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SURVEY ARTICLE

A Systematic Review of Ten Years of Research on Human Interaction with Social Robots

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ABSTRACT

While research and development related to robotics has been going on for decades, the past decade in particular has seen a marked increase in related efforts, in part due to technological advances, increased technological accessibility and reliability, and increased commercial availability. What have come to be known as social robots are now being used to explore novel forms of human-robot interaction, to understand social norms, and to test expectations and human responses. To capture the contributions of these research efforts, identify the current trends, and future directions, we systematically review 10 years of research in the field of social robotics between 2008 and 2018, which includes 86 publications with 70 user studies. We classify the past work based on the research topics and application areas, and provide information about the publications, their user studies, and the capabilities of the social robots utilized. We also discuss selected papers in detail and outline overall trends. Based on these findings, we identify some areas of potential future research.

1. Introduction

While research and development related to robotics has been going on for decades, the past decade in particular has seen marked advances, with new sensors, actuators, and algorithms for example, leading to a wide range of more versatile, robust, and commercially and technologically accessible robots. Over this time frame we have seen corresponding advances in the field of Human-Robot Interaction (HRI), leading to an improved understanding of how humans perceive and interact with robots, and new uses of socially aware personal robots to enrich our society. New research directions and applications include the exploration of the effects of moral decisions between humans and robots (Malle et al., 2015), social assistants for people diagnosed with Autism Spectrum Disorder (Clabaugh et al., 2018) or diabetes (Van Der Drift et al., 2014), and new or improved uses of robots for education and healthcare (Benitti, 2012; Dahl & Boulos, 2014; L.-Y. Li et al., 2009; Mubin et al., 2013; Okamura et al., 2010).

To gain a deeper understanding of the research efforts conducted to date, we carefully identified and then studied the existing survey papers related to social robotics shown in Table 1. Each of these papers focused on specific aspects of social robotics research such as the behavioral requirements of the robot or the design needs of a specific population. A result of this effort was our sense that a domain-independent review of the field would add significant value to the existing surveys. To our knowledge the highly informative work by Fong et al. (2003) is one of the few domain-independent surveys on social robotics which dates back to 2003. In our survey we examine a broad range of research conducted in the field of social robotics and HRI within the last ten years, identify and classify areas where user studies have been conducted, and highlight innovative and emerging HRI research trends and application areas for social robotics. Our primary objective was to answer the following research questions for the time frame:

- **RQ1**: What are the primary application areas of social robots?
- **RQ2**: What are the primary research topics within each application area?
- **RQ3**: What are the emerging challenges and potential future research areas?

Our goal is to examine these questions through a general and domain-independent review of research in social robotics during the ten-year period from 2008 to 2018. By characterizing interesting research directions we hope to help identify and even inspire future research and applications in social robotics.

We structure this paper as follows. In Section 2 we describe the methodology that we used for our structured literature review. In Section 3 we present the research topics we covered. In Section 4 we provide a high-level overview of the numbers of publications and topics areas. In Section 5 we cover the application areas and discusses representative publications. In Section 6 we provide a general discussion of the findings and trends. In Section 7 we offer some concluding thoughts.

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Table 1. Previous surveys in the field of social robotics.

Previous Surveys	Time Span[a]	Reviewed Publications	Domain
Fong et al. (2003)	pre 2003	~169	Social robotics
Bruce (1993)	1944 to 1993	~77	Facial expression
Langton (2001)	1963 to 2000	~51	Eye behavior
Bethel and Murphy (2008)	1967 to 2006	~46	Affective expression
Broadbent et al. (2009)	1970 to 2009	~89	Healthcare robots for older adults
Duncan and Murphy (2012)	1974 to 2011	46	Approach distance
Díaz et al. (2013)	1965 to 2012	~43	Affective aspects of at home assistive robots for the elderly
Cabibihan et al. (2013)	1992 to 2013	~88	Autism therapy for children
Leite et al. (2013)	2003 to 2011	24	Long-term interaction
Ferreira and Dias (2014)	1980 to 2013	~144	Automatic attentional mechanisms
Robinson et al. (2014)	1979 to 2014	~159	Healthcare robots for older adults
Kachouie et al. (2014)	2002 to 2012	86	Socially assistive robots for older adults
Peng et al. (2015)	1990 to 2014	~84	Robotic dance
Bharatharaj et al. (2015)	1995 to 2015	~41	Bio-inspired therapeutic pet robots
Yilmazyildiz et al. (2016)	2001 to 2014	32	Social robots and semantic-free utterances
Charisi et al. (2016)	2000 to 2015	135	Child-robot interaction
Crumpton and Bethel (2016)	1939 to 2015	~97	Affective expression
Pennisi et al. (2016)	2005 to 2014	29	Autism therapy
Petrie and Darzentas (2017)	2005 to 2016	71	At home assistive robots for the elderly
Honig et al. (2018)	1966 to 2017	221	Socially aware person-following robots
Hortensius et al. (2018)	1963 to 2017	138	Emotion perception
Vandemeulebroucke et al. (2018)	2010 to 2016	23	Socially assistive robots for older adults
Saunderson and Nejat (2019)	2001 to 2018	96	Influence of nonverbal communication
Syriopoulou-Delli and Gkiolnta (2020)	2008 to 2018	13	Socially assistive robotics and children with autism
Mou et al. (2020)	2006 to 2018	40	Personality of Robots

[a]For publications that did not include a time period in their methodology, the time span was based on the oldest and most recent paper in their work.

2. Methodology

In this work, we conducted a systematic review following the guidelines introduced by previous work (Dey et al., 2018; Kim et al., 2018), which also comport with the core steps of the PRISMA method for systematic reviews (Liberati et al., 2009). We conducted a structured search for publications using the digital libraries of the Association for Computing Machinery (ACM) and the Institute of Electrical and Electronics Engineers (IEEE). Within these libraries, we used search terms with a focus on personal and social robotics. The specific search terms we used were "personal robot" and "social AND robot AND personal." These terms were searched in the title, abstract, and keyword fields of the above libraries within the time range of 2008 to 2018. Only English publications were considered in our search. Publications dated prior to 2008 were excluded as they were covered in earlier literature reviews and the most relevant technological innovation for our review has occurred more recently. This resulted in 566 publications. We then semantically screened the publications as follows:

(1) We excluded publications that included the search terms but were not aimed at understanding, testing, or implementing social robots – the search terms were associated with different aims.

(2) We excluded publications that included duplicates between the two libraries, or publications where the same or similar results were presented in different venues or publication formats. For example, the same work might have appeared in a poster or extended abstract form, and later published in a more extensive proceeding or journal article. In such cases, we included only the final relatively comprehensive publication, omitting the earlier preliminary publications.

Table 2. Keywords used to code the publications.

Aspects	Keywords
Type of robot	Commercial name Physical presentation Locomotion behavior IoT capabilities
Human-subject evaluation	Experimental design: within-subjects, between-subjects, or mixed factorial Participant demographics: age, gender, number of participants (NoP) Data type: quantitative, qualitative, or both

(3) We excluded publications that focused on industrial robots – we were focused on research involved in the personal or social aspects of human-robot interaction. While some publications on industrial robots explored the societal impact of their integration into industry, we excluded them from this review.

The above procedures resulted in a total of 86 relevant publications between the years 2008 and 2018. We do not claim that this is a complete list of publications representing research in social and personal robotics between the years 2008 and 2018, however we believe that the body of work provides a useful snapshot of motivations, findings, themes, and trends in the social robotics community over that time frame.

Working with the set of 86 relevant publications resulting from the above process, we carried out our review in the following manner:

(1) We classified the publications based on their research contributions in relation to applications of their research, which include:

- Companionship
- Healthcare

- Education
- Social definition (i.e., defining the expectations assumed of robots in a social context)
- Social effects (i.e., evaluating the effects of a social interaction with a robot designed to elicit a specific reaction)

(2) We determined a set of relevant keywords, and coded the publications based on those keywords. Our process for choosing keywords was inspired by methods from previous review papers (Cabibihan et al., 2013; Fong et al., 2003; Kim et al., 2018; Leite et al., 2013; N. Norouzi, Bruder et al., 2019; N. Norouzi et al., 2018; Pennisi et al., 2016), contextualized in robotics. We also considered the robotic capabilities, and the presence or absence of a formal human-robot experiment. Table 2 shows the keywords.

(3) We collected the citation count for each publication from Google Scholar, as it existed during the time frame November 24–26, 2018.

(4) We carefully read the 86 relevant publications and created a written summary for each paper. Similar to an approach presented by Dey et al. (2018), we calculated the *average citation count (ACC)* as a quantitative indication of the impact of each publication, and identified publications with an ACC higher than the average of the 86 relevant publications. The most recent publications (2017–2018) had shorter time frames within which they could have been cited, and therefore the ACC could have been less indicative of the impact at this point. We chose to study them as potential representative papers, because they capture the most recent ideas of the field. Through these measures, we ended up with a pool of papers, which we used to choose the representative publications for each application area.

From the identified publications, we explored novel and emerging trends and future directions that are inspired by the research in these publications.

3. Research topics

While conducting our literature search, we formulated publication groups each focused on distinct research topics. Specifically we grouped the publications into nine dominant research topics identified from words and themes that were common throughout the publications, including keywords, specific applications, as well as independent and dependent variables that were discussed. We classified each of the publications in our search as belonging to one or more of these topics:

(1) *Personalization*: Research that approaches the robot's ability to dynamically change their personality based on a user's responses.

(2) *Social Awareness*: Research that addresses the robot's ability to simulate socially appropriate responses during an interaction.

(3) *Physical Awareness*: Research that addresses a robot's ability to navigate and interact with its surroundings.

(4) *Physical Structure*: Research associated with studying the role of robot physicality, its extensibility, and adaptability.

(5) *Social Companionship*: Research focusing on a robot's intended design for social companionship.

(6) *Predictive Behavior*: Research that explores a robot's ability to accurately convey its intentions before moving.

(7) *Telepresence/Teleoperation*: Research with a teleoperated robot.

(8) *Healthcare*: Research with social robots for scenarios in healthcare.

(9) *Education*: Research with social robots to improve the learning capabilities and information retention of students.

As indicated above, many of the publications we collected were identified as relevant to more than one category. To better further distinguish the research in each category, we classified publications using a maximum of two categories from the list above.

4. High-level analysis of reviewed publications

For all publications, we looked at the applications of each publication with regards to primary information such as ACC, publication type, and information about those that conducted user studies such as experimental design, demographics, data type, and research topics. Table 3 and Table 4 summarizes these information. Table 5 summarizes the information about the robots in the publications that mentioned them. Separately, we looked at the evolution of publications in this domain over the 10 years with regards to application (see Figure 2) and percentage of publications with and without user studies (see Figure 1). We also looked at the impact of each application area using its ACC (see Figure 4) and the contributing research topics to each application area (see Figure 3).

4.1. Publication information

The average number of authors per publication for all publications included in this review was three to four. The total number of authors across the 86 reviewed publications was 320.

The Social Definition area had the highest average number of authors at 5.2, likely because these publications were generally larger multidisciplinary efforts to design guidelines for creating a social personality for a robot. This application area

Table 3. Summary of the 86 publications with regards to publication and study information.

	Publication Type		Mean		Publication		Experimental Design			Demographics			Data Type		
Application	All	User Study	ACC	Author	Journal	Conference	Within	Between	Mixed	Age	Gender	NoP	Quan.	Qual.	Both
Companionship	22	14	4.21	3.5	1	21	7	6	1	12	11	14	2	7	5
Healthcare	16	9	2.34	4.2	0	16	6	1	1	4	4	9	2	4	3
Education	14	7	3.26	2.1	2	12	1	5	0	4	2	5	3	2	2
Social Definition	19	13	5.9	5.2	1	18	5	4	1	9	9	12	3	5	5
Social Effects	22	16	3.8	3.8	0	22	7	7	2	11	13	15	3	6	7
Overall	93	59	3.90	3.76	4	89	26	23	5	40	39	55	13	24	22

Table 4. Summary of the 86 publications with regards to average number of participants and research topics.

Application	Average NoP	Research Topics: Personalization	Social Awareness	Physical Awareness	Physical Structure	Social Companionship	Predictive Behavior	Telepresence/ Teleoperation	Healthcare	Education
Companionship	54	13	11	0	1	8	0	2	2	0
Healthcare	19	7	2	0	1	5	0	0	12	0
Education	51	7	7	0	2	0	0	2	1	7
Social Definition	79	9	11	0	2	4	2	1	0	0
Social Effects	63	9	14	1	3	5	5	3	0	0
Overall	49	45	45	1	9	22	7	8	16	8

Table 5. Categorization of specific aspects of the most often used social robots in the publications.

Robot Name	Physical Presentation	IoT	Locomotion	References
Travis	Other	Yes	No	Hoffman (2012); Hoffman et al. (2016)
KOBIAN	Humanoid	No	Yes	Zecca et al. (2008), Zecca et al. (2009)
Jibo	Other	Yes	No	Burger et al. (2009)
NAO	Humanoid	Yes	Yes	Aly and Tapus (2013); Bechade et al. (2015); Chevalier et al. (2015); Korn et al. (2018); J. Li (2016); J. Li and Ju (2016); Petit et al. (2016); Rouanet et al. (2013); Tahir et al. (2014); Van Der Drift et al. (2014)
iCub	Humanoid	Yes	Yes	Moulin-Frier et al. (2018); Petit et al. (2016); Ribes et al. (2015)
Baxter	Humanoid/ Other	No	Yes	Petit et al. (2016)
Acroban	Humanoid	No	Yes	Ly and Oudeyer (2010)
TEROOS	Animal	Yes	No	Saga et al. (2014)
ROBOHON	Humanoid	Yes	Yes	Wang et al. (2018)
CLASH	Other	No	Yes	Saga et al. (2014)
Pleo	Animal	N/A	Yes	Paepcke and Takayama (2010)
AIBO	Animal	Yes	Yes	Paepcke and Takayama (2010)
HERB	Humanoid/ Other	N/A	Yes	Cha et al. (2013)
PARO	Animal	No	No	Birnbaum et al. (2016); Heerink et al. (2009); Korn et al. (2018); Paletta et al. (2018)
PR2	Humanoid/ Other	Yes	Yes	Goodfellow et al. (2010); Mitzner et al. (2013)
Cosero	Humanoid	Yes	Yes	Schwarz et al. (2014)
Tofu	Animal	No	No	Wistort and Breazeal (2009)
Philos	Animal	Yes	No	Hornfeck et al. (2012)
Keepon	Animal	No	No	Baek et al. (2014); Leyzberg et al. (2014)
PEARL	Humanoid	Yes	Yes	Heerink et al. (2009)
Therabot	Animal	No	No	Darrow et al. (2018)
Reeti	Animal/ Humanoid	Yes	No	Ritschel (2018); Ritschel and André (2017)
Snackbot	Humanoid	Yes	Yes	M. K. Lee et al. (2012)
Ono	Animal/ Humanoid	No	No	Vandevelde and Saldien (2016)
SARA	Other	Yes	No	Pecune et al. (2018)
UXA-90	Humanoid	Yes	Yes	Choi et al. (2014)
KMC-EXPR	Humanoid	Yes	No	Jung et al. (2012)
Robobear	Animal/ Humanoid	Yes	Yes	Korn et al. (2018)
Care-o-Bot	Humanoid/ Other	Yes	Yes	Korn et al. (2018)
Sophia	Humanoid	Yes	No	Korn et al. (2018)
Pepper	Humanoid	Yes	Yes	Korn et al. (2018); Paletta et al. (2018)
IdleBot	Animal	No	No	Overgoor and Funk (2018)
Robovie	Humanoid	Yes	Yes	Imayoshi et al. (2013); Malle et al. (2015); Sabelli et al. (2011)
Cozmo	Other	Yes	Yes	Tan et al. (2018)
MDS	Humanoid	Yes	Yes	J. K. Lee and Breazeal (2010)

had several publications with 6 or more authors, including one publication with 18 authors that was used to demonstrate a cognitive architecture for robots.

On average there were nine publications per year, with the exceptions of 2011 with one publication, and 2018 with 15 publications. In general through the time frame there has been a steady increase in research related to social robotics.

4.2. Individual studies

54 out of 86 publications (63%) reported at least one experiment during their research. From the total of 70 experiments in 86 publications, the majority of publications reported only one user study (44 publications, 51%). 32 publications (37%) reported no experiment or no experiment results. six publications (7%) reported two experiments. The remaining 4 publications (5%) reported 3 or more experiments. The Social Effects area included the most user studies (24 studies, 31%), followed by Companionship (19 studies, 24%), Social Definition (17 studies, 22%), Education (9 studies, 11.5%) and Healthcare (9 studies, 11.5%). Some studies were counted under two categories, resulting in a total of 78 category studies. Although we observed a drop in user studies in the years 2010 and 2016, in most years half or more of the

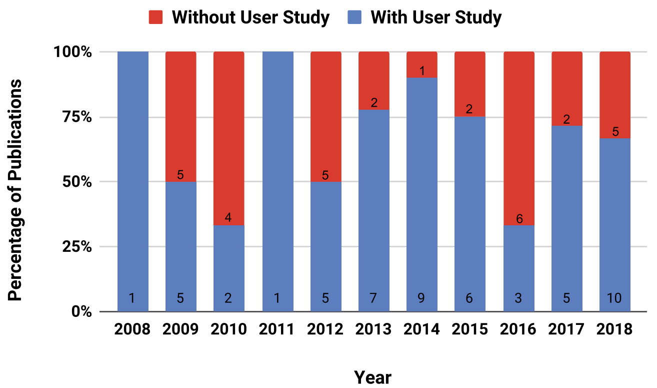

Figure 1. Percentage of publications per year with and without user studies. The absolute numbers show the total publications per year. Note that each publication can address multiple research areas (see Figure 3).

publications included user studies in their publications shown in Figure 1. Looking at publication venues, the majority of the publications were published at conferences (95%) while only a few of the ones we found were published in journals (5%).

The average number of participants per study was 49. The application area with the highest average number of participants was Social Definition at a 79 participant average, which was also the area with the largest number of authors. Many of the studies categorized in the Social Definition area were conducted online through Amazon Mechanical Turk, and therefore had a relatively large number of participants. Additionally, these publications typically explored several aspects of a robot's social presence, which also resulted in a higher number of studies per publication. Following Social Definition, Social Effects had a 63 participant average, Education had a 51 participant average, Companionship had a 54 participant average, and Healthcare had a 19 participant average. We believe the Healthcare application area had a low participant average because the logistical aspects of the studies made it difficult to conduct experiments on larger groups of participants. The most common goal of the relevant studies was to test social robots over a period of time, at work or at home. Because they couldn't use the same robot for each participant over the same period of time, the cost of facilitating a study with a larger participant group would increase by the price of one robot per participant. Other robots were used in a group therapy setting in which only the members involved in group therapy could be included in the study, resulting in a smaller capacity for participants.

We defined age, gender and number of participants (NoP) as basic demographics information and looked at how this information was reported in each user study. 57% of the publications (31) reported all three of them with age and gender separately being reported for 64% of the publications (35) and NoP being reported most consistently in 92% of the publications (50) which suggests a more standardized approach in reporting demographics information.

Most publications with studies adopted a within-subject experimental design (24 or 44%) or a between-subject experimental design (22 or 41%). 3 studies (6%) adopted a mixed-factorial design, and the remaining 5 publications (9%) conducted other forms of studies such as loosely defined studies used as a pilot, interviews, and surveys.

The majority of the publications used both quantitative and qualitative measures in their analysis (22 or 41%), followed by qualitative measures (19 or 35%), and only 24% of the publications (13) adopted solely quantitative measures. We observe similar patterns in Table 3 with most application areas as well, indicating that the research publications were aimed at exploring and formally analyzing human interaction with robots.

4.3. Categorization

4.3.1. Application areas

Looking at application areas, overall Companionship and Social Effects were the most researched fields, each covering 22 (24%) of the 93 total publication categories, followed by Social Definition with 19 (20%), Healthcare with 16 (17%), and Education with 14 (15%) publications, which is understandable since researching social robotics in Healthcare and Education requires a general understanding of the social aspects of the robots covered partly by the first three application areas mentioned above. Similar to the overall publication rates, Companionship and Social Effects were published more consistently over the span of the ten years followed by Social Definition and healthcare. For Education, apart from 1 publication published in 2009, this area received more attention from 2013 onward. Figure 2 shows the application area trends over the years.

With Social Definition publications evaluating and defining what is socially expected of a robot, which is partly a prerequisite of the remaining 4 areas, we observed higher ACCs at 5.9 followed by Companionship (4.21), Social Effects (3.8), Education (3.26), and Healthcare (2.34) which is shown in Figure 4.

4.3.2. Research topics

Looking at the contribution of each research topic in different application areas shown in Figure 3, we observed that personalization and social awareness of a robot were the most covered research topics among the different application areas, followed by social companionship although this topic was not researched for educational purposes. We also observed the topic of physical structure in some of the

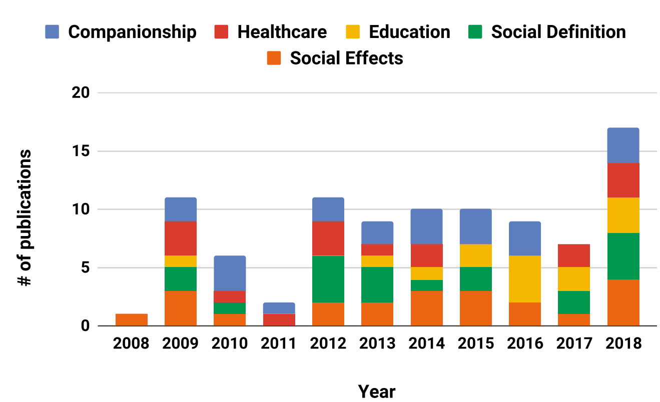

Figure 2. Plot showing the numbers of publications as trends of application areas each year.

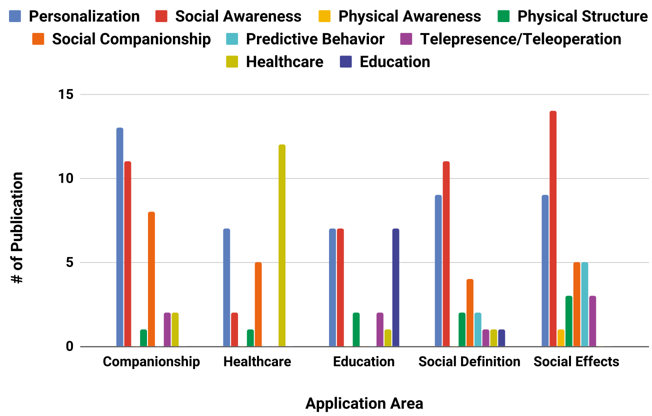

Figure 3. Contributions of each research topic to different application areas.

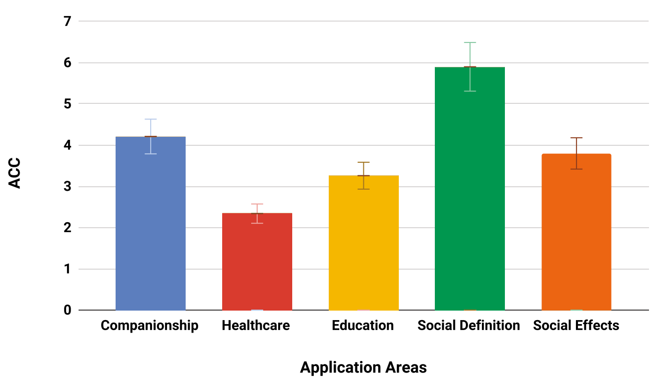

Figure 4. Impacts of the publications in the application areas based on their ACCs. The error bars show the standard error.

publications in each application area but in much smaller numbers. Telepresence/teleoperation, predictive behavior and physical awareness were among the less focused researched topics, which might suggest a need for studying social robots with more sophisticated movement capabilities.

4.4. Characteristics of the robots

As part of our evaluation process we created a spreadsheet of all of the robots in the publications, as depicted in Table 5. The robots were categorized using the robotics keywords in Table 2.

By far, the most commonly used robot in research was the NAO robot created by Aldebaran Robotics. This is a commercially available robot that retails for around 9,000–13,000 USD NAO is a humanoid bipedal robot that is IoT enabled and has locomotion capabilities including detection of objects in its path. Other popular robots used were PARO, a therapeutic robot created by PARORobotics, and iCub, a robot created for research in robot learning algorithms and social interaction.

A total of 35 robots were reported to be used in the publications we reviewed. When looking at physical representation, we defined 3 categories: (a) *humanoid* for those that have some of the human-like physical features like eyes, head, hands, etc., (b) *animal* for those that had physical likeness to animals or made up creatures, and (c) *other* for those that mostly had a solely robotic representation and not a full likeness to either a human or an animal. It's important to note that some robots are categorized in more than one group. The majority of these robots (21 or 60%) adopted a humanoid physical presentation. The humanoid robots had a variety of sizes, but as previously mentioned, the NAO robot was most popularly used. This robot was a small, portable robot with a pre-programmed personality that was intended to match a playful child. This was a common design choice among humanoid robots because they are commonly marketed as toys. 12 robots (34%) resembled an identifiable animal or made-up creature. Animal robots were most commonly used for studies involving therapy and educational tools for children. The remaining 9 (26%) robots were either designed to be clearly identifiable as robots or were not found after searching for more information.

23 robots (66%) were identified as IoT enabled, and 12 robots (34%) were identified as either incapable of IoT functionality or provided no information on this matter. This shows promising results for applying IoT interaction with the robot's environment without requiring dexterity of the robot, as well as interaction with Augmented Reality to assist in visualization of the robot's distinct features and capabilities. 21 robots (60%) were identified as capable of locomotion, while 14 (40%) were identified as stationary.

5. Application areas

In the following section, we review publications in each of the 5 application areas that have previously been described. We discuss a selection of representative publications in their respective application areas so that readers can understand the body of work that these selected publications represent.

5.1. Robots for companionship

A total of 22 publications were identified in the Companionship application area. The publications collected in this area comprised 19 user studies. Most of these studies revolved around developing and testing social robot interfaces and investigated participant responses in their feelings of companionship or willingness to divulge personal information. Out of these publications, we found that 11 were primarily associated with Social Awareness, 13 were associated with Personalization, 8 with Social Companionship, 2 with Telepresence and Teleoperation, 2 with potential applications in Healthcare, and 1 with Physical Structure.

5.1.1. Representative publications

An example of a relatively highly cited publication for the Companionship application area was the paper titled "Sacrifice One for the Good of Many? People Apply Different Moral Norms to Human and Robot Agents" by Malle et al. (2015). This paper focuses on a study involving the use and creation of moral human-robot interaction to discern whether people apply different norms to humans and robots. To test this, the researchers conducted two studies judging the moral decisions of a robot and a human. The first study was an online between-subjects experimental design with 157 participants, 66 of which were female and 90 male. The participants read through a classic trolley problem scenario with an agent type (repairman or robot) and action (direct the train or leave it). They were asked a series of questions about the moral obligations of the repairman or robot and asked to complete a series of 7-point ratings on whether the robot was believed to be capable of making a moral decision. The second experiment had 159 participants, 90 female and 68 male, with the only change that the decision of the repairman or robot was revealed before the participant answered whether such a decision was morally wrong. The paper concluded that there are differences in the norms that people impose on robots, and blame they associate with the robot's actions. This warrants further research in HRI and psychology to investigate the reasons for this effect.

Another representative paper in the Companionship application area is entitled "A Model for Synthesizing a Combined Verbal and Nonverbal Behavior Based on Personality Traits in Human-Robot Interaction" by Aly and Tapus (2013). In this article, progress is made to create an adaptable verbal-nonverbal robot behavior that reflects an engaging personality based on the user's personality dimensions. The experiment was a within-subject study where the user was exposed to two personalities and communication through speech only versus speech and gesture. The subject pool consisted of 21 participants, 14 male and 7 female, and users' opinions were assessed on a 7-point Likert scale. Results showed that human-like behavior was more engaging than generic robot behavior.

A recent study by Clabaugh et al. (2018) entitled "Month-Long, In-home Case Study of a Socially Assistive Robot for Children with Autism Spectrum Disorder" evaluates the effects of having a robot companion for a child with autism spectrum disorder (ASD). The robot companion in this study was specifically designed to interact with children that have ASD. A single case study was conducted with a family over the course of 30 days. The paper discusses benefits of the robot and includes information on a post-session survey that focused on the family and their child's interaction with the robot.

5.1.2. Discussion

The work done in this category focuses on robots that are meant to build relationships with their human owners. Many of the studies done in this area investigate what social cues robots should emit to impact human emotion and create emotional attachment (Baek et al., 2014; Choi et al., 2014; S.-Y Lee et al., 2018). Not many of these studies spanned over a long period of time, which is crucial to finding extended effects of social aspects that the robot may emulate. There were also very few studies comparing the effects that different robots may have on the user. For example, having a robot that appears more feminine may pose as less of a threat than a robot that appears more masculine, or having a robot that appears to be animal-like in behavior may create the illusion that it will be more conceding to the user's wishes. These studies would help contribute to research that address the overall effectiveness of a social robot in its intended environment.

5.2. Robots for healthcare

A total of 16 publications focused on the Healthcare application area. Nine studies were conducted as part of the research in these publications. Research in the Healthcare application area includes robots built for assistance in assisted living facilities, robots to monitor the physical and mental well-being of a patient, and robots to enhance the social learning experience for those with conditions that may influence their effectiveness in communication. Out of these publications, 2 showed impact in the Social Awareness category, 7 impacted Personalization, 5 worked in Social Companionship, 12 performed specific research in Healthcare, and 1 involved Physical Structure.

5.2.1. Representative publications

The paper that best represents this application area is entitled "A Remote Social Robot to Motivate and Support Diabetic Children in Keeping a Diary" written by Van Der Drift et al. (2014). The paper focused on a 6-participant, within-subject experiment where the children were asked to complete questionnaires that included Likert-scale questions with the addition of emoticons to clarify the answers. The paper concluded that the children grew attached to the friendship of the social robot and were encouraged to keep a diary as an activity to do with their friend.

Another notable paper that was recently written is entitled "AMIGO: Towards Social Robot Based Motivation for Playful Multimodal Intervention in Dementia" by Paletta et al. (2018). Researchers interviewed 6 individuals and held 3 focus groups to determine the most beneficial uses for a robot to assist elderly with dementia. Results showed that most believe that the best application for such a robot would be avoiding danger, communication, and assisting in personal and recreational activities. Further results imply that those suffering from dementia are open to welcoming a robot assistant/trainer to help with motivation and social stimulation.

5.2.2. Discussion

The publications in the healthcare application area covered a large range of ages and disabilities. However, we noticed a focus in elderly assisted living and children with diabetes or autism. Another big focus of these robots was to have a method of monitoring the patient's physical and mental health outside of a healthcare provider's direct supervision. Some robots, such as those designed to stay on body, focused on things like correcting posture, such as the publication by Saga et al. (2014). Other robots were designed to help elderly with memory training, such as in the paper by Hirsch et al. (2017). Most research focused on creating companions that would enhance the social presence of the patient, as they are oftentimes isolated in comparison to the average person. Most of the research in social robotics in healthcare are designed to inspire positivity in the context of the patient's living environment.

5.3. Robots for education

A total of 14 publications focused on the Education application area. These publications cumulated a total of nine studies. These studies evaluated the effects of a social robot in an educational context. The subjects of these studies were most often young children, and the robots were intended to expand their attention span so that they may retain more information over the course of one lesson. Out of these publications, we found that 7 focused on Social Awareness, 7 focused on Personalization, 2 on Telepresence/Teleoperation, 1 on Healthcare, 7 on Education, and 2 on Physical Structure.

5.3.1. Representative publications

To represent this application area, we chose an impactful paper entitled "Personalizing Robot Tutors to Individuals' Learning Differences" written by Leyzberg et al. (2014). In an 80-participant (ages 18 to 40) between-subjects experiment with the participants experiencing either no lessons, randomized relevant lessons, personalized lessons by an additive skill algorithm, or personalized lessons by a Bayesian skill algorithm. A Keepon robot was used as a referee and tutor as the participant solved a puzzle. Results indicated that participants with personalized lessons felt that they were significantly more relevant, and those that received personalized lessons did significantly better than those in non-personalized lessons.

Recent research in a paper entitled "Socially-Aware Reinforcement Learning for Personalized Human-Robot Interaction" by Ritschel (2018) evaluated the effects of a robot's social actions in storytelling based on the user's introversion and extroversion. Their work included changing personality expression based on the user's interest in the interaction as a robot reads "Alice in Wonderland." They further refer to learning other emotions and humor preferences.

5.3.2. Discussion

Educational applications for social robots typically involve intervention at an early age. Several of the studies in the Education application area involved having a social robot change their responses to a student to better engage them in the material they are learning (Leyzberg et al., 2014; Ramachandran & Scassellati, 2015; Ritschel, 2018; Spaulding, 2018). Some studies focused on catering the personality type of the robot to the student based on their Myers-Briggs Type Indicator (MBTI) personality type, with special consideration for introverted versus extroverted behavior (Abe et al., 2014; Andrist et al., 2015; Jung et al., 2012). Other studies looked to create a robot that would dynamically adapt to the responses of the student to continually maintain interest in the subject (Leyzberg et al., 2014; Ramachandran & Scassellati, 2015). A few studies evaluated the effectiveness of telepresence in an educational context and learned that the teleoperated robot's ability to simulate physical social cues greatly enhances the user's sense of presence and the participants' sense of the robot's presence (Abe et al., 2014). There was a lack of research that we found on the effects of a social robot teaching multiple students as in a study group or class behavior. This may present interesting results, as a robot could be more engaging than a traditional instructor.

5.4. Social definition for robots

A total of 19 publications were found to be in the Social Definition design area, with a total of 17 studies conducted as a result. Publications in this design area aim to define the best methods to incorporate social attributes into human-robot interaction. Robots have a separate set of rules and expectations than humans, so their social expectations reflect different priorities. In this design area, we found 11 publications to be in the Social Awareness Category, 9 in Personalization, 4 in Social Companionship, 1 in Telepresence/Teleoperation, 1 in Healthcare, 1 in Education, 2 in Predictive Behavior, and 2 in Physical Structure.

5.4.1. Representative publications

The most impactful work in this area is "How to Approach Humans? Strategies for Social Robots to Initiate Interaction" by Satake et al. (2009). This study attempts to find the best approaches for a robot to initiate conversation with a person that it wishes to communicate with. The largest issue found with approaching a target is that people do not recognize robots as an object to interact with. Many subjects were unaware or confused about the robot's purpose, and therefore chose not to engage. Results of the activity concluded that a specialized model for approaching people is much more effective than a basic to-target movement and language.

A similarly successful paper was "The Robotic Social Attributes Scale (RoSAS): Development and Validation" by Carpinella et al. (2017), which determines which attributes imply human perception and how these attributes affect the quality of interaction between a human and robot. Over the course of 4 studies, researchers gathered opinions of hundreds of people to derive a pattern that would most fit the ideal robot social personality preferences. The resulting studies detailing expectations of a robot using the Godspeed scale (Bartneck et al., 2009), social attributes closely related to the Godspeed scale, the association with discomfort and robots and its ties to unfamiliarity, and the role of gender in the perceptions of a robot's personality. Results were recorded and used to create the RoSAS scale, which is intended to be used as a tool for designing and improving robots in a social context.

A notable 2018 article that contributes to this research area is "What Does it Mean to Trust a Robot? Steps Toward a Multidimensional Measure of Trust" by Ullman and Malle (2018). In a study of 45 adults, participants were asked to associate words with different kinds of trust such as capacity trust and personal trust. Results were broken down into four distinct dimensions of trust: capability, ethicality, sincerity, and reliability of the robot. These dimensions were given five closely related adjectives to define what they mean and how they may be implemented in a robot's social trust measures, for use in future questionnaires.

5.4.2. Discussion

The research that is represented in the body of work that defines the Social Definition design area of this literature review focuses on defining positive and negative effects of a robot's decision making, social cues, and conversation.

Research by Moulin-Frier et al. (2018) introduced work on creating a socially competent robot that would dynamically interact with the user. In a similar vein, Goodfellow et al. (2010) published research addressing human-robot interaction models in the context of human-computer interaction models that have been previously established. Ultimately, robots are expected to have human-like qualities for decision-making, conversation, and social cues, but the more robotic they look, the more computer-like they are expected to act. This was noted in a study by Malle et al. (2015) in which they concluded that people had different expectations for a robot's decision-making versus a human's decision-making in moral predicaments. Robots are expected to make the most efficient decisions regardless of the social implications of those decisions, as they are known to be making these decisions based on algorithms. Conversely, humans are expected to make a more socially weighted decision based on the context of the situation. The research in this field is still at its early stages, and it is difficult to find studies that are applied outside of small, short initial studies. An important step toward a better understanding of robots in this area would be to see the long-term effects of interaction with a robot that adapts to one's own personality, which presents an area for this field to explore further in the future.

5.5. Social effects of robots

A total of 22 publications were part of the Social Effects design area. This area consists of research on the effects that a robot with social qualities has on its audience. A total of 24 studies were conducted over the course of these 22 publications. After reviewing, we found that 14 fit into the Social Awareness category, 9 addressed Personalization, 1 included Physical Awareness, 5 addressed Social Companionship, 3 used Telepresence/Teleoperation, 5 included Predictive Behavior, and 1 addressed Physical Structure.

5.5.1. Representative publications

The representative paper for this design area is entitled "Personalization in HRI: A Longitudinal Field Experiment" by M. K. Lee et al. (2012). It addresses the social effects of having a robot with memory retention so that it can collect and tailor social responses with the user. In a mixed factorial study, researchers used a personalization and no personalization condition to evaluate the social interaction of a robot versus personalized interaction of the robot. A total of 21 participants were provided snacks by a Snackbot machine for a series of weeks. Measured information included self-disclosure, greeting the robot by name, and self-connection. Evaluation included questions on service satisfaction and what the service would be worth. Results suggested that personalizing human-robot interactions reinforces rapport, cooperation, and engagement between the human and robot, and helps to build a relationship between the two entities.

Another noteworthy paper representing this section is "Judging a Bot By Its Cover: An Experiment on Expectation Setting for Personal Robots" by Paepcke and Takayama (2010). This paper evaluates the effects of how a human perceives a robot's ability to carry out a task based on information they were provided about the robot beforehand. An experiment of 24 participants evaluated the effects of setting high expectations versus low expectations of robots with people-sensing and interactive capabilities. Results concluded that setting high expectations of a robot's interactive capabilities increased the amount of disappointment the participant experienced, which resulted in the robot being determined incompetent. Those with low expectations were impressed by the robot's capabilities and reviewed it with positive remarks. Future research may include expectation setting on humanoid robots, open-ended interaction versus goal-oriented interaction, and setting different types of expectations for the robot's capabilities.

Recent research has presented us with a paper entitled "Inducing Bystander Interventions During Robot Abuse with Social Mechanisms" by Tan et al. (2018). This paper evaluates a human's attachment to a robot based on how and when they intervene in abuse of the robot based on three different types of reactions on the robot's part: no effect to the abuse, shutting off in response to the abuse, and the robot exhibited sad and angry response behaviors to the abuse. In a 56 participant study, researchers evaluated the level of bystander intervention verbally and physically. About half of participants self-reported intervening to stop the abuse of the robot. The robot's shutdown response was the most effective in encouraging intervention, and findings suggest that a majority of people will help a robot experiencing abuse. Future research could explore other limiting factors and giving the participants other options to intervene in the interaction.

5.5.2. Discussion

The area that is defined as Social Effects of Robots contributes to all categories of social robots in any context because it monitors the effects of a social interaction between human and robot. The publications that were specifically included in this section have researched the average human reaction and expectations to a robot's social capabilities and contributed findings that may affect the design of social robots in the future. Studies by Paepcke and Takayama (2010), Cha et al. (2013), and Kahn et al. (2015) focused on setting expectations of a robot's capabilities to see whether the participant will trust them to do the tasks they are assigned to. Other studies focused on what the participant expects the robot to behave like, such as a study by S.-Y. Lee et al. (2018). This collection of studies makes significant contributions to the way humans perceive robots, but many studies focus on setting expectations versus changing the robot to shift expectations. Formally instrumentalizing the knowledge gained in this field would be an interesting area for future studies involving the participant's level of trust and expectations for the robot's capabilities.

6. Findings and suggestions

At the end of their 2003 survey of socially interactive robots, Fong et al. posed several open questions with regards to research and the development of social robots (Fong et al., 2003). While advances in technology brought answers to some, there are still multiple unanswered questions, such as the impact of long term human-robot interaction, which may be due to the inherent difficulties in evaluating these interactions. Also, new topics have opened up such as those related to the convergence of robotics, augmented reality, and IoT (N. Norouzi, Bruder et al., 2019).

Our analysis suggests an increase in user studies over a longer span of time. Surveys by Fong et al. (2003) covering pre 2003 and Leite et al. (2013) covering 2003–2011, which specifically focused on long-term interaction with social robots, emphasize the importance and difficulty of this type of research. Leite et al. (2013) also point out that a long-term study can be defined by the novelty of the interaction, suggesting that a study can be considered long-term when the users are fully familiarized with the robot. The disappearance of novelty is highly dependent on the length and the qualities of the interaction. For instance, Ahmad et al. (2017) found that the novelty effect of children's interactions with the NAO robot during a game of snake and ladders only persisted for two sessions and had worn off by the third session, which took place in a 10-day period. It was mentioned by M. K. Lee et al. (2012) in their study involving a Snackbot robot that much research done in this field is based on temporary studies of social interaction, despite the real-world applications only being viable as a product used over a longer period of time. The effect of this is that research does not reflect a user's continued interest in the robot or satisfaction in their social interaction over the period of time. It could easily be the case that a user will lose interest as early as their second interaction with a social robot if there is not enough of a dynamic change in the robot's purpose or conversation. The issue with social interaction is that humans intend it to be a unique experience every time, while robots are typically programmed to react to similar situations with the same pre-programmed responses.

Looking at robotic capabilities with regards to their application areas, we identified more opportunities for enhancing locomotion for the companionship application area initially identified by Fong et al. (2003), as only 45% of the robots in the publications of this application area had locomotion capabilities. Similarly, topics of predictive behavior and physical awareness were less focused than others in all application areas suggesting opportunities for deeper research. With the increasing focus in the field of personal and companion robots, topics such as the stress-buffering capabilities of these robots require a more in-depth understanding. Although a few papers in the companionship application area pointed out the potential and capability of their robots in terms of stress reduction, more research can be beneficial (Birnbaum et al., 2016; Nalin et al., 2012; Sabelli et al., 2011; Stiehl et al., 2009). Also, it can be valuable to further research user's desire for impression management and self-disclosure preferences in the context of companion robots and whether similar effects will be observed to short term interactions with intelligent virtual agents and the influence of the robot's physicality on these aspects (Lucas et al., 2014; Pickard et al., 2016).

In the health care application area, we identified more opportunities for the promotion of healthy eating and physical activity in youth. Past findings suggest that interaction with virtual characters can increase physical activity in children and positively influence their eating habits (Byrne et al., 2012; Johnsen et al., 2014). Interestingly with robotic entities, Van Der Drift et al. (2014) were able to find that the remote interaction of children with diabetes with a robot did increase their self-disclosure enjoyment. These findings warrant further research to understand the influence of the robot's physicality in the aspects above.

Additionally, when looking at some focuses of publications, researchers clarified that they had to make sure the robot was non-threatening and friendly in demeanor (Sardar et al., 2012; Tan et al., 2018). Other publications noted that the physical limitations of the robot broke some of the socially immersive qualities of the interaction between robot and human (Birnbaum et al., 2016; Zecca et al., 2008), similar to virtual animals and humans (N. Norouzi, Kim et al., 2019; Kim, 2017b). Interestingly, even with these physical limitations in mind, comparing a humanoid robotic entity to a virtual entity with a similar appearance on a flat screen display, researchers were able to observe the impact of a robot's physicality on users' behavior in a large-scale study conducted by Kim et al. (2017). They indicated higher levels of reactive and proactive behavior with a physical robot in subjects.

Previously, a few researchers introduced the idea of mixed reality robotics by merging augmented reality and robotics together (Dragone et al., 2006, 2007). With the growing fields of Virtual Reality (VR) and Augmented Reality (AR) (Welch et al., 2019), new research can be done in the direction of augmenting the physical appearance of the robot to make it appear more friendly, capable, or malleable so that the human it interacts with may perceive the robot in a different way and provide new approaches to enhance human-robot interaction in various areas such as entertainment (Carroll & Polo, 2013; M. Lee et al., 2019), locomotion (Katzakis & Steinicke, 2018), gestures (Rosen et al., 2017) and verbal communication (Sibirtseva et al., 2018). AR poses new possibilities to the world of social robotics in that it extends the capabilities of an IoT-enabled robot by allowing a visually augmented version of itself to carry out tasks that the user would have not otherwise thought possible. It also allows the robot to dynamically change its appearance according to a user's preference or the robot's intended task.

7. Conclusion

In this paper, we surveyed the previous research in the area of social robotics for the time span of 2008 to 2018. By looking at the different topics, application areas, and experimental approaches of the past work, we provided high-level findings regarding research trends and future directions. Looking at some of our findings, majority of the research in this time span evaluates human's expectation of social robots and their perceptions after human-robot interaction. We also identified a trend for the increase of research for educational purposes. We observed the highest number of publications at the year 2018 with an almost equal contribution from all identified application areas involving social robots. We predict that with increased popularity of companion and personalized robots in recent years, the trend of increased research will continue. We hope that this work can contribute to this research direction and its evolution.

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