A Survey of Nonverbal Signaling Methods for Non-Humanoid Robots

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Contents

Abstract

The goal of this survey is to inform the design and usage of nonverbal signals for human-robot interaction. With robots being increasingly utilized for tasks that require them to not only operate in close proximity to humans but to interact with them as well, there has been great interest in the communication challenges associated with the varying degrees of interaction in these environments. The success of such interactions depends on robots' ability to convey information about their knowledge, intent, and actions to co-located humans. In this work, we present a comprehensive review of literature related to the generation and usage of nonverbal signals that facilitate legibility of non-humanoid robot state and behavior. To motivate the need for these signaling behaviors, we survey literature in human communication and psychology and outline target use cases of non-humanoid robots. Specifically, we focus on works that provide insight into the cognitive processes that enable humans to recognize, interpret, and exploit nonverbal signals. From these use cases, we identify information that is potentially important for non-humanoid robots to signal and organize it into three categories of robot state. We then present a review of signal design techniques to illustrate how signals conveying this information can be generated and utilized. Finally, we discuss issues that must be considered during nonverbal signaling and open research areas, with a focus on informing the design and usage of generalizable nonverbal signaling behaviors for task-oriented non-humanoid robots.

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Introduction

One of the primary goals of robotics is enabling robots to work alongside and with humans. This requires robots to be capable of not only navigating and manipulating in human environments but communicating and collaborating with humans as well [Khatib et al., 1999]. As autonomous robots are increasingly required to operate in concert with humans, the communication challenges associated with varying levels of proximate interaction must be explored [Arras and Cerqui, 2005, Dautenhahn et al., 2005, Forlizzi and DiSalvo, 2006].

In recent years, a significant portion of human-robot interaction (HRI) research has employed humanoid robots that possess highly anthropomorphic forms and features [Goodrich and Schultz, 2007]. However, there are also many robots which lack not only those features but humanoid form entirely. *Non-humanoid robots* typically have simpler embodiments that are targeted towards specific tasks or domains [Coeckelbergh, 2011, Terada et al., 2007]. As a result, these robots, such as those in Figure 1.1, are utilized in a wide variety of settings and applications, including healthcare, agriculture, space, industry, automotive, and service [Billingsley et al., 2008, Bualat et al., 2015, Fong et al.,

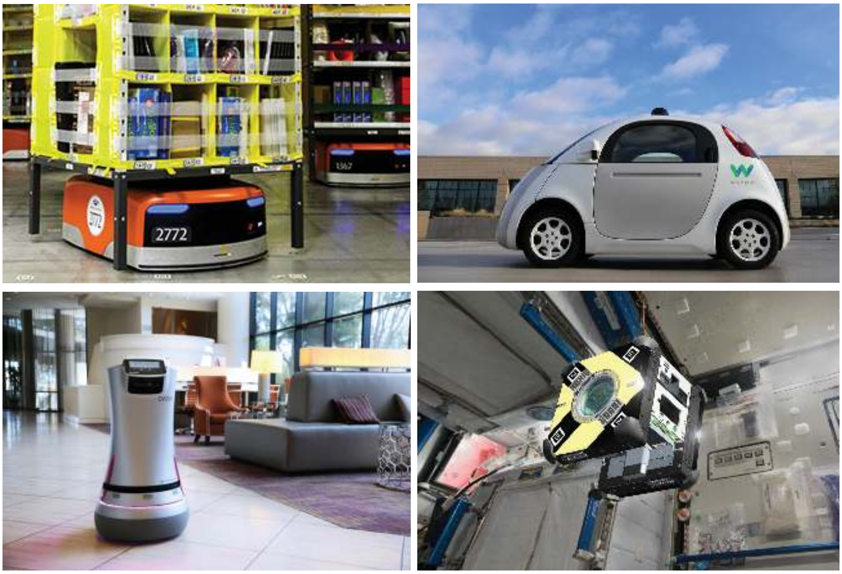

Figure 1.1: Non-humanoid robots, such as the Amazon warehouse robot, Waymo autonomous car, Savioke Relay, and NASA Astrobee (clockwise), are being regularly deployed and must use nonverbal signals to interact with co-located humans.

2013, Forlizzi and DiSalvo, 2006, Kittmann et al., 2015, Urmson et al., 2008, Wurman et al., 2008].

Historically, many commercial robots have been non-humanoid, with origins in industrial applications [Hockstein et al., 2007]. Consequently, past HRI research with these robots has largely focused on issues relating to safety, operation, and control within the context of highly regulated environments [Goodrich and Schultz, 2007, Thomaz et al., 2016]. However, as robots are deployed in other environments, their behavior must evolve to account for the needs and expectations of humans [Lee et al., 2010, Paepcke and Takayama, 2010].

Since non-humanoid robots are often more machine-like in appearance, humans are likely to have different expectations of them than of humanoid robots [Goetz et al., 2003]. Unlike other machines, however, robots can also operate as autonomous, intelligent agents that act in surprising ways. Therefore, it is vital that robots are capable of accurately conveying their knowledge and capabilities in ways that humans can easily interpret and respond to.

A key challenge for utilizing intuitive and descriptive signals is the limited communication modalities available to most non-humanoid robots. Compared to human channels, many of these modalities are simplistic, making it challenging to generate a wide range of unique and recognizable signals [Bethel and Murphy, 2008, Harrison et al., 2012]. As a result, non-humanoid robots must also carefully consider how to optimally utilize the limited number of signals they have available.

The overarching goal of this work is to *facilitate the development and usage of communicative robot signals that support varying levels of interaction while increasing transparency of a robot's internal state.* This requires careful consideration of a number of factors, such as co-located humans and the robot's environment, in order for the robot to act intelligently.

Currently, more research is needed to understand these challenges in the context of non-humanoid robots. In particular, we focus on non-humanoid robots with few to no anthropomorphic features that perform primarily functional (i.e., non-social tasks). As this encompasses a wide range of platforms utilized in research and commercial applications, we also present a selection of use cases to better illustrate factors that must be considered when designing communicative signals for such robots.

1.1 Levels of Interaction

Since humans and robots can interact in many different ways, we first propose the varying degrees of interactions that are of interest in this work [Yanco and Drury, 2004]. We focus on *proximate interactions* in which the human and robot are co-located, share the same environment, and can interact physically [Goodrich and Schultz, 2007]. Importantly, the robot's *internal state* is not readily accessible by the human. Instead, humans must utilize cues emitted by the robot to reason about the robot's internal state, similar to the cognitive processes that occur when interacting with another human [Klein et al., 2005].

- **Coexistence**- The lowest level of proximate interaction requires the robot and human to *coexist* in the same physical space. Coexistence does not require direct communication, but information is naturally exchanged through unconscious, nonverbal cues. In this lowest level of interaction, humans take on the role of bystanders or observers and do not directly interact with the robot.

- **Coordination**- A higher level of interaction involves the human and robot not only sharing space but coordinating their actions in time or space to deal with shared resources [Lorenz et al., 2011]. Often, the desired result of successful coordination is greater efficiency or the prevention of conflicts between agents [Fuks et al., 2007]. The term *coordination* is often used for single actions rather than long-term activities. In robotics, it is primarily used for physical tasks, such as two agents navigating the same area or jointly moving an object. To create fluid, seamless coordination, each agent must communicate enough information to create a degree of shared attention to support action prediction and planning [Bauer et al., 2008, Sebanz et al., 2006].

- **Collaboration**- The highest level of interaction, *collaboration*, requires high degrees of coordination as each party works actively towards an agreed upon, shared goal [Bauer et al., 2008]. To achieve a successful collaboration, the human and robot must communicate such that their actions are complementary and coordination between them is fluid [Bauer et al., 2008, Mutlu et al., 2013]. Human-robot collaboration (HRC) is important for HRI researchers as it leverages the strengths of both the human and robot for overall benefit [Fong et al., 2003c] and may facilitate robot deployment into environments where they are not yet capable of performing all tasks autonomously.

HRC research often focuses on methods for achieving fluid, effortless coordination [Bauer et al., 2008, Dragan et al., 2015, Hoffman and Breazeal, 2007, Strabala et al., 2013, Unhelkar et al., 2014]. Literature has emphasized the role of nonverbal communication in enabling this synchronization among multiple agents [Breazeal et al., 2005]. However, *nonverbal communication* also plays an important role in all levels of interaction, facilitating intent prediction and the generation of more accurate mental models [Breazeal et al., 2005, Dragan et al., 2015]. As a result, HRI research has started to explore nonverbal signaling for a wide range of robot states and task-related information.

1.2 Nonverbal Communication

Communication is the process of transmitting information from one agent to another [Mortensen, 2017]. The sender is the source of information and encodes the information into a form, such as a signal, that is transmitted to the other agent, the receiver, across a channel or medium [Shannon and Weaver, 1998]. The channel (i.e., signaling modality) is subject to noise or environmental disturbances (e.g., ambient sounds) which can interfere with the receiver's ability to decode the message and obtain the signal's contained information Figure 1.2. The sender can utilize the receiver's response or reaction as feedback about the message.

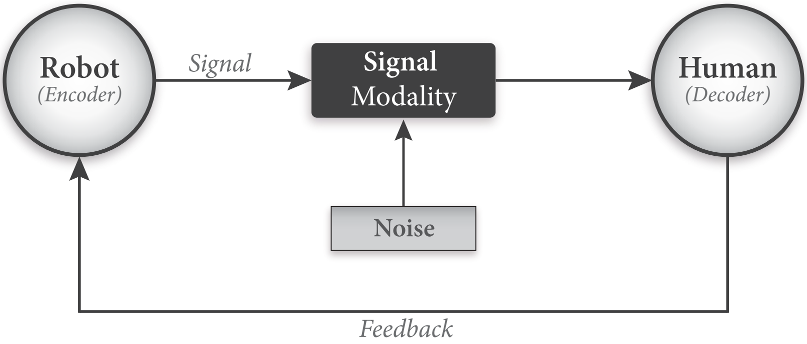

Figure 1.2: The robot encodes and sends information via a signal to a human receiver who decodes it and responds with feedback.

In human-human communication, the sender is a human who encodes information using available communication channels. Much of this process is done using nonverbal channels, such as facial expression, body language, and gaze [Knapp et al., 2013]. Due to the prominence of nonverbal cues in human communication, humans are quite adept at consciously and subconsciously noticing, interpreting, and reacting to them [Knapp et al., 2013]. However, as these cues are somewhat abstract, they can still be misinterpreted if the receiver is unfamiliar with a specific cue, receives conflicting information, or is a noisy environment.

Nonverbal communication is a powerful tool that has been studied both in the context of human-human and human-robot interactions [Breazeal et al., 2005]. In this work, we define *nonverbal cues* as anything the receiver perceives as providing information. This includes both the *implicit*, unconscious behaviors that we can derive meaning from as well as *intentional signals* from the sender [Breazeal et al., 2005]. However, due to robots' goal-oriented nature and complexity of control, most robots do not naturally emit many of the cues humans do [Mutlu et al., 2009b]. Instead, much of their communication must take the form of planned nonverbal signals.

Many envisioned tasks require the robot to convey information about their internal state for human collaborators and bystanders [Knoblich et al., 2011, Mutlu et al., 2013, Breazeal et al., 2004]. Nonverbal cues have already been shown to improve humans' understanding of robots' behavior and improve trust [Kiesler, 2005, Knoblich et al., 2011]. While recent work in HRI represents an important first step towards enabling non-humanoid robots to utilize nonverbal signals, there are still many challenges that require further research and development.

1.3 Motivation and Goals

Human and robot behavior often differ, particularly in cases for which actions should take into account nearby humans [Alami et al., 2005, Kruse et al., 2013, Saez-Pons et al., 2014]. Although co-located humans are typically considered for safety, robots often fail to consider their presence from an interaction perspective. The resulting breakdowns have led to recent efforts to incorporate social norms into robot behavior in order to improve interactions with humans [Breazeal and Velasquez, 1999, Mead and Matarić, 2017, Montreuil et al., 2007, Nakauchi and Simmons, 2002, Shiomi et al., 2014].

Humans are highly expressive; we possess several modalities that continuously emit information, such as body posture and gaze [Mutlu et al., 2009b]. This natural expressiveness is combined with intentional, learned signals to make humans very effective communicators [Knapp et al., 2013].

To be complementary and effective interactors, robots must also exploit a broad range of signaling mechanisms to achieve a necessary degree of expressiveness [Bauer et al., 2008, Szafir et al., 2015]. While the most straightforward solution is for robots to employ similar nonverbal cues as humans (e.g., arm gesture, posture, facial expression), this is often impossible for non-humanoid robots due to physical limitations of their embodiment [Bethel and Murphy, 2008, Szafir et al., 2014].

Instead, non-humanoid robots can utilize alternative nonverbal signals on commonly available signaling modalities (e.g., light). Although more limited than human nonverbal behaviors, these signals can improve the readability, trustworthiness, and acceptance of robots and enable various levels of interaction [Takayama et al., 2011, Beer et al., 2011, Desai, 2012].

Increased expressiveness can also improve a robot's chances of success at its functional task [Fischer et al., 2014]. By utilizing nonverbal signals, the robot can elicit assistance while minimizing disruption and human annoyances, as it manages non-deterministic scenarios that arise from the dynamic and unpredictable nature of its environment and task [Cha and Matarić, 2016, Fischer et al., 2014, Saulnier et al., 2011]. In addition, research has shown the benefits of state-expressive nonverbal signals for robotic applications that typically do not involve direct human interaction, such as navigation and manipulation [Dragan et al., 2013, Kruse et al., 2012].

When deciding how to convey information about the robot's internal state, we must consider which communication modality best fits the situation [Rehbinder and Sanfridson, 2004, Weaver, 1953]. Although

HRI research often promotes speech as a natural and flexible form of communication, it is not well suited for many settings and applications. In loud environments, speech may be subject to environmental masking due to high ambient noise levels. Conversely, in sound-sensitive areas such as schools and hospitals, speech can be disruptive. Speech is also inefficient and overly verbose when transmitting small amounts of information (e.g., low power) [Cha et al., 2015, Kiesler, 2005].

Hence, when choosing signaling actions, the robot should utilize information about the environment and its interactors. For instance, in a dimly light environment, the robot can utilize a bright light to enhance visibility. Humans are experts at modulating their behavior to dynamically respond to the world state, such as increasing their speech volume in loud environments or utilizing several modalities for increased effectiveness.

The goal of this review is to survey past works to inform researchers in designing and utilizing nonverbal signaling behaviors for effective HRI. In addition to exploring signaling mechanisms for non-humanoid robots, this work also seeks to understand the challenges and important research areas of this field.

This survey also builds on previous surveys [Fong et al., 2003b, Yanco and Drury, 2004] to inform the young and rapidly growing field of HRI. The quickly evolving nature of HRI makes it challenging to apply past and ongoing work towards open research problems. Thus, our hope is that utilizing insights from this diverse set of past works across different fields can inspire new approaches for researchers working in this area.

1.4 Organization

In Section 2, we provide background from related fields, particularly in the cognitive processes that humans utilize during communication. The purpose of that section is to highlight past research that serves as the foundation of nonverbal communication in HRI. Although many alternative concepts exist, the ones reviewed are primarily utilized by the HRI literature surveyed in this work as well other works related to our proposed areas of signaling research.

Section 3 presents selected use cases of non-humanoid robots that are relevant both in research and commercially. For each use case, we identify several applications and discuss potential signaling needs in the context of these scenarios. This analysis enables identification of common signaling scenarios across platforms, environments, and applications, which can facilitate the development of signaling standards.

In Section 4, we identify three categories of internal robot state inspired by these use cases that are relevant to HRI. These categories enable us to present features of robot state that are often communicated together. While there are also alternative categorizations, our approach is intended to be broadly applicable to the wide range of non-humanoid robots discussed in this work.

Section 5 presents key signaling characteristics that must be considered when designing and utilizing nonverbal signals. These descriptors enable us to specify the intent of a signal in features relating to the signal's design and usage.

Section 6 surveys past work in signal generation. While nonverbal signaling is a relatively young field of research in HRI, similar signals have been utilized in other fields and applications. We draw inspiration from these signaling mechanisms, including those found in everyday life, and discuss how similar methods can be applied to signals for non-humanoid robots.

Finally, Section 7 presents considerations that must be addressed to enable successful nonverbal signal design and usage. These considerations are motivated by challenges encountered in prior work in HRI and human-computer interaction (HCI). We suggest three open areas of research that will help to address these issues and discuss approaches. We conclude by summarizing our key insights in Section 8.

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