Computational Human-Robot Interaction

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Contents

Abstract

We present a systematic survey of computational research in human-robot interaction (HRI) over the past decade. Computational HRI is the subset of the field that is specifically concerned with the algorithms, techniques, models, and frameworks necessary to build robotic systems that engage in social interactions with humans. Within the field of robotics, HRI poses distinct computational challenges in each of the traditional core research areas: perception, manipulation, planning, task execution, navigation, and learning. These challenges are addressed by the research literature surveyed here. We surveyed twelve publication venues and include work that tackles computational HRI challenges, categorized into eight topics: (a) perceiving humans and their activities; (b) generating and understanding verbal expression; (c) generating and understanding non-verbal behaviors; (d) modeling, expressing, and understanding emotional states; (e) recognizing and conveying intentional action; (f) collaborating with humans; (g) navigating with and around humans; and (h) learning from humans in a social manner. For each topic, we suggest promising future research areas.

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1

Introduction

The field of human-robot interaction (HRI) is expanding and maturing. At the time of writing, dedicated publications on HRI and social robotics research include two special-interest journals and three conferences, in contrast to a single conference and no dedicated journals in 2005. In addition, HRI is a research topic which is increasingly solicited and included in the broader robotics community.

The goal of this survey paper is to provide a systematic overview of the field of HRI over the past decade (from 2005 to 2015), with a focus on the computational frameworks and algorithms currently used to enable robots to interact with humans. Two influential surveys of the field were published in 2003 and 2007 [Fong et al., 2003, Goodrich and Schultz, 2007], and a book chapter surveyed part of the HRI literature in 2008 [Breazeal et al., 2008]. This survey starts roughly where Goodrich and Schultz [2007] left off, covering what has proven to be the most active period of HRI research thus far.

This paper's focus, however, is different from the previous surveys. As the research area has developed, we have identified a lack of a systematic survey focusing specifically on computational HRI research. This subfield of HRI, which includes algorithmic and systems-oriented

work is distinct from the large body of research dealing with the empirical, psychological, cultural, and user-interface aspects of the field. So far, there has not been a comprehensive survey article covering computational HRI. In addition, to the best of our knowledge, there has never been a systematic review of the literature in an attempt to represent the bibliometric trends, balance, and distribution of work in HRI. This paper aims to fill these gaps.

1.1 Methodology

While no survey paper can argue for exhaustiveness, we employed a systematic methodology when selecting for inclusion. Our search covered the entire archive of the top-rated journals and refereed conference proceedings which publish work on HRI and social robotics. This included traditional robotics journals and conferences, one human-computer interaction conference, and specialized HRI and social robotics venues. In total, we surveyed twelve venues:

- IEEE Transactions on Robotics (T-RO)
- International Journal of Robotics Research (IJRR)
- Autonomous Robots (AuRo)
- Journal of Human-Robot Interaction (JHRI)
- International Journal of Social Robotics (IJSR)
- Robotics: Science and Systems (RSS)
- International Conference on Robotics and Automation (ICRA)
- International Conference on Intelligent Robots and Systems (IROS)
- International Conference on Human-Robot Interaction (HRI)
- International Symposium on Robot and Human Interactive Communication (RO-MAN)

- International Conference on Social Robotics (ICSR)
- ACM Conference on Human Factors in Computing Systems (CHI)

For these twelve venues, we considered the entire archive published since January 2005 and selected papers based on pre-defined inclusion criteria, described in the following section.

1.1.1 Inclusion Criteria

Delineating the research which contributes to the technologies underlying socially interactive robots is a non-trivial question of field boundary and demarcation. With an eye on the grand challenge of building autonomous socially intelligent robots, our goal was to specifically cover computational, i.e., algorithmic and robotics-oriented (as opposed to psychology-oriented), and synthetic (as opposed to descriptive or inferential) research. This excludes all user studies only measuring human responses to robot behavior or designs. Of the computational papers considered, we further limited the survey by including only work that has a clear element of robotics and a clear element of social interaction.

In other words, our rule-of-thumb for inclusion requires that both the social and the computational should be present in the research, and that the intended application of the work is in robotics. To formalize this, we defined several inclusion and exclusion criteria, organized by type and topic of the research papers we considered:

- **Perception of Humans** — There is a large body of work in the robotics and HRI literature concerned with the perception of humans. Out of those we include only the subset of papers in which the perception was geared towards, or focused on, social interaction. We either exclude or only briefly mention work that is aimed at detecting and tracking people in the environment generally, without specific application to HRI, such as perception for situational awareness or context understanding.

  There are a number of venues concerned with computational perception, such as the Conference on Computer Vision and Pattern Recognition (CVPR) and the International Conference on

Computer Vision (ICCV), to name two. The fact that we did not survey these venues inherently narrows our scope to research aimed at robotics applications and at HRI in particular. This means that we do not survey some of the core computational perception work, even though it has undoubtedly affected the field of HRI significantly.

- **Learning** — Machine learning also constitutes a large part of robotics research. We focus on the subset of papers in which learning happens either with an eye on social interaction or directly through social interaction. We do not include work merely treating human data as a learning database for inference, even if it is geared toward robotics.

  A similar point can be made for foundational work in machine learning as we made earlier with respect to computational perception. Research in venues such as the International Conference on Machine Learning (ICML) or Neural Information Processing Systems (NIPS) is not represented in this survey, even though much of it has clear relation to the work discussed herein.

- **Collaboration, Navigation, and Manipulation** — In human-robot collaboration, navigation, and manipulation papers, we focus on those that include a distinctly social aspect. This means that we exclude a large body of efficiency-centric collaborative robotics work found in industrial robotics research. We do include a few selected works on collaborative manipulation, in particular those that relate to intentionality.

- **Autonomy** — As a rule, we include only research in which the robot has at least some autonomy, or that is concerned with developing methods that serve robot autonomy. This excludes most, if not all, work with the Wizard-of-Oz (WoZ) methodology, with a few exceptions, described below.

We cannot claim that the boundaries of this survey are crisply delineated. In fact, it would be fair to say that more papers were borderline for inclusion than clear-cut. For example, we include some

purely empirical studies which are designed with computational questions in mind, or have clear implications for autonomously interactive robotic systems. We include such work in particular when it helps frame the discussion of subsequent computational research.

Overall, we identified, read, and considered 926 papers out of the original several thousands of papers published in the above-mentioned venues in the survey time frame. Our criteria narrow this list even further, resulting in a total of 375 papers representing the state of the art in computational HRI.

1.2 Overview

HRI is an interdisciplinary field with roots and connections in several more established disciplines of robotics and computer science. This is reflected in the categorization of the work surveyed here. Each section can be viewed as the application and extension of robotics research to the socially interactive context.

For example, techniques from the field of robot perception have been adapted and extended to specifically perceive information used for social interaction, and in particular to reason about human intention. Similarly, whereas the broader field of robotics studies kinematics and motion planning, a socially interactive robot needs to view these issues in the context of nonverbal communicative behavior. Motion planning is made socially aware in order to communicate intents and create bonds. The broader topic of machine learning for robotics gives rise to research in socially-guided robot learning, building on human models of tutelage and instruction. Similarly, the long tradition of robot navigation is seen through a new lens of social navigation, both accounting for human social needs and expressing social signals during navigation.

Inspired by this perspective, Figure 1.1 shows an overview of this paper. The paper flows from fundamental robot capabilities, such as perception of human activities, expression of verbal and nonverbal behavior, and the role of emotion models in HRI, to higher-level social robot skills, including reasoning about intentions, collaboration, navigation, and learning.

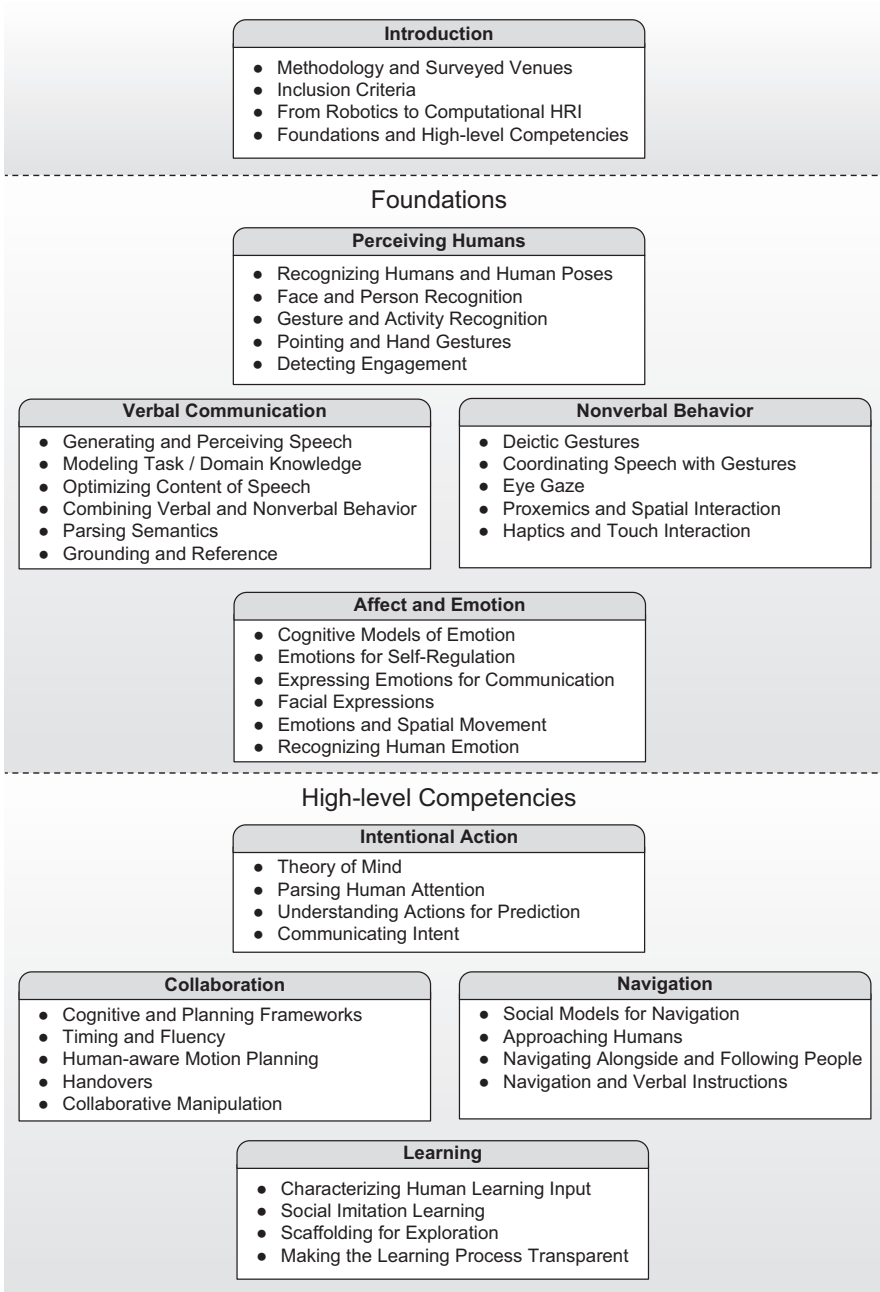

Figure 1.1: Overview of the Paper Structure

1.2.1 Foundations

Sections 2–5 cover basic capabilities and modalities of interaction. These core behaviors are precursors to successful interaction with humans.

The first of these skills, covered in Section 2, is the ability to perceive humans in a social context. The computational issues arising from this goal include a number of challenges: First, a robot might need to recognize a human social partner, find their face, and possibly recognize their identity. Then, a robot could recognize gestures, track the focus of the human's attention, identify activities, and detect the human's engagement or disengagement with the robot.

Next, Section 3 covers systems and methods aimed at generating and understanding verbal expression, geared toward human dialog with social robots. This includes a variety of technical challenges, including optimizing speech content, expressing task and domain knowledge, understanding context, and grounding verbal content in the physical world. We also cover work that looks at paralinguistics, such as the tone of voice (vocalics) and the timing of speech acts.

Section 4 considers nonverbal behavior. To support social interaction, robots need the ability to generate and understand the variety of nonverbal behavior exhibited in human communication. This includes the detection and generation of body movements (kinesics), pointing gestures, speech-accompanying gestures, and gaze, as well as space and territory management (proxemics), and touch interactions (haptics).

A central aspect of human nonverbal behavior is the perception and generation of emotional behaviors and signals. Work on this topic, covered in Section 5, skirts the boundary between Affective Comput-ing and HRI, including computational models representing emotional states and the use of emotion for robot self-regulation. We also cover frameworks and methods for generating emotion expression and techniques for detecting human emotional states in the context of human-robot social interaction.

1.2.2 High-level Competencies

In the second portion of this survey we discuss social behaviors that build on the skills covered in the first portion. This begins with the expression and recognition of intentional behavior. Humans have natural tendency to parse the world on intentional boundaries. Therefore, understanding, predicting and reasoning about intentions is fundamental to interaction. Section 6 surveys work concerned with the automatic detection, classification, and recognition of human intention. This includes work on Theory of Mind capabilities for robots, on the prediction of human activities as intentional agents, and on mechanisms to achieve joint attention. This section concludes by looking at how robots can generate actions that communicate intent in an appropriate way, based on animation principles and legibility optimization. The capacity to understand and communicate intentional action then serves as the basis for the last three sections covering the social behaviors of collaboration, navigation, and learning.

Section 7 includes research focused on human-robot collaborative activities, a highly active subfield of computational HRI. In order to collaborate successfully with a human, a robot needs to adjust its motion planning algorithms, optimizing for social aspects of the movement. A large body of work deals with computational challenges in embodied shared activities, including collaborative planning and scheduling, while others consider timing, anticipation, and team fluency. Finally we look at two highly-studied instances of human-robot collaboration: object handovers and collaborative manipulation of a shared object.

All of the above sections are equally applicable to stationary and mobile robots. However, mobile robots have unique challenges associated with the social aspects of their use of space. Section 8 surveys research on socially-aware robot navigation and mobility. In many ways this is a particular case of collaborative behavior. First, mobile robots need to recognize and generate intentional behavior. Then, there are social aspects of the navigation itself, including approaching people, moving around people, and accompanying humans along their walking path.

Finally, Section 9 looks at machine learning in the context of HRI, including robot learning guided by humans. This capacity also builds

on the robots' ability to represent and reproduce intentional behavior in order to help human teachers give better instruction. The section covers the particular features of human-generated machine learning input as well as human-inspired learning techniques, such as scaffolding. In this section, we stress the importance of social signals in robot learning, enabling a more transparent learning process by the robot.

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