and bad news	2+1+1+4	surprise+disgust+anger+sadness
Good news	2+1+2	surprise+disgust+happiness
Bad smell or taste	1+1	anger+sadness
Discover something unknown/lost	2+1	surprise+sadness
In a funeral/missing someone	9+1+7	disgust+anger+sadness
Interesting/impressive information	7+1+3+2	surprise+fear+disgust+happiness
When you see a bug (spider/cockroach) in rotten food or approaching you	4+3+1	surprise+fear+disgust
See or been chased by a huge animal (lion/ dog/ Rottweiler)	3+1	fear+disgust
Something strange, out of character is happening	5+2+2+1+1	surprise+fear+disgust+ anger+happiness
Unpleasant unexpected event (something came out/ popped)	2+17+3	surprise+fear+disgust
Unpleasant sight	3+2	fear+anger
Just talking	1+1+1+7	surprise+fear+disgust+happiness
A bit apologetic, feeling guilty/morally wrong	5+1	disgust+sadness
Someone just found a simple solution to a problem, that he and others are working on, but haven't told it yet/ I know more than you think	1+1	disgust+happiness
Getting to understand something	1+1	surprise+fear
Flirting	1+4+1	disgust+anger+sadness
Have no money	1+1+1	surprise+anger+sadness
Depressed/melancholic	2+6	disgust+sadness
Win in a game	1+1	fear+happiness
Witness a car accident	1+8	surprise+fear
Surprise Party/ Receive a present	7+2+2	surprise+fear+happiness
When I'm sad/ unhappy	7+1+8	disgust+anger+sadness
A bit afraid/ fear/scared	1+4+2+1+1	surprise+fear+disgust+anger+sadness
Content	1+2	disgust+sadness
Anger/ bit angry	6+2	anger+sadness
Surprise/ when surprised	14+10+1+6	surprise+fear+disgust+ happiness
Disgust	1+2	disgust+anger

Table 3 Correlation coefficient matrix for each possible pair of emotions



	Surprise	**Fear**	**Disgust**	**Anger**	**Happ.**	**Sadness**
Surprise	1					
Fear	0.4461	1				
Disgust	0.0845	0.1039	1			
Anger	-0.1087	-0.1079	0.0509	1		
Happiness	0.2017	0.0867	-0.0107	-0.0941	1	
Sadness	-0.0768	-0.0908	0.7130	0.1741	-0.094	1

Disgust and Sadness were the only emotions that seemed to confuse the subjects, as their descriptions often overlapped. As statistical analysis indicated, Disgust and Sadness have a positive correlation of 0.713, implying that there is a strong connection between them. If we consider that a bowed head (in Fig. 1c-Disgust and Fig. 1f-Sadness, the head of the robot is headed slightly downwards) is proposed by many researchers as a component of sadness [26], and that disgust is considered as one of the four negative emotions along with anger, fear, and sadness [27], the result can be justified. In addition, the Geminoid technology does not possess many actuators around the mouth and lip area, and is difficult to reveal the emotion of Disgust persuasively [20], a fact that confused the subjects. In another study with the BERT2 humanoid, subjects also displayed a tendency to confuse Disgust with other expressions, with correct recognition rates of 21.1% [28]. Experiments conducted in the Cohn-Kanade database (used for facial expression recognition in the six basic facial expressions) indicated that the most ambiguous facial expression was disgust, since it was misclassified as anger, and then sadness, followed by the emotions of anger, and sadness [29]. Apart from the pairs of Surprise-Fear, and Disgust-Sadness, the rest of them presented a correlation value near zero, indicating that they tend to be unrelated. Last, but not least, we consider the 0.2 value of the correlation between Surprise and Happiness too weak to further discuss.

Androids and other social robots need to present a human-friendly interface that will encourage interaction. Ability to display negative nonverbal behaviors in a truthful manner might cause discomfort to users, and dramatically extend the adaptation time for the acceptance of an android robot as a communicative partner [30]. A recent study by Nicole Krämer et al. [31] showed that human interaction partners smiled longer when communicating with an artificial agent that looked happy and smiled back at them. It seems that robotic nonverbal behavior holds the power to shape the outcome of human-robot social interaction.

Furthermore, the retrieved information from Table 2 can assist the roboticist when programming the face of the android with the provision of a probability statement indicating the degree to which an emotional expression is involved in a specific situation. Let us take, for example, the first instance of the table "*In serious conversation/situation: 4+1: anger+sadness*". This statement can be translated into "*In case the robot needs to engage in a serious conversation, an Anger face will be 80% appropriate, whereas a Sadness face will be 20% appropriate*". Such information could be part of a database system receiving input from both an intelligent computer vision tool focused on scene understanding, and a speech recognition/synthesis tool, having as an output a sequence of actuator values that could make the robot behave in an appropriate manner. Machines today can recognize a person's face with ease, can analyze the face for emotional content relatively accurately, but cannot give an explanation for the behavior of this person.

5. CONCLUSION

We presented an open-ended methodology for evaluating android facial emotional expressions, by collecting all the intentionality directed towards an android in the form of situations relevant to a specific Android face, and then analyzing it. The employed qualitative paradigm, aimed to perceive an android affective interface from the perspective of the respondents, in order to equip both the robot engineers, and the interaction designers with a database of validated emotional faces for appropriate use in every situation. As more situations are collected (after an experiment, or an observation), and analyzed, the more enriched the validated the database will become, thus increasing the chances for maintaining HRI at satisfactory levels. For future work, we recognize the need to conduct this line of research across cultural boundaries, involving all available related technologies, including other existing androids. We would welcome such collaborations to further the common understanding.

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PAPER G. EVALUATING USER PREFERENCE AND PERCEPTION BETWEEN A MECHANOID AND A HUMANOID IN AN ART CONTEXT

Evgenios Vlachos, Elizabeth Jochum, and Louis-Philippe Demers

The paper has been submitted to

Interaction Studies, **John Benjamins Publishing Company**

The layout has been revised.

ABSTRACT

We present the results of an experiment investigating how users' perception can change after direct interaction with a robot. Visitors to an art gallery exhibition interacted with two robots: a mechanoid that communicated through tactile interaction, and a humanoid that communicated verbally. At the simultaneous trials visitors were free to engage with either, or both robots. Comparisons of impression were made based on pre/post questionnaires, material, touch, and speech. While the results indicated a constant preference for the mechanoid, there was a significant positive change in the visitors' opinion towards the humanoid which was deemed better for educational, and conversational activities. Post interactions, visitors preferred hard material to soft, despite their initial stated preference. Visitors stated preferences for the subject to initiate touch with the robot remained constant, but afterwards were more willing to consider mutual touch. Gender had no impact on the results.

Keywords: Social Human-Robot Interaction; Perception; Touch; Humanoid; Mechanoid

1. INTRODUCTION

The multiplicity of social robots, and the plethora of interfaces for Human-Robot Interaction (HRI) have grown dramatically in recent years. More than ever before, we recognize the need to investigate which robot type can better satisfy the requirements of a given task. The given tasks for social robots are usually related to healthcare (Robins et al., 2009), wellness (Kuwamura et al., 2014), assistance (Sim and Loo, 2015; Feil-Seifer and Matarić, 2005), entertainment (Jochum et al.,2014; Hoffman, 2011), companionship (Moyle et al., 2013), and education. (Li et al., 2015). Since 2003, Goetz et al. have revealed the necessity for social robots to match their behavior to the task in order to improve their acceptance rates. As the number of social robots increases, the number of tasks they can perform also increases, therefore leading to more and diverse HRI scenarios (Vlachos and Schärfe 2013; Bemelmans et al., 2012). Consequently, it is important to understand how people perceive these robots prior to HRI (Vlachos and Schärfe, 2015a), as well as after HRI (Haring et al., 2015; Haring et al., 2014; Syrdal et al., 2014; Dautenhahn et al., 2006). Apart from very few occasions where humans encounter social robots "in the wild", as in the Henn-na Hotel which is staffed with robotic personnel (Rajesh, 2015), the majority of direct HRI is still limited within laboratories, research facilities, exhibitions, and museums.

We present the results from a double HRI experiment that suggests a novel approach to research that considers user perception, expectations, and preferences against a robot's communicative properties in an entertainment setting – in this case an art exhibition that mirrored the conditions of an art gallery. Contrary to traditional experimental settings, art exhibitions allow open-ended, less structured, playful and flexible interactions, while providing a useful platform for conducting research on natural HRI (Kroos & Herath, 2012; Ogawa et al., 2012; von der Putten et al., 2011; Velonaki et al., 2008; Shiomi et al., 2006; Maeyama et al., 2002). In our experiment, communication is mediated through two distinct tele-operated robotic avatars: a mechanoid robot called the Blind Robot (see Figure 1), that engages in non-verbal tactile interaction by using robotic arms and articulated hands to explore the user's face and body , and the naturalistic-looking android robot Geminoid-DK (see Figure 2) that interacts verbally through recorded speech played through off board speakers, and corresponding facial expressions (synchronized mouth movements that simulate speech, head orientation, eye gaze, and emotive facial expressions) (Vlachos and Schärfe, 2015; Vlachos and Schärfe, 2012). We compared visitor expectations and preferences before and after their visit to the art exhibition, and compared pre-and-post responses concerning mechanical versus humanoid appearance, touch, type of material, and ability of the robot to communicate via speech. *Our main goal is to investigate whether direct HRI in real life situations changes peoples' attitude and preferences towards social robots.* The setting of the interactions also raises a critical question about how context affects responses to difference types of robots. In the following sections we explain how the experiment was conducted, describe our methodology, present our results along with their statistical analysis, and conclude with a discussion of our findings.

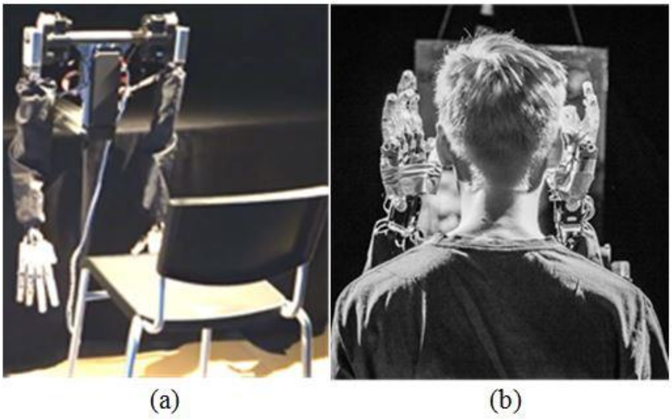

Figure 1 The Blind Robot setup before (a) and during the experiment (b).

(a) (b)

Figure 2 The Geminoid-DK setup before (a) and during the experiment (b).

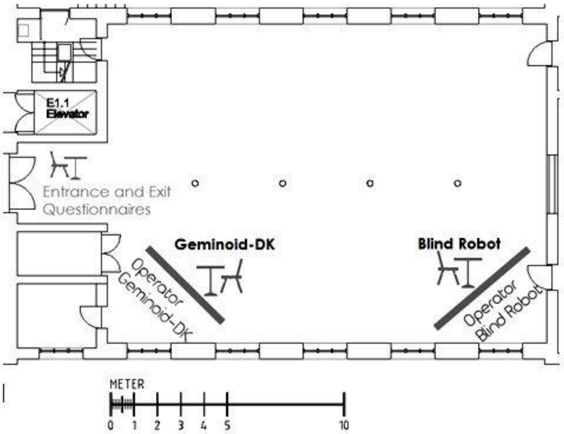

Figure 3 The Exhibition Area and Robot Location Map.

2. THE EXPERIMENT

The robots were exhibited simultaneously as part of a one-day art exhibition (4th April, 2014). Visitors were invited to interact with the robots simply by means of an empty chair positioned directly in front of the robots. The visitors were mostly art students and university faculty and staff, although the event was advertised to the general public, and attracted other community members. The visitors were informed of the experiment only upon entering the exhibition, when they were given a short introduction of the setting, and asked to fill out an entrance survey before viewing the robots. The survey asked visitors a range of questions, including whether they had ever previously interacted with a robot. The visitors were then free to explore the exhibit for as long as they wished, and were asked to fill out a questionnaire before leaving. Both the entrance, and the exit questionnaire were anonymous. Many chose to stay for the duration of the exhibition (three hours) to observe other visitors interacting with the robots. The mean duration time of each HRI - independent of the robot- lasted almost 90 seconds per visitor.

STIMULI

The exhibition featured only the two robots in mirrored conditions. For the Blind Robot, visitors were allowed to sit down in a chair facing the robot while two robotic arms physically touched the visitor's head, shoulders, and face. The interaction did not include any spoken dialogue, and was meant to emulate the physical processes a blind person's efforts to "see" another person. A mirror was positioned directly behind the robot allowing the visitors to observe themselves during the interaction (see Figure 1b). The Geminoid-DK was equipped with subtle pre-programmed facial movements that invited an intimate encounter (mostly depicting head nods, eyebrow raises, neutral and mild positive emotions like happiness, and surprise) running on an autonomous mode. The selected emotional expressions would go unnoticed if the robot failed to attract and maintain the visitors' attention and focus (Cassell and Thorisson, 1999). In light of this, verbal commands and responses running on a Wizard-of-Oz mode (controlled by a live human operator) were pre-scripted and categorized into five distinct phases: i) Introduction, including greeting phrases and invitation to sit down, ii) Content, including phrases that would assist the robot to encourage information from the visitors, iii) Meta, with phrases that facilitated dialogue, iv) Consent form, where the robot asked visitors to sign a consent for the video recordings of the experiment, and v) Outro, with thankful and parting phrases. A detailed list with all the phrases is available in Table 1. All dialogues, and facial expressions were "natural" and realistic, rather than abstract, or artistic. Lastly, the Geminoid-DK could be touched by the visitors. Both robots were tele-operated by different operators who were seated behind the respective robot, and kept hidden from the visitors in a small space surrounded by black curtains.

SETTING

Figure 3 depicts the trial area, the location of the robots and their operators. Information concerning robot intelligence, abilities, and control mechanisms were deliberately concealed in order not to influence the visitors. The ambience during the experiment was deliberately designed to be an artistic venue rather than a clinical trial. The area for the visitors to fill out their entrance and exit forms was in a corner of the room at a small table opposite the robots. The room was lit using theatrical lighting, and black curtains and masking were used to create a gallery-like atmosphere. Video recording equipment was positioned on both sides of the Geminoid-DK to record the interaction from a distance, and a video camera was mounted directly next to the Geminoid-DK facing the visitor to provide the robot operator with visual feedback to guide the interaction. Consent forms were on the table on the left side of the Geminoid-DK.

METHOD

All subjects were asked to complete voluntary entrance questionnaire prior to the HRI trials. Entrance questionnaires were completed before entering the main hall where the robots were located, so the visitors would not be influenced by the exhibits. In addition to demographic details, visitors were asked to answer questions regarding previous interactions, robot preferences, and preferences concerning initiation of interaction prior to their HRI. During the exhibition subjects could engage with one of the robots, both of them, or none of them and sign the respective consent forms. Before exiting the exhibition, all visitors were asked to fill out an exit questionnaire with separated sections depending on their individual exhibition experience. For example, they were given a specific set of questions to answer based on which robot (if any) they chose to interact with. Due to the fact that the questionnaire was in paper format, subjects failed to reply to all of the questions, or choose not to fill them, making some of the responses invalid. While there are many trusted assessment questionnaires for social robots (Bartneck et al., 2009; Heerink et al.,2010; Saini et al.,2005) we chose to generate our own questions that were more aligned with our study, and objectives.

Table 1 The Geminoid-DK scripted dialogue.

1. INTRODUCTION	1.1 Hi, welcome. 1.2 Hello – how do you do? 1.3 Thank you for asking. I’m fine 1.4 Do you want to talk? 1.5 Whistle.
2. CONTENT	2.1 Yes indeed, I am ready for new adventures. 2.2 Ok, let’s begin. 2.3 Tell me about yourself. 2.4 Just tell me what you feel is relevant. 2.5 What did you expect before you came here? 2.6 How do you feel about it now?
3. META	3.1 That sounds fantastic. 3.2 Can you speak up please? 3.3 Can you please center your chair? 3.4 Yes. 3.5 No. 3.6 Ok. 3.7 Thank you. 3.8 What?

4. CONSENT FORM	4.1 Will you please sign the form on your right? 4.2 We want to study our interactions at a later point. 4.3 We do these experiments because we need to figure out how androids affect communication.
5. OUTRO	5.1 Have a nice day. 5.2 It was nice talking to you. 5.3 Thank you and goodbye.

VISITORS

We obtained 68 questionnaires in all; 60% females (N: 41), 35% males (N: 24) and 5% (N: 3) who did not specify their gender. The majority of visitors were university students and personnel, while their mean age was 23.4 years old (ages ranging from 13 to 41). From the 68 visitors only two were underage, 13 and 15 years of age, respectively, and both were accompanied by their parents. The exhibition was a free public event open to everyone; we did not invite visitors to a research facility, we did not pay the subjects to participate, and our data are kept in-house according to university ethical guidelines. Danish law does not require researchers to obtain informed consent under these conditions. We have furthermore cleared this procedure with the Ethical Review Board of Aalborg University, under whose auspices we conducted our investigation.

3. RESULTS

We present our results in three sections; the analysis of the Entrance Questionnaire, the analysis of the Exit Questionnaire and the analysis of Before-After questions.

ENTRANCE QUESTIONNAIRE

Prior Interaction

Figure 4 depicts the percentages of visitors’ prior HRI experience according to the entrance questionnaire. In total, 69% (N: 44) of them indicated that they had no previous interaction with any type of robot before, and only 31% (N: 20) stated that they had interacted with a robot. There were 4 invalid inputs that failed to indicate an answer at all. Pearson's Chi-squared test reveals that there is no trend between gender and previous interaction with a robot (X-squared = 0.0087, df = 1, p-value = 0.9255). Figure 5 illustrates the gender differences in previous HRI. There were 3 more invalid inputs that failed to indicate a gender, which in total make 7 invalids.

Preference for Robot Type

For the robot type preference (Machine Like – Human Like – No preference) for domestic applications, 79% (N: 53) of the total population of the visitors stated that they prefer a Mechanoid robot, followed by 18% (N: 12) preferring a Humanoid and 3% (N: 2) who had no preference. There was only one invalid answer. Figure 6 reports the preference of males and females to the robot type. We implemented a Fisher’s Exact Test (p-value = 0.3548, alternative hypothesis: two.sided) which reveals that the preference for robot type and gender are two independent variables. In total there were 4 invalid answers (three did not indicate gender and one did not indicate a preference).

Preference for Physical Interaction: Touch

We asked visitors to state their preferences for physical contact – specifically touch - with robots. In circumstances that involve physical contact between robots and humans, we asked whether visitors would prefer the robot to be more human-like or machine- like. 70% (N: 46) of the subjects stated that a machinic looking robot would be adequate, and the remaining 30% (N:19) stated that a human-like robot would be better (3 invalid). A Pearson's Chi-squared test (X-squared = 0.5113, df = 1, p-value = 0.4746) indicates that gender and preference for robotic touch are not dependent. Figure 7 shows the gender preference for robotic touch (6 invalid).

Material Preference for Physical Contact

A majority of the visitors stated that if they were to have physical contact with a robot, they would prefer the robot be made of soft material (56% - N:36), while 30% (N:19) stated that the robot should be made of metal, and only 14% (N:9) expressed no preference (4 invalid answers). Fisher's Exact Test (p-value = 0.7039, alternative hypothesis: two.sided) indicates no significant relationship between gender and preference for robotic material (7 invalid). Figure 8 depicts the column chart with the frequencies.

Being Seen or Being Touched

The questionnaire also included two rating scale questions for gauging the importance of a given robot’s ability to see, and touch the user visitor. A Friedman Rank Sum Test (Friedman chi-squared = 28.1739, df = 1, p-value = 1.109e-07) indicates a statistically significant difference in a user preference for being seen versus being touched by a robot. The mean ranking for the robot’s ability to see the user was 3.26, while the mean ranking for the robot’s ability to touch the user was only 2.43.

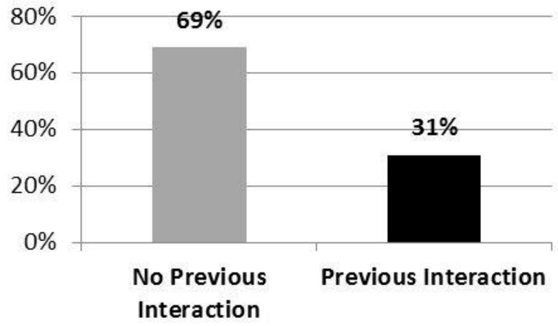

Figure 4 Percentage of previous HRI.

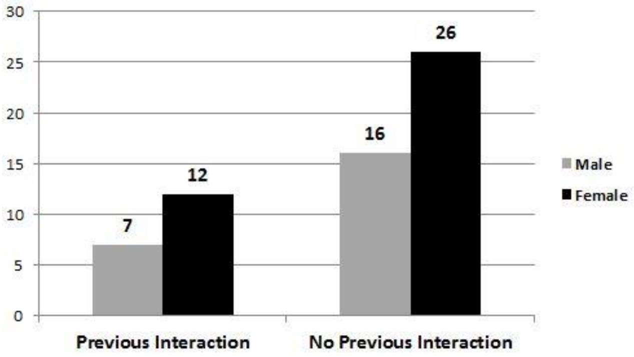

Figure 5 Gender differences in previous HRI.

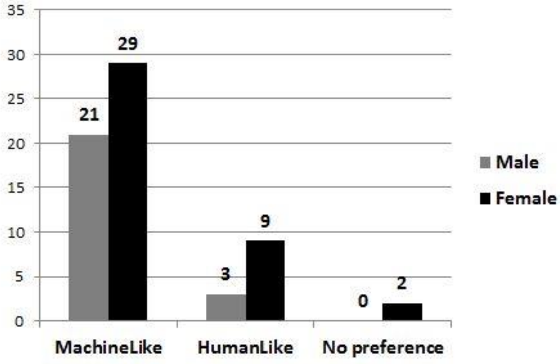

Figure 6 Male and female preference for robot type.

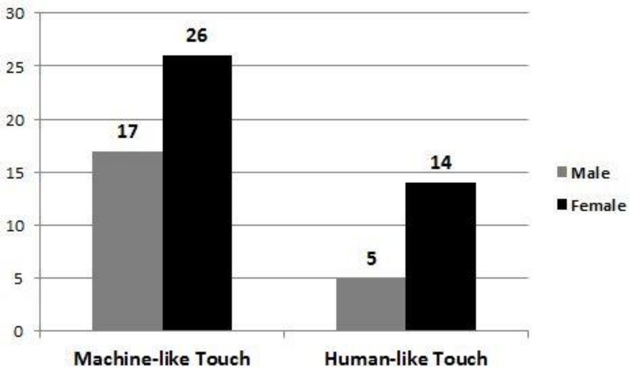

Figure 7 Gender preference for type of robotic touch.

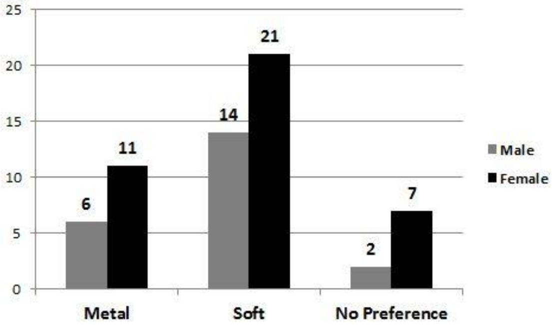

Figure 8 Material preference for physical contact.

EXIT QUESTIONNAIRE

Robot Interaction

The total population of the experiment is 68 persons, but as there were 5 invalid responses, the total population is reduced to N: 63. Out of 63visitors, 47% of them (N: 31) chose to interact with the Geminoid (25 of them also interacted with the Blind Robot), 75% of them (N: 47) chose to interact with the Blind Robot (25 of them also interacted with the Geminoid), 40% of them (N: 25) chose to interacted with both of the robots, and 16% of them (N: 10) with neither robot. Differences in Fisher’s Exact Test (p-value = 0.53, alternative hypothesis: two.sided) indicated that gender did not affect the selection of robotic at the exhibition. Figure 9 presents the frequencies of males and females that interacted with either one of the robots, both of them, or none of them.

Likert Scale Ratings

Visitors were asked to rate both robots on various statements according to a five-level likert scale (1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree, 5: strongly agree). In order to meaningful compare the experience of the visitors during their two distinct HRI trials, we limited our analysis to the answers provided by those visitors who interacted with both robots.

- *The robot met my expectations*. A Friedman Rank Sum Test (Friedman chi-squared = 5.7619, df = 1, p-value = 0.01638) illustrates a significant difference upon meeting the visitors expectations. The mean rankings revealed that the Blind Robot mostly met the visitors expectations (mean ranking = 3.96), while the Geminoid-DK met their expectations to a lesser degree (mean ranking = 2.96).
- *I felt I had a strong connection with the robot*. A Friedman Rank Sum Test (Friedman chi-squared = 7.3478, df = 1, p-value = 0.006714) suggests a significant difference in the levels of connection the visitors felt with the respective robot. Visitors felt a stronger connection with the Blind Robot (mean ranking = 2.92) than with the Geminoid-DK (mean ranking = 1.85), however both robots received low ranking.

- *I wanted to touch the robot*. A Friedman Rank Sum Test (Friedman chi-squared = 0.0588, df = 1, p-value = 0.8084) indicated that the rankings for touch were not different from each other. Actually, both robots had exactly the same high mean ranking (4.03), meaning that the visitors were equally curious to physically touch both of them robots.

- *I wanted to learn more about the robot*. A Friedman Rank Sum Test (Friedman chi-squared = 2.8824, df = 1, p-value = 0.08956) did not show any significant difference in desire to learn for each robot. Despite that fact, the mean ranking for the Geminoid-DK (4.35) was higher than that of the Blind Robot (3.85).

- *I was curious to have a conversation with the robot*. A Friedman Rank Sum Test (Friedman chi-squared = 0.4737, df = 1, p-value = 0.4913) revealed no significant difference among the rankings for curiosity to converse with one robot over the other. Again, the Geminoid-DK was rated higher (mean ranking = 4.18) than The Blind Robot (mean ranking = 3.92).

- *The robot's movements were appealing*. A Friedman Rank Sum Test (Friedman chi-squared = 6.3684, df = 1, p-value = 0.01162) indicated that the robotic movements significantly differed from each other. The mean rankings suggest that visitors found the Blind Robots' movements more appealing (mean ranking = 3.5) than the Geminoids' (mean ranking = 2.85).

Reasons for Not Interacting

We asked visitors who chose not to interact with the robots to write a comment about their reason for not doing so. The most frequent responses appea in Table 2. The two primary reasons for not interacting with the robots were:

a. the robots appeared scary, or spooky, and

b. visitors were content observing other visitors' interactions.

This latter, is one interesting finding of conducting HRI experiments in gallery settings. Participation in a HRI study in laboratory settings or clinical trials presupposes interest and/or engagement with robots. However, we know from experience that not everyone is comfortable with interacting with robots in real life settings. Identifying those factors which motivate, or prevent visitors from interacting with robots – especially when people are given a free choice - is relevant for HRI studies of user preference and engagement.

Overall Experience

As stated by 94% (N: 54) of the visitors, the exhibition met and exceeded their expectations (N: 54), whereas 6% (N: 3) did not feel the same (11 invalid answers). In addition, 93% (N: 55) of the visitors stated that art galleries, or similar installations are considered good ways for encountering robots, while 7% (N: 4) disagreed (8 invalid answers).

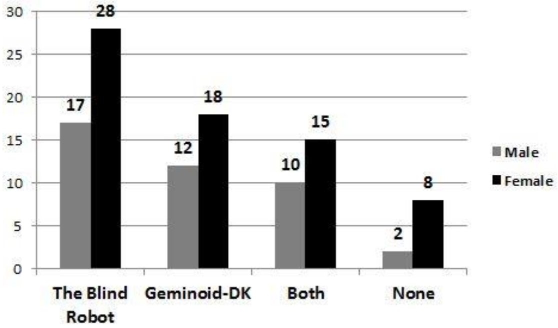

Figure 9 *Actual robot interaction*.

BEFORE-AFTER QUESTIONS

Mechanoid or Humanoid

The entrance questionnaire asked visitors to state their preference for which type of robot would they prefer as an assistive domestic robot. After the HRI, visitors were asked again to provide information about the robots they interacted with during the experiment. We matched the machine-like appearance with the Blind Robot and the human-like appearance with the Geminoid-DK in order to examine if the experiment had any effect on their initial preferences. Figure 10 shows the Before-After frequencies in the robot type preference for the visitors. Pearson's Chi-squared test (X-squared = 7.2207, df = 1, p-value = 0.007207) indicated a significant change of visitors preference towards Humanoid robots. There were approximately 150% more visitors that preferred the Humanoid robot as stated at the exit questionnaire (N: 31) in contrast to the entrance questionnaire (N: 12).

Actively Touch a Robot or be Touched by a Robot

One question that we predicted would show major differences in how the experiment would influence user preference and perception concerned physical contact with robots: “*If you have physical contact with a robot, would you rather be touched by a robot, or have a robot touch you*?” The visitors could select one of the predefined answers “I would rather initiate the contact”, “I would rather the robot initiate the contact”, “There should never be any physical contact between a robot and a human”, “The physical contact should be mutual”. Our null hypothesis (H0) states that there will be no difference between the entrance and exit results, and our alternative hypothesis (H1) states that there will be differences, but without indicating any specific direction (towards a robotic, or a human initiation to touching). Pearson’s Chi Squared Goodness of Fit test (X-squared = 9.396, df = 3, p-value = 0.02446) illustrates that the alternative hypothesis (H1) is true indicating that the visitors changed their point of view about initiating contact with a robot significantly after the experiment. From Figure 11 we conclude that the majority of the visitors initially preferred to initiate the contact themselves, and afterwards, even though this remained the most popular preference, the selection of mutual contact increased and even nearly constituted an equal second alternative. We should note that for this question the invalid replies reached the number of 17, almost 25% of the population, mainly because many subjects selected more than one option despite the request to “select only one” (a fact that suggests preference concerning initiation of touch is complex, and visitors might be conflicted, or undecided themselves). It is indeed a very high percentage, and so we looked more closely at these responses. Of the 17 invalid replies only 8 of them listed no answer whereas the remaining 9 had double results only in the exit questionnaire. In the entrance questionnaire 7 visitors chose the subject to initiate the contact and 2 mutual contact, while the exit questionnaires deliver these results: 6 visitors preferred to initiate contact, 3 visitors preferred the robot to initiate contact, and 9 visitors preferred mutual contact. All 9 visitors selected mutual contact at the exit questionnaires, while only 2 selected it in the entrance one. That means that almost 78% of this group reconsidered their initial selection. Therefore, we can suggest that the invalid answers would follow the same tendency and not affect the outcome.

Table 2 Reasons for NOT interacting.

Geminoid-DK	**The Blind Robot**
He was a little scary /it's creepy/too spooky.	Saw the Wizard of Oz.
Saw others interact with DK/explored it by observing other's conversation.	It looked kind of scary/too scary.
I was frightened by the "realness" and didn't want to interact.	A little intimidating.
I was too afraid/it scares me.	It reminded me of a spider :(
I did not feel comfortable with all other spectators looking at me…	I don't like to be touched.
It didn't invite me to interaction.	I did not see any outcome of it.
I didn't want to be the one asking questions in a crowd.	I saw others interact.
It looked interesting but I didn't want to try it.	Too many who wanted to interact.
I came too late.	Too long a line.

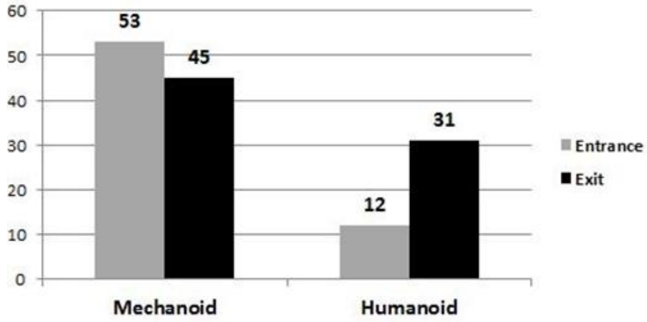

Figure 10 Preference for robot type (entrance and exit questionnaires).

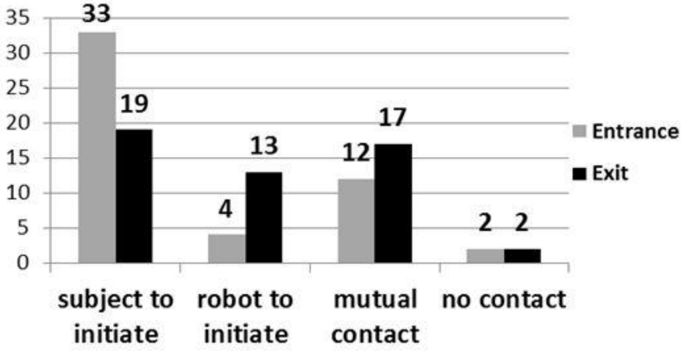

Figure 11 Touch or be touched by a robot (entrance and exit questionnaires).

4. DISCUSSION

According to the results of the two HRI trials, the majority of visitors had no prior interaction with any type of robot. Therefore, when interpreting the results we should take account for the elements of surprise, excitement, or disappointment that follow any first interaction with a robot. In laboratory experiments it is common practice that subjects spend some time with the robot prior to the experiment. Moreover, the HRI design recommendations of the MIT Media lab suggest introducing first the subject to the experiment and the robot (Kidd and Breazeal, 2005). In an art exhibition this is not always possible or even desirable, as entertainment settings sometimes rely on the nature of surprise, and spectacle. We also note that the majority of the visitors were university students and perhaps our findings do not express the opinions of the general public.

Visitors showed a clear preference towards the machine-like robot at all levels of the experiment, despite the fact that in other surveys human-like robots are more often preferred and praised (Walters et al., 2008; Bartneck et al., 2006). In addition, the mechanoid robot met the visitors' expectations to a higher degree and created a stronger bond with them. The low preference and satisfaction rate for the humanoid may be related to the fact that the Geminoid-DK was communicating in English which could create discomfort for non-native English speakers (which is true for a majority of the visitors). Another possible explanation could be the limited range of appealing movements, and the limited speech options available to the robot. The Geminoid-DK has a limited set of actuators restricting the movement to the facial, head, torso, and shoulder area (which emulates the human breathing function). The appearance of a humanoid – and especially of an android - increases the effects of the Media Equation Theory that suggests that people behave and respond to computers and other media as if they were real people (Reeves and Nass, 2002), and possibly persuading users that the robot can engage in more advanced HRI tasks that are currently beyond the robot's capability. Nevertheless, the exit questionnaire indicated that approximately 150% more visitors interacted with the Geminoid-DK than initially expressed an interest in doing so.

Most visitors stated that it is of greater importance for a robot to have a vision/perception system that enables the robot to see the subjects rather than have hands, and be able to touch them. In the case of physical contact with a robot, visitors clearly stated a preference for robots made of soft materials. The material question stands in contrast with the actual outcome of the experiment, as most of the visitors felt very comfortable when touched by the Blind Robot (which is made of much harder material than the silicon skinned Geminoid-DK). Results also indicate that prior to the experiment a majority of the visitors wanted to initiate physical contact with the robot themselves, but in fact that preference for initiating contact became less important after the exhibition. At the exit questionnaire we witnessed a major change in visitors' overall attitude as the option of "mutual contact" gained ground, and the option of "robot initiating the contact" almost tripled. In both cases, visitors were equally curious to physically touch both robots. Topics such as physically touching a robot, robot's reaction to touching, expectations on how a robot should respond to human touch, or how robots should touch humans are relevant for HRI, and active sites of investigation (Basoeki et al., 2015; Van Erp and Toet, 2013).

Visitors wanted to actively communicate with both of the robots to the same degree, but also stated their preference to learn more about the humanoid one. This is an expected outcome since humanoid robots, and especially androids, bare remarkable physical resemblance to humans. The more a robot looks like a human, and/or behaves like a human, the more likely users will recognize, and project human features on its behavior, applying cultural rules, and following behavioral norms while expecting the robot to be able to understand them and act accordingly (Breazeal, 2004; Vlachos and Schärfe, 2014). Hence, the visitors of the subjects were more curious to converse with the humanoid.

We thoroughly tested whether gender differences affected any of the results, but we found no evidence to support this claim. It seems that either the population of the experiment was quite homogenized, or that visitor preference and perception were not affected by gender. The fact that the Geminoid-DK robot is male and the Blind Robot is genderless did not directly impact how visitors interacted with the robots, which contrasts with existing literature that suggests a same-gender preference (Gass and Seiter, 2014; Cialdini, 1993). Human preference, social categorization processes, and gender also apply to social robots (Eyssel and Kuchenbrandt, 2012). Siegel et al. (2009) have found that male subjects were more keen to trust, and engage with a female robot, and that in general, questionnaires tended to rate the robot of the opposite sex as more credible, trustworthy, and engaging. A follow-up study with a female android could provide more solid results, as subjects usually respond differently to the same questionnaires when the gender of the stimuli changes (Crowell et al., 2009).

5. CONCLUSION

In this study visitors to an art exhibition were invited to observe, and interact with robots in a set up that emulated a gallery setting.   Visitors were asked to respond to entrance, and exit evaluation to gauge their stated preferences with regards to a robot’s aesthetic appearance, the type of robotic materials, initiation of physical contact and ability for the robot to communicate through speech. We discovered three of the attributes that supported amusement and emotional excitement goals of an inexperienced with robotics group of subjects when interacting with a machine-like, and a human-like robot during an entertainment activity. A mechanoid made of hard materials was deemed better than a humanoid for satisfying entertainment needs, whereas a humanoid was deemed better for educational purposes, and conversational activities. In both cases, visitors wanted to touch the robots regardless of their material, and felt more comfortable when they were able to initiate physical with the robot. Visitors also showed a willingness to consider mutual touch. Our findings support the hypothesis that a user’s perception can change based on an actual interaction with a robot, even if the HRI is brief, and unscripted. Lastly, we confirmed that studies “in the wild” - such as art exhibitions and installations in galleries where users can choose their level of interaction- are useful testbeds for identifying key factors in HRI research.

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PAPER I. ANDOID HANDS: A STATE-OF-THE ART REPORT

Evgenios Vlachos, and Henrik Schärfe

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"Android Hands: A State-of-the-Art Report," by Evgenios Vlachos and Henrik Schärfe, Paper No. ESDA2014-20564, ASME

The layout has been revised.

ABSTRACT

Humans have adjusted their space, their actions, and their performed tasks according to their morphology, abilities, and limitations. Thus, the properties of a social robot should fit within these predetermined boundaries when, and if it is beneficial for the user, and the notion of the task. On such occasions, android and humanoid hand models should have similar structure, functions, and performance as the human hand. In this paper we present the anatomy, and the key functionalities of the human hand followed by a literature review on android/humanoid hands for grasping and manipulating objects, as well as prosthetic hands, in order to inform roboticists about the latest available technology, and assist their efforts to describe the state-of-the-art in this field.

1. INTRODUCTION

Today's social robots should combine all the defining parameters of an industrial robot, namely acceleration, speed, durability, carrying capacity, accuracy, and repeatability, with communication functions, and behavioral skills for a realistic Human-Robot Interaction (HRI). A robotic system designed with the aim to resemble humans in their external appearance/form, featuring anthropomorphic attributes in its behavior, regarding intelligence, motion and interaction patterns, is called an android robot [1]. Goetz et al. (2003) have stated that people expect a robot to look and act appropriately for different tasks [2]. Increased anthropomorphic appearance of a robot affects the way people interact with it, since it encourages the formulation of social bonds between humans and the robot [3]. Therefore, when interacting with a domestic, caregiving, assistive, service robot, or a robot companion, in most of the cases one should expect the robot to bear strong similarities to a human. Additionally, experimental research has demonstrated that anthropomorphic robots are praised more, and punished less in collaborative human-robot team interactions [4].

Making an android is a complex task requiring knowledge from admittedly diametrically opposite disciplines like Engineering, Art, Computer Science, Psychology, Materials, Mathematics, Neuroscience, Communication, and Biology to name a few. Research facilities, universities, institutions, and corporations from around the world have put significant effort in creating the “perfect” android, or humanoid. Despite that fact, we still have not seen a robot that combines appearance, functionality, dexterity, accuracy, and operability, with adequate size and weight for all its body parts/components. Currently there exists a plethora of robots that excel in few of the aforementioned qualities, but for only one -maybe two- of their body parts. This state-of-the-art report is concentrated only on one of the android components, the hands. Engineering a hand to provide the same form and function as a human one is a task that challenges many perspectives. We summarize the results of an extensive search and review of available literature on robotic and humanoid hands for grasping and manipulating objects, with particular reference to the android ones, and offer an overview of topological, geometric, and kinematic issues. An object is considered to be grasped (extrinsic movement) when it is immobilized in a static position by contact with the fingers and the palm [5]. For manipulating (intrinsic movement) an object coordinated actions of the finger and the palm are required. The critical parameters which determined the selection of the presented android hands are (i) size, (ii) number of fingers equal to exactly five (even though one can find skillful robotic hands with less fingers like the 4-fingered human mimetic hand of the humanoid robot Twendy-One [6]), (iii) joints and degrees-of-freedom (DoF), and (iv) dexterity and grasping. A three finger hand with heuristic combination of position, and force control fingers for grasping used to be considered as a robotic hand back in 1979 [7], today, robotic hands with two, or three fingers are considered to be grippers.

For achieving a steady and uniform performance in the workspace, the performance parameters that affect the robotic hands such as manipulability, mechanical advantage, control accuracy, isotropy, dexterity and grasping should avoid extreme fluctuations. Additionally, in order to provide more realistic results in grasping and manipulation soft fingers are often used as fingertips [8]. The kinematic performance index of robotic mechanisms is proved to be a very popular topic of discussion throughout the last thirty years at least. Apart from the “standard” performance indices of Salisbury and Craig [9], Yoshikawa [10], Klein [11], Gosselin and Angeles [12], Kim and Khosla [13], there have been also numerous alternative ones suggested more recently [14]. The typical questions prior to designing a kinematic structure of a mechanism are the number of links in the chain, the way one link connects to another and by which type of joint, and the clarification of the frame link, as well as of the input (output) links [15].

Our scope is neither to determine which hand is the most qualified, since that can be only achieved in accordance to a specific task, nor to classify them, but to project the advantages of the finest existing android hands in order to enrich the knowledge of the roboticists, and assist them in deciding upon future directions in android, and humanoid science.

2. THE HUMAN HAND

Extensive research on the anatomy and the mechanics of the human hand has been conducted in many disciplines; anatomy, animation, robotics, music, and graphics. Here we will only briefly mention the main components, and functions of the human hand. The bone structure of the human hand consists of 27 bones; 19 of them are grouped together in the five fingers (#1 thumb, #2 index finger, #3 middle finger, #4 ring finger, and #5 little finger), while the remaining 8 bones group themselves into the carpus forming the wrist and root of the hand [16]. The fingers from 2 to 5 consist of four bones (metacarpal, and proximal/medial/distal phalanx), and the thumb only consists of three (metacarpal, proximal/distal phalanx). After a series of experiments [16] the average finger phalanx lengths as percentages of the hand length are presented in Table 1. Apart from the bone structure which is illustrated in Figure 1 [23], the most essential part concerning the humanoid hand design is the muscles that flex, extend, abduct, and adduct the wrist and the fingers, and oppose to the thumb, or in other words the degrees of freedom (DoF) of the human hand. The finger can flex and extend the metacarpophalangeal joint, and flex and extend both the interphalangeal joints. Figure 2 depicts the four main positions a finger can take which are [18]:

- Full extension (Metacarpo-phalangeal and Interphalangeal extension)
- The lumbrical position - Intrinsic plus (Metacarpo-phalangeal flexion and Interphalangeal extension)
- The hook grip - Intrinsic minus (Metacarpo-phalangeal extension and Interphalangeal flexion)
- Full flexion (Metacarpo-phalangeal flexion and Interphalangeal flexion)

Table 1 Phalanx length as percentage of the hand length [16].

	Proximal (L_{pp})	Medial (L_{mp})	Distal (L_{dp})
Thumb	17.1	–	12.1
Index finger	21.8	14.1	8.6
Middle finger	24.5	15.8	9.8
Ring finger	22.2	15.3	9.7
Little finger	17.7	10.8	8.6

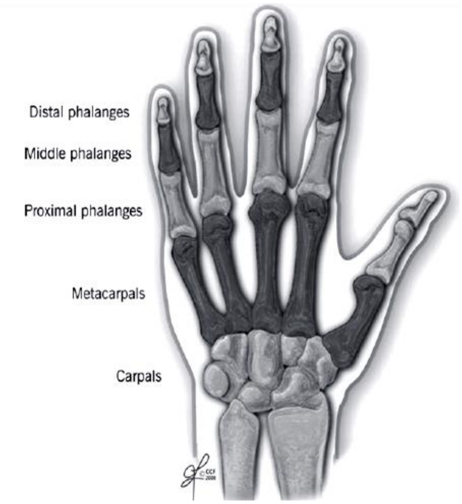

Figure 1 Bones of the hand as presented in [23].

Notable instances of human hand models are the ones of Cobos et al. [19] who have proposed a model with 24 DoF, of Davidoff and Freivalds [20] who have proposed a modelwith 23 DoF, of ElKoura and Singh [21] with a model of 27 DoF "4 in each finger, 3 for extension and flexion and one for abduction and adduction; the thumb is more complicated and has 5 DOF, leaving 6 DOF for the rotation and translation of the wrist", and of Sturman [22] who proposes a model of 29 DoF (23 from joints on the hand including 1 DoF on the Metacarpocarpal Joints for the digits 4 and 5), three for the free translation of the hand, and three for the free rotation of the hand as a result of the degrees of freedom of the wrist, elbow, shoulder, and body.

The performance of the natural human hand can be described by the following indicators [24, 25]:

- Total volume: 50 cc
- Weight: 400 g
- Type of Grasps: Power Grasps, Precision Grasps
- Force of power grasp: >500 N (age 20–25); >300 N (age 70–75)
- Two fingers force: >100 N
- Tapping force: 1–4 N
- Max. tapping frequency: 4.5/sec.
- Range of flexion: ~100°, depending on the joint
- Max. duration of grasp: Variable with energy
- Number of sensors: 17'000~20'000
- Proprioceptive sensing: Position, Movement, Force
- Exteroceptive sensing: Acceleration, Force, Pain, Pressure,Temperature
- Proportional Control: Ability to regulate force and velocity according to the type of grasp, the object, etc.
- Stability: The grasp is stable against incipient slip or external load
- Number of flexions: Limited only by muscular fatigue

3. ROBOTIC AND PROSTHETIC HANDS

In spite of the global interest and the vast research on artificial hands during the last decade, only few robotic hands can demonstrate human like features, and dexterity to a high, degree. In the following subsections we will present the robotic hands that exhibit the best combination of appearance functionality, dexterity, accuracy, and operability, with adequate size and weight. In total, there will be presented fifteen hands which are either available on the market, or will be developed in the near future, or have already been developed recently.

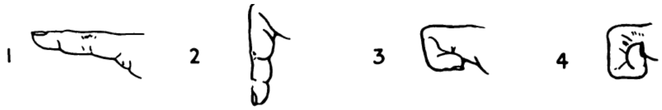

Figure 2 The main positions a finger can take (1) Full extension, (2) The lumbrical position , (3) The hook grip, and (4) Full flexion [18].

Figure 3 The Schunk Dexterous Hand.

THE SCHUNK DEXTEROUS HAND

In 2012 the Schunk company provided the market with both right, and left intelligent gripping robotic hands (Fig. 3) that resemble the human hand in size, shape, and mobility, by reproducing 27 DoF [26]. The motor controllers have been integrated in the wrist of the anthropomorphic gripper hand, providing compact solutions by connecting it with any lightweight arm available on the market. The energy supply of the 5-finger hand requires a battery-servable 24 V DC. The hand is controlled via a serial bus, and by means of nine drives, its five fingers can carry out various gripping operations. Additionally, numerus gestures can be constituted, whereby the visual communication between human and service robot is simplified, and the acceptance for applications in the human environment are increasing. The use of tactile sensors in the fingers will grant the necessary sensitivity of the gripper hand for mastering gripping and manipulation tasks even in unstructured and unforeseeable environments. Elastic gripping surfaces ensure a reliable hold of the gripped objects.

THE DLR/HIT HAND II

The DLR - German Aerospace Center, and HIT have jointly created a five fingered hand with an independent palm, and five identical modular fingers to achieve a high degree of modularity. Actually, the Schunk hand discussed above is based on this model. Each finger has three DoF and four joints. It is an internal actuation hand where there needs not any forearm and all the actuators and electronics are integrated in the finger body and the palm [27]. By using powerful flat brushless DC motors, tiny harmonic drivers and BGA form DSPs and FPGAs, the whole finger’s size seems quite human like (length 169.1mm, and width 32mm). By using the steel coupling mechanism, the phalanx distal’s transmission ratio is exact 1:1 in the whole movement range. At the same time, the multisensory dexterous hand integrates position, force/torque and temperature sensors. The hierarchical hardware structure of the hand consists of the finger DSPs, the finger FPGAs, the palm FPGA and the PCI based DSP/FPGA board. The hand can communicate with external with PPSeCo, CAN and Internet. Instead of extra cover, the packing mechanism of the hand is implemented directly in the finger body and palm to make the hand smaller and more human like. The whole weight of the hand is about 1.5kg and the fingertip force can reach 10N.

THE GIFU HAND II

The anthropomorphic robot hand Gifu hand II from the Dainichi Company, Ltd. Kani, Japan has a high potential to perform dexterous object manipulations like the human hand [28]. It resembles a relatively large human hand, and has an opposable thumb and four fingers, all the joints of which are driven by servomotors built into the fingers and the palm. The thumb has four joints with four DoF, the other fingers have four joints with three DoF, and two axes of the joints near the palm cross orthogonally at one point, as is the case in the human hand. It can be equipped with six-axes force sensor at each fingertip and a developed distributed tactile sensor with 624 detecting points on its surface. The minimum bandwidth of the robot hand is 7.5 Hz, which exceeds the responsibility of the human finger, the bandwidth of which is, at most, 5.5 Hz., meaning that it can move quicker than a human hand, and can be used as a research tool for dexterous robot manipulation using force sense and tactile sense. The output torques of the first joint and the second joint are 3.46 Nm, and the output force at the fingertip of the thumb is 4.9 N.

THE SHADOW HAND

The Shadow Hand is one of the closest robotic hands to the human one available. It provides twenty-four movements (24 DoF), allowing a direct mapping from a human to the robot and weights 3,9 kg since it is a combination of metal and plastic parts [29]. The general movement is on average about half the speed of that of a human. For example, the time for transition from opened to clenched is 0.2 seconds approx. The hands dimensions are:

- Finger length: 102mm
- Thumb lenght: 102mm
- Palm lenght: 99mm
- Palm width: 84mm
- Palm thickness: 22mm
- Thumb base thickness: 34m
- Forearm: 434mm

It has integrated sensing and position control, allowing precise control from off-board computers, or integration into an already existing robot platform. It contains an integrated bank of 40 Air muscles which make it move. The muscles are compliant, which allows the hand to be used around soft and/ro fragile objects. The Air Muscle, as its name suggests, is a pneumatic actuator that behaves much like a biological muscle. It consists of two essential materials: an expandable rubber tube, surrounded by inextensible plastic braiding. The braiding has the property that, when it is pulled axially, it contracts radially. Conversely, if one were to force it to expand radially, it would contract axially. The rubber tube is used to inflate the braiding from the inside; a slight pressure producing a surprisingly high contraction force. To complete the muscle, plastic bungs are used to seal the end, and provide a means of attachment. A muscle is clearly a lightweight object yet can easily exert forces of up to 70 kg at 4 bar, while contracting 30 per cent of its length, 38 actuators, each delivering about 3Wof power. The hand itself is a dense network of tendons and sensor wiring. Each of the 23 joints in the hand (not including the wrist), requires one or two tendons to connect it to its muscle(s).

For applications requiring highly detailed sensing capabilities the Shadow Hand can be equipped with Bio Tac tactile sensors on the fingertips (Fig. 4), offering sensivity sufficient to detect a single small coin. BioTac sensors allows for detailed force, micro-vibration and temperature gradient sensing. Data from the BioTac sensors is fully integrated and available via the same EtherCAT interface as other sensors.

Figure 4 The Shadow Hand with tactile sensors.

THE SOUTHAMPTON REMEDI-HAND

The University of Southampton has produced a functional hand intended to be used as a prosthetic hand, the Southampton Remedi-Hand, with six DoF, one for each finger and two for the thumb [30]. It is myoelectrically driven (control signals are derived from a flexor tensor muscle pair) with independently driven fingers and a two axis thumb. The palm of the hand and fingers are made of a light weight epoxy carbon fiber making the total assembly weight less than 500g - even lighter than a real hand. The hand uses six sets of motors and gears so that each of the five fingers can move independently, can clutch objects such as a ball, can move the thumb out to one side and grip objects with the index finger like opening a lock with a key, or wrap the fingers around an object. Thus, it has a precision, lateral and power grip. The Remedi-Hand uses screen printed thick film piezoresistive resistors and piezoelectric dynamic sensors to provide a cheap and compact solution for detecting grip force and slip of an object from a prosthesis. It uses a new type of fingertip that allows direct screen printing of thick-film sensors onto the surface. The fingertip has an array of thick-film sensors deposited on it to both measure the grip force exerted by the independently driven fingers and also to detect the onset of slippage of an object held in the hand. Two types of sensors used: piezoresistive thick-film sensors arranged to detect the force on the finger, and piezoelectric thick-film sensors to detect the onset of slip. This lets the hand know how tightly to grip an object without dropping it, but not so tightly that it's crushed. It also haς an integrated slip-sensor which informs the hand if something is beginning to slip out of its grip so it can grip slightly harder.

ROBONAUT 2- R2

The Robonaut 2 is a dexterous anthropomorphic robot developed by NASA and General Motors and it was scheduled to arrive on the International Space Station in early 2011 and undergo initial testing by mid-year. It encompasses two 7 DoF arms, two 12 DoF hands among others. It has two finger groupings; thump, index and middle finger form the dexterous set, and the 4th and 5th finger form the grasping set. Robonaut 2's series elastic arms do not sacrifice strength, or payload capacity, to achieve fine torque sensing at each of its joints. This is made possible by the custom planar torsion springs that are integrated into each arm actuator and the two 19 bit absolute angular position sensors that measure each spring's deflection. To achieve R2's strength, its arm speeds of over 2 m/s, and the data processing required for the robot's many sensors and control modes, a considerable amount of capability has been distributed to the low level joint controllers embedded in each of the arm joints. The performance of the Robonaut 2 hand is measured by its ability to emulate Cutkosky's grasp taxonomy [32] allowing for successful grasps across 90% of the taxonomy. Since the tendons can only transmit forces in tension, the number of actuators must exceed the DoF to achieve fully determined control of the finger. It turns out that only one tendon more than the number of DoF is needed. The impedance control strategy limits the force that the robot applies to the environment. This ensures that when inadvertent human contact occurs, the resulting force felt by the person is comfortable and the robot can be easily restricted by just manually pushing its limb out of the way. In parallel to R2's torque control are software monitoring routines that use multiple force sensors in the robot's arm in addition to the arm and waist joints' torque sensing to independently monitor the robot's forces. If a predefined limit is exceeded at either the joint or the arm level, the robot disengages motor power and stops [31].

MODULAR PROSTHETIC LIMB

The Revolutionizing Prosthetics program [33, 34] has developed the Modular Prosthetic Limb (MPL), which can support varied uses as a prosthetic, human assistive device, or a general robotic arm (Fig. 5). To accomplish the technical challenges of engineering the hand system, it was critical to comprehend and address issues concerning quality of like comfort, appearance, natural control, and sensory feedback. The MPL is a modular and extensible limb with 25 DoF (17 actuated), sensors throughout the hand, and impedance control. It can curl more than 18 kg at the elbow approaching the human strength, and has controllable dexterity featuring open system architecture bus structure, open system principles for electronics and hardware components, three DoF shoulder, an integrated powerful elbow with active extension, three DoF wrist assembly, and an articulated hand with ten actuated joints. It is working with Lithium batteries, and its overall weight is less than 8 lb. It is equipped with small-scale, powerful, and efficient integrated motors and transmissions, mesofluidics (full limb and dexterous hand applications for robotics), monopropellants, which are also applicable to robotics, particularly in extreme and austere environments. The MPL has also a simplified, platform-independent communication interface called Virtual Integration Environment (VIE), which visualizes and monitors the performance of various design approaches, pilot neural signal analysis algorithms, simulates emerging mechatronic elements, trains end-users to control real or virtual neuroprosthetic devices, and configures and customize clinical and take-home devices. The MPL is offered in two designs, the Intrinsic Hand where all motors are located in the hand, and the Extrinsic Hand where had all motors are located in the forearm in a cooperative robotic (cobotic1) drive unit controlling a tendon-actuated hand, similar to our human hand.

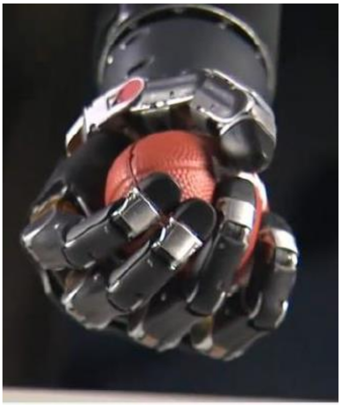

Figure 5 The Modular Prosthetic Limb.

OPEN HAND PROJECT DEXTRUS HAND

The aim of the Open Hand Project [35] is to make a low cost robotic prosthetic hand that will be more accessible to amputees. The full development of the hand will start next year. All of the motors and electronics will fit inside the palm of the hand, and will be connected to an existing fitted prosthesis using standard connectors, meaning that everyone can use it without requiring a custom fitting. An intuitive and simple control system will be implemented with two EMG sensors that can be placed on any muscles. It will also have a documented serial communication interface so users can create their own custom control hardware. ABS plastic -the same material that Lego bricks are made from- will be used to create the majority of the parts in the Dextrus hand, and will be 3D printed. If a part does wear, or break, a replacement can simply be printed and it can be replaced easily, making replacing parts quick and easy to adjust. In the Dextrus hand, each finger is actuated by a single tendon that runs through all of the joints to the tip. This means it will grasp just like a human hand, adapting to fit any form that's placed in it. Marine grade stainless steel tendons are used in the fingers, which have a minimum breaking load of 18Kg (per finger) and a nylon coating to make sure they move smoothly through the joints. To ensure flexibility, a 7×7 tendon is used; this means the cable has 7 cores, each made up of 7 strands of stainless steel wire. Extended use of the hand is likely to cause changes in tension on the tendons and joints that will eventually result in failure of a part. To maximize the lifetime of the joints in the hand, the tendons are held taught by a compression spring tensioner assembly. If one bumps a finger by accident, instead of the tendon breaking, the compression spring will flex and the finger will return to its original position. When someone grabs an object, usually they do not think how to move each finger towards a specific position; instead, they use feedback and the sense of touch. The Dextrus hand works in the exact same way, by using feedback sensors as the fingers close; it understands when it is gripping an object, and how hard it's gripping the object.

The Dextrus hand can articulate each finger, and thumb individually, enabling it to grasp all sorts of different shapes, and sizes of objects. Each finger has its own feedback sensor, allowing for individual grasp, providing feedback on whether they have come into contact with an object, in order to stop their movement and grip firmly the object. Highly efficient miniature, epicyclic geared motors are used to achieve the power necessary to grip household objects with enough force to hold heavier household objects. Power preliminary tests and calculations suggest that the Dextrus hand will be able to operate for around 8-12 hours on a single charge with lithium ion batteries.

THE I-LIMB HAND

The firm Touch Bionics from Scotland has developed the i-LIMB Hand (Fig. 6) with five individually powered multi-articulated fingers, using a traditional myoelectric signal input to extend and flex the hand's life-like fingers [36]. It has six DoF, five degrees of actuation, weights 518 g, and is able of precision, lateral and power grip. Myoelectric controls utilize the electrical signal generated by muscles in the remaining portion of a patient's limb. This signal is picked up by electrodes that sit on the surface of the skin. Touch Bionics has also developed a custom covering, the i-LIMB Skin, which is a thin layer of semi-transparent material that has been computer-modeled to accurately wrap to every contour of the hand. ARTech Laboratories and LIVINGSKIN work at the forefront of high-definition cosmesis to offer a life-like solution to compliment the life-like motions and performance of the hand. In a recent case report comparing the i-Limb hand with a Dynamic Mode Control hand (DMC plus hand) [37], the patients reported a tendency in favor of the i-LIMB since it was more reliable when holding objects, but also reported its lack of power , and the fact that it was less robust. The case study concluded that the i-LIMB hand had limited additional functionality compared to the DMC plus hand.

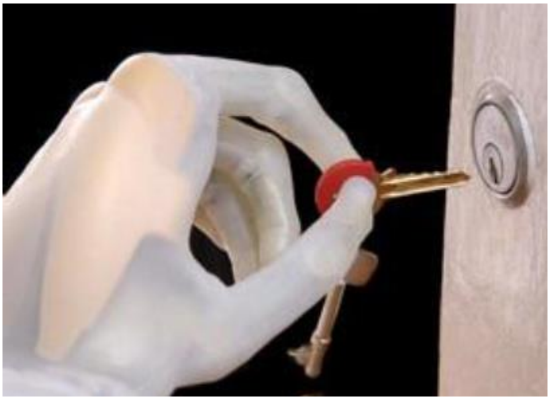

Figure 6 The i-Limb Hand.

WASEDA SOFT-HAND 1

The Waseda Soft-Hand 1 is attached to the humanoid robot KOBIAN of Waseda University in Japan. The hand has soft fingers made by silicon and palm made by Septon for interacting with other humans, and the actuation is provided by four DC servo motors integrated in the forearm that control five underactuated fingers by using antagonist wires for flexion and extension of the index, the middle finger and the thumb/ring finger/pinkie, and the abduction/adduction of the thumb [24]. The hand weights 180g, or 950g including the forearm, its height is 160 mm, and its width is 148mm, proportional to the size of the robot.

ASIMO

Asimo (Advanced Step in Innovative Mobility) [38] is maybe the most famous bipedal robot, and was developed by HONDA in 2000. Apart from being able to run, walk, climb, recognize people, talk, interact, learn, and play, it can also move/push/carry/grasp/manipulate objects with its dexterous hands. It is made of magnesium alloy covered with a plastic resin, which makes it very durable and lightweight. It is powered by a 51.8 rechargeable lithium ion battery (Li-ION) that lasts for 1 hour. ASIMOs hands have independent opposable thumbs allowing to carry odd-shaped objects til 300 gr (in each hand) and up to 1kgr using both hands. It has 14 DoF in its arms, and 4 DoF in its hands (not counting the joints for the five bending fingers). Last, but not least, it has force (kinesthetic) sensors in its wrists to synchronize with a person’s movement. It will step backwards when its hand is pushed and forward when its hand is pulled [39].

ICUB

iCub is a humanoid robot for research in embodied cognition and has the size of a three and half year old child able to crawl on all fours and sit up to grasp and manipulate objects of reasonable size and appearance [40, 41]. Its 9 DoF hands (each) have been designed to support sophisticate manipulation skills. It has three independent fingers and the fourth and fifth are used for additional stability and support (1 DoF). The hands are covered with a distributed sensorized skin (under development) using capacitive sensor technology. Each joint is instrumented with positional sensors, in most cases using absolute position encoders. Tendon driven joints are the norm both for the hand and the shoulder, but also in the waist and ankle. This reduces the size of the robot but introduces elasticity that has to be considered in designing control strategies where high forces might be generated. Seven motors are placed remotely in the forearm and all tendons are routed through the wrist mechanism (a 2 DoF differential joint). The thumb, index, and middle finger are driven by a looped tendon in the proximal joint. Motion of the fingers is driven by tendons routed via idle pulleys on the shafts of the connecting joints. The flexing of the fingers is directly controlled by the tendons while the extension is based on a spring return mechanism. This arrangement saves one cable per finger. The last two fingers are coupled together and pulled by a single motor which flexes 6 joints simultaneously. Two more motors, mounted directly inside the hand, are used for adduction/ abduction movements of the thumb and all fingers except the middle one which is fixed with respect to the palm. The overall size of the palm has been restricted to 50 mm in length; it is 34 mm wide at the wrist and 60 mm at the fingers. The hand is 25mm thick.

THE PINCHING HAND

The purpose of the “Pinching Hand” from the University of Tsukuba, and Japan Science & Technology Agency was to generate the action of pinching motion with finger tips [42]. It is a small-sized and light-weight robotic hand with 8 DoF and three joints for all the fingers except for the thumb; MP joint with 2 DoF for bending and stretching, and for abduction functions, PIP joint, and DIP joint with 1 DoF respectively for bending and stretching. Human PIP and DIP move together in many cases, thus the majority of robotic hands these two joints are linked by one motor. In the “Pinching Hand”, this concept is further developed and all three joints are moving as if they are interlocked. The four fingers are interlocked for MP motion used for abduction from viewpoints that no problem is observed in motion reproduction capability. The middle finger is fixed to the palm since this finger is not moved significantly at abduction with regard to the palm. The thumb has three joints each referred to from the root as CM joint (2 DoF), MP joint (1 DoF), and IP joint (1 DoF). One of the key competences of the hand is the addition of twisting motion (1 DoF) to the thumb which is not present in the human hand. When the tip of the thumb touches the tip of another finger, the contact portion between the two is the cushion at fingertip on the thumb, but it is often a position off the fingertip cushion on the part of other fingers. This phenomenon is produced because the thumb does not have any twisting function. A human hand has soft skin and flesh at the fingertip and a high control performance of motion and force at the respective finger tips, and can therefore realize a stable pinching function even if the two groups of finger do not face each other exactly at the cushion part. However, a general robot hand has only a much lower control performance of motion and force compared with a human hand. The fingertip force produced by the terminal joint drive mechanism at the tip of the two finger groups should face each other justly, namely the two finger tips should oppose each other exactly at the cushion.

THE SMART HAND

The aim of the EU funded Smarthand project is to develop a transradial prosthesis with all the main characteristics displayed by a human hand [43]. The Smart Hand (Fig. 7) has 40 embedded sensors, its size is slightly bigger than 50 percentile male hand size; 12 mm longer (122 mm instead of 110 mm from the middle fingertip to the wrist attachment) and the palm is 8mm thicker (39 mm instead of 31 mm). The overall volume is about 1,3 times the natural hand. The weight, including sensors and electronics (excluding the cosmetic glove that should cover the hand, and the batteries that could be placed in the prosthetic socket) is 520, again 1,3 of the natural hand weight (about 400 g). It has 4 degrees of actuation, with 16 DoF that allows for execution of power/precision/lateral grips, but minimal gesture like counting and index pointing. It has been calculated that a full day operation (estimated in 4000 grasps) would be guaranteed with a 12 V, 1,5 Ah battery for supplying the motors and a 6 V 1,5 Ah battery for the sensors and embedded controller (two batteries are required).

THE KCL METAMORPHIC HAND

Based on the principle of metamorphosis (change in form, topology and configuration to meet environmental demands), a metamorphic robotic five fingered hand with an articulated palm has been invented and developed at King's College London which is capable of implementing flexible manipulation in an augmented workspace [44-46]. It consists of a reconfigurable palm -a spherical five bar linkage made out of five links in a circular confiuration with every joint axis passing through the centre of the sphere-, a 4-DoF thumb, a 3-DoF index/middle/ring/little fingers, and an one tendon per finger actuation. The first and last joints of the palm are actuated, while the remaining three are rotating based on the constraints imposed by the geometry of the spherical linkage. The functionality of the hand was investigated using opposition space model with computer simulation results, and while it's manipulability was analyzed based on characteristic matrix equation resulting in Jacobian matrices for singular value decomposition operations.

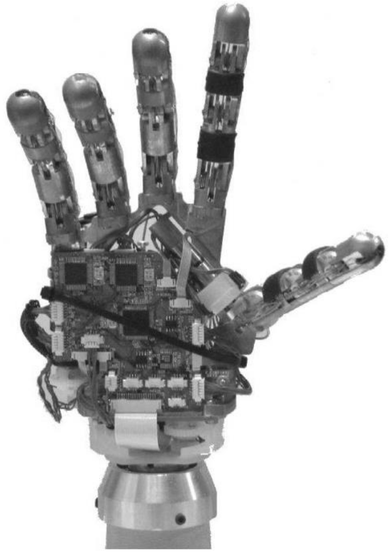

Figure 7 The Smart Hand.

4. CONCLUSION

The human arm, and hand form a highly complex system, capable of intricate movements that let us interact with the world, and execute daily life-tasks related to grasping, manipulating objects, and making gestures. Thus, for a functional android robot a pair of skillful hands is needed. We have presented a report on the anatomy, the bone structure and the key functionalities of the human hand, followed by the structure and performance of fifteen of the most dexterous available robotic hands that resemble the human one. The hands were either part of an existing robot, or were standing alone, and could be mounted on already existing interfaces.

Kinematics and actuation systems vary from one robotic hand to another, while grasping and manipulation requirements also vary as they depend on the executed tasks, and the users' needs. This paper highlighted the advantages of a plethora of existing android hands in order to assist roboticists in deciding upon future directions in android, and humanoid technology. The next generation of android robots should be equipped with hands that could accommodate most of the activities of daily living. Emphasis shall be given in keeping the hands lightweight, low cost, making them easy to install/extract, enduring, durable, easy to control, less complex, with simple kinematic chains, and of course maintaining a human-like aesthetic. Technology has not yet progressed to the degree of being able to satisfy all our needs, thus, when selecting a hand, the roboticist will automatically (and unfortunately) be put in the position of balancing the loss of one quality, or more, in return for gaining another.

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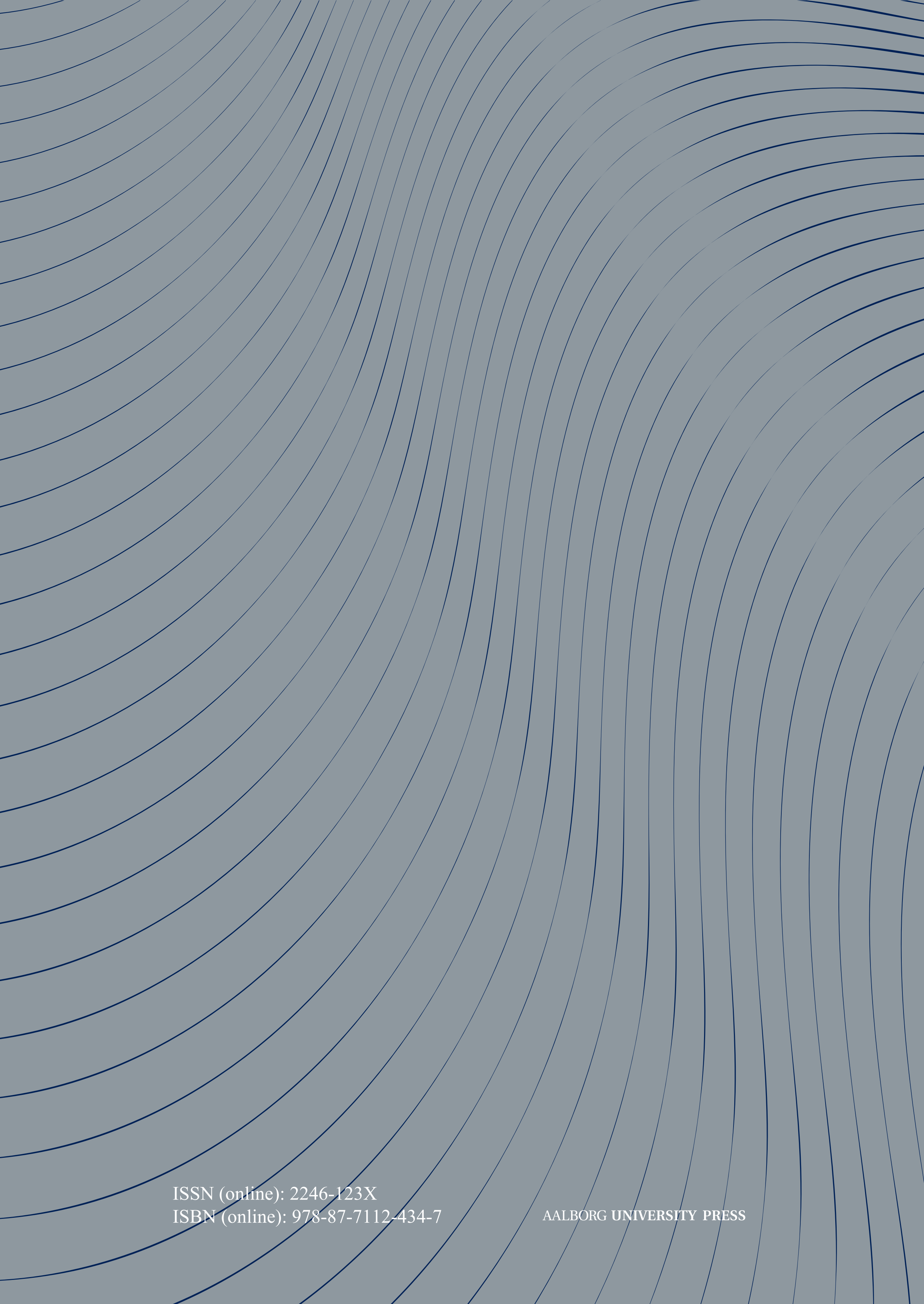

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