

Toward Humanlike Task-Based Dialogue Processing for Human Robot Interaction

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■ Many human social exchanges and coordinated activities critically involve dialogue interactions. Hence, we need to develop natural humanlike dialogue-processing mechanisms for future robots if they are to interact with humans in natural ways. In this article we discuss the challenges of designing such flexible dialogue-based robotic systems. We report results from data we collected in human interaction experiments in the context of a search task and show how we can use these results to build more flexible robotic architectures that are starting to address the challenges of task-based humanlike natural language dialogues on robots.

Interactions in natural language dialogues are an essential part of human social exchanges, ranging from social conventions such as greetings, to simple question-answer pairs, to task-based dialogues for coordinating activities, topic-based discussions, and all kinds of more open-ended conversations. As a result, the ability of future social and service robots to interact with humans in natural ways (Scheutz et al. 2007) will critically depend on developing capabilities of humanlike dialogue-based natural language processing (NLP) in robotic architectures. However, different from other NLP contexts such as story understanding or machine translation, natural language processing on robots has at least the following six properties: *real-time*, *parallel*, *spoken*, *embodied*, *situated*, and *dialogue-based*.

Real-time means that all processing must occur within the time frame of human processing, both at the level of comprehension as well as production. It also means that constraints will have to be incorporated incrementally as they occur, analogous to human language processing.

Parallel means that all stages of language processing must operate concurrently to mutually constrain possible meaning interpretations and to allow for the generation of responses (such as acknowledgements) while an ongoing utterance is being processed.

Spoken means that language processing necessarily operates on imperfect acoustic signals with varying quality that depends on the speaker and the background noise. In addition to handling prosodic variations, this includes typical features of spontaneous speech such as various types of disfluencies, slips of the tongue, or other types of errors that are usually not found in written texts.

Embodied means that robots have to be able to process multi-modal linguistic cues such as deictic terms accompanied by bodily movements, or other gestures that constrain possible interpretations of linguistic expressions. It also means that the robot will have to be able to produce similar gestures that are expected by human interlocutors to accompany certain linguistic constructs.

Situated means that, because speaker and listener are located in an environment, they will have a unique perspective from which they perceive and experience events, which, in turn, has an impact on how sentences are constructed and interpreted. This includes the incremental integration of perceivable context in the interpretation of referential phrases as well as being sensitive to nonlinguistic coordination processes such as the establishment of joint attention.

Dialogue-based means that information flow is not unidirectional but includes bidirectional exchanges between interlocutors based on different dialogue schemes that constrain the possible dialogue moves participants can make at any given point.

While these six aspects present significant challenges for the development of robotic architectures with dialogue capabilities, there are also several advantages to natural language processing on robots that other NLP contexts do not have. For example, spoken natural language exchanges typically consist of shorter sentences with usually simpler grammatical constructions compared to written language (thus making parsing easier and more efficient). Moreover, the employed vocabulary is much smaller and the distribution of sentence types is different (including more commands and acknowledgements, and few declarative sentences compared to written language). Also, different from written texts, perceptual context can be used to disambiguate expressions, and most importantly, ambiguities or misunderstandings in general can often be resolved through subsequent clarifying dialogue. The option to request clarification also allows interlocutors to handle new, unknown expressions naturally.

Since there are many different forms of dialogues that have their own rules and conventions based on social norms and etiquette (such as small talk, interviews, counseling talks, and others) and might, moreover, require tracking of various non-linguistic aspects (such as contextual information, interlocutor eye gaze and affective as well as other mental states), we focus on task-based dialogues in the article. We start by briefly reviewing the shortcomings of current dialogue-based natural language understanding (NLU) systems on robots and then discuss our attempts to address some of them. We next report results from human experiments that we conducted to collect a data set as the basis for the architecture development and then give examples of the kinds of dialogue exchanges our current system can handle.

Previous Work

Although rapid progress in this field of research has been made recently, no current systems are yet

capable of these types of dialogue interactions. Moreover, most robotic systems lack one or more of the other essential requirements such as incrementality of processing and real-time operation, the inclusion of contextual constraints on semantic processing, the usage of a training grammar rather than an exclusively rule-based grammar (created laboriously by hand), and mechanisms for handling disfluencies and other distortions of spontaneous speech.

For one, robotic systems that use natural language for robot instruction either do not have natural language fully integrated into the robotic architecture (for example, Michalowski et al. [2007]) or are limited to simple instructions (for example, Firby [1989], Atrash et al. [2009]). And many systems use rule-based grammars due to the difficulty of producing a well-trained grammar on what is invariably the small amount of data applicable to the domain. For one example, Bos and Oka (2007) use Nuance to produce first-order λ -expressions according to a rule-based grammar. Disfluencies are not allowed, and the system is nonincremental, in that it must process the full utterance before proceeding further.

While there are several examples of incremental systems (for example, Winograd 1972; Erman et al. 1980; Lowerre and Reddy 1980; and more recently DeVault and Stone 2003; Allen et al. 1996; Varges and Purver 2006), they usually only process linguistic information. An exception is the system by Schuler, Wu, and Schwartz (2009) which integrates phonological, syntactic, and referential semantic information into a single language model, thus enabling semantic information to boost probabilities for word hypotheses of existing objects in the space. However, the system has not been used on a robot and would require a large amount of training data (often not available) in order to be able to extract the relevant statistical information. Other complete NLU systems that do not require large data sets for training (for example, TRIPS [Allen, Swift, and de Beaumont 2008]) are typically not incremental and have usually not been designed with the challenges of NLP on robots in mind.

One approach to improving robustness is to allow for partial parses. For example, Rickert et al. (2007) uses OpenCCG, a rule-based, nonincremental parser, to produce an unconstrained λ -logical semantic representation of an input. When it is not able to form a complete semantic parse, it produces partial parses for further processing, rather than failing outright. In Atrash et al. (2009), disfluencies are not specifically handled, but if a parse fails, the speech recognizer output is passed to the goal manager as a *bag of words*. Kacalak and Majewski (2009) extract known words into commands rather than attempting to create a full parse from input that may also contain unknown words,

and the word-recognition module allows malformed words to be corrected.

Human Performance in a Search Task

It is difficult, if not impossible, to anticipate a priori the wide variety of spoken task-based natural language interactions that will be initiated by humans during interactions with robots, even when the task is well defined. Hence, we conducted several human-human studies in a task where two humans must coordinate their activities through remote audio communication only (that is, no visual links); their transcribed interactions form the Cooperative Remote Search Task (CREST) corpus (Eberhard et al. 2010; Scheutz and Eberhard 2008), which we use to identify natural interaction patterns as well as potential pitfalls.

Dialogue-based natural language interactions are quite different from natural language instructions as they would be given in written form. For example, consider a written instruction for following a particular route such as “Continue to walk straight, going through one door until you come to an intersection just past a whiteboard.” (Kollar et al. 2010). An interactive version of the same instruction from the corpus is substantially more complex:

Instructor: OK, continue to walk straight.
 Robot (continuing straight): OK.
 Instructor: You should be seeing a door in front of you.
 Robot (looking out for a door): Yes.
 Instructor: Good, go through that door.
 Robot (moving through the door): OK, I’m through the door.
 Instructor: Alright. Keep going. There should be a whiteboard.
 Robot (looking for whiteboard): OK, I’m not seeing it yet. Ah, there it is.
 Instructor: Great, then you should see an intersection, go there.
 Robot (looking out for an intersection while moving): Got it, OK.

Note that natural language instructions are given piecemeal with the expectation of rapid feedback, and meanings as well as goals are negotiated through a sequence of dialogue moves and actions, rather than being fixed in a sequence of instructions. As a result, perception, NLU, and behavior have to be tightly intertwined. It is also expected that any possible ambiguities (for example, the presence of multiple doors) can be resolved quickly online, hence there is no need to provide abundant, fully self-contained information; rather humans provide minimal information, happy to refine it or add to it during the ensuing dialogue interaction. Among the most frequently occurring issues identified in the corpus¹ are ungrammatical

sentences, including incomplete referential phrases, missing verbs, corrections, and others; wrong word substitutions for intended target words such as *block* and *book* for *box*; underspecified directions, referents, and directives, which assume shared task knowledge, knowledge of subgoals, perspectives, and others; frequent *ums*, *uhs*, and other disfluencies and pauses indicating cognitive load; and frequent coordinating confirmations and acknowledgments as dialogue moves including prosodically different *okays*, *yeahs*, and others.

Despite attempts to address individual challenges of robot NLP, no existing system successfully manages the real-time, parallel, spoken, embodied, situated, and dialogue-based NLP just described. Almost all current robotic architectures suffer from insufficient NLP speed, inability to systematically handle the disfluencies that come up naturally in spontaneous speech, and from limitations on the dialogue side, including feedback through gestures and integration of dialogue schemes to ensure appropriate feedback is given.

Tackling Task-Based Dialogue HRI

The dialogues in the corpus are typical examples for the kinds of coordinating natural language interactions humans exhibit in limited domains like cooperative search tasks. The ten most frequent word types in the entire corpus (excluding acknowledgments) are *the*, *box*, *I*, *a*, *'s*, *there*, *you*, *on*, *and*, and *that*. The 151 most frequent words cover 60 percent of the tokens, 280 words reach 80 percent coverage, and 712 reach complete coverage. Yet, despite their seemingly very limited nature (based on vocabulary), the dialogues present a major challenge for HRI. It is clear that meanings are not constructed from sentences alone but from interactions that serve particular purposes and accomplish particular goals. Perception, action, and language processing in humans are obviously all intertwined, involving complex patterns of actions, utterances, and responses, where meaningful linguistic fragments result from their context together with prosodic, temporal, task and goal information, and not sentence boundaries. Consequently, we need to develop new models of interactive natural language processing and understanding for HRI that process language in very much the same interactive, situated, goal-oriented way as humans. In particular, we need to integrate the timing of utterances, back-channel feedback, perceivable context (such as objects, gestures, eye gaze of the participants, posture, and others), as well as background and discourse knowledge, task and goal structures, and others, if we want to achieve human-level performance on robots. This poses both functional challenges and architectural challenges.

Functional challenges include (1) mechanisms for providing appropriate feedback that humans expect even while an utterance is still going on, using different kinds of acknowledgment based on dialogue moves; (2) new algorithms for anaphora and reference resolution using perceptual information as well as task and goal context; and (3) mechanisms for handling various kinds of disfluencies and incomplete and ungrammatical utterances, including robust speech recognition, parsing, and semantic analysis.

Architectural challenges include (1) real-time processing of all natural language interactions within a human-acceptable response time (for example, typically acknowledgments have to occur within a few hundred milliseconds after a request); (2) integration of various natural language processing components (including speech recognition, parsing, semantic and pragmatic analyses, and dialogue moves) that allows for parallel execution and incremental multimodal constraint integration; and (3) automatic tracking of dialogue states and goal progress to be able to provide meaningful feedback and generate appropriate goal-oriented dialogue moves.

While each of these functional challenges is a research program in its own right and we are nowhere close to addressing any of them in a satisfactory manner, it is still possible to make progress in parallel on the architectural challenges, that is, on defining appropriate functional components in the architecture with appropriate data structures and information flow among them to facilitate the integration of the algorithms that will meet the functional challenges.

Over the last decade, we have started to address natural language dialogue interactions on robots in our distributed, integrated, affective, reflective, cognitive (DIARC) architecture (Scheutz et al. 2007). DIARC is implemented in the agent development environment (ADE), a framework for implementing architectures that provides infrastructure support for deploying functional components of the architecture across multiple hosts, discovery of available services (provided by other components), and mechanisms for improved reliability and, when necessary, recovery from component failures. The DIARC architecture features tight multilevel integration of goal management and action selection with low-level sensor and effector components providing access to a wide variety of hardware (mobile robots, humanoid torsos, cameras, three-dimensional imagers, microphone arrays, and others). The priority-based goal manager supports concurrent pursuit of multiple goals in independent action script interpreters, as long as there are no conflicts; when two goals require access to the same resource, the conflict is resolved in favor of the one with the highest priority.

Of greatest relevance to the present context, however, are DIARC's natural language processing capabilities. For example, we developed and implemented algorithms for humanlike incremental reference resolution on a robot (Scheutz, Eberhard, and Andronache 2004), which we subsequently extended to allow for dialoguelike HRI with simple forms of backchannel feedback such as nodding or saying okay (Brick and Scheutz 2007). We also integrated NLP components tightly with action execution (Brick, Schermerhorn, and Scheutz 2007), a prerequisite for the robot's ability to start actions quickly (for example, nodding). More recently, we demonstrated algorithms for automatically converting natural language instructions into formal goal interpretation (expressed in a fragment of the computational tree logic [CTL]) and action interpretation for achieving the goal (expressed in propositionalized first-order form in propositional dynamic logic [PDL]). The conversion into logical forms is effected by combining lexical items with syntactic annotations from a combinatorial categorial grammar (CCG) and semantic annotations from the two logics extended by λ -expressions. Repeated λ -conversions then lead to λ -free temporal and dynamic formulas that represent the goals and actions specified in the natural language instruction, respectively. We also have developed algorithms for handling disfluencies, in particular, lexical disfluencies, abandoned utterances, repetitions, as well as some repairs and corrections, in the context of spoken instruction understanding (Cantrell et al. 2010). Much of this work was directly based on our CRESt corpus.

We will now present three example dialogues to illustrate different aspects of typical humanlike dialogues currently possible in our DIARC architecture (Scheutz et al. 2007). All dialogues have been performed on different types of robots.

Handling Disfluencies

There are several basic types of disfluencies in CRESt: repetitions, insertions, abandoned utterances, and repairs. *Repetitions* of exact words or word sequences may be one word:

Director: so two doorways and then *you'll* you'll be staring straight at a platform

or several words in length:

Director: *is that a new* is that a new green box that you didn't tell me about

Insertions may be words (lexical) or nonwords (nonlexical). Nonlexical insertions include, for example, *uh*, *um*. Lexical insertions can be similar to repetitions but are not exact:

Director: *how many box* how many blue boxes do we have

Repairs, a subclass of insertions, denote instances in which one word is replaced by another. This

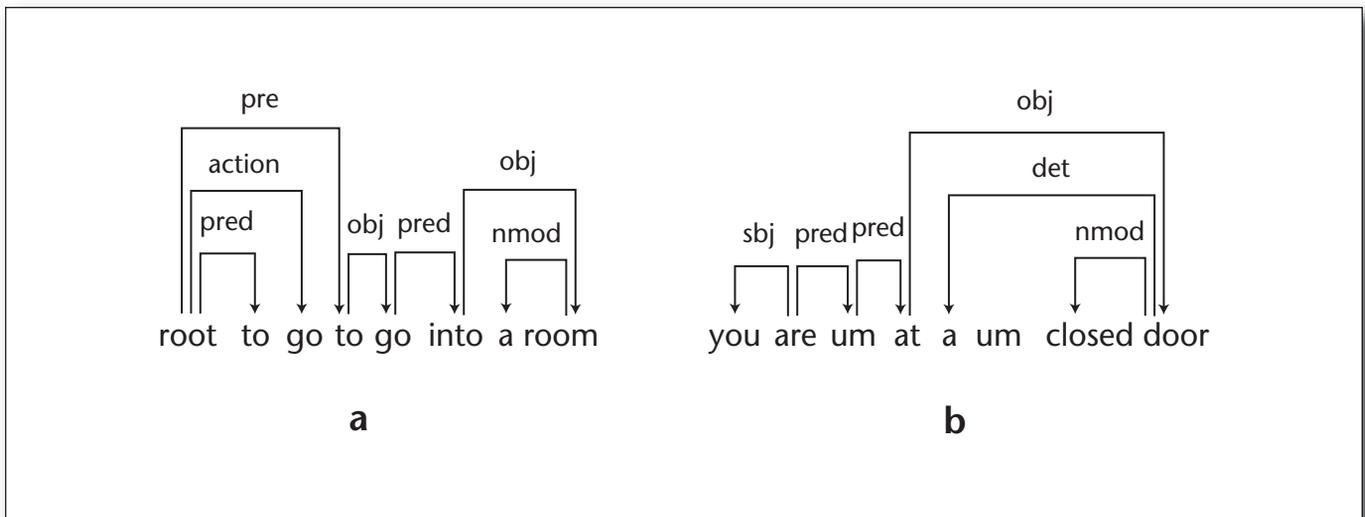


Figure 1. Graphical Examples of Disfluent Dependency Graphs.

Arcs represent head-child relations, with the arrow pointing from the head to the child. Children of the *root* node are considered to be heads of distinct phrases or utterances.

example shows a simple one-word correction — replacing *at* with *by*:

Searcher: one green box at the corner *at* by the end of the hallway

In the next example, an *aborted word* (that is, a nonword) is inserted:

Searcher: and *gre*-green box in the right hand cubicle

Abandoned utterances may or may not be followed immediately by a distinct sentence. In the first example, the speaker abandons an utterance and does not start a new one:

Director: so pink boxes should uh only be in

while in the next example an utterance was abandoned and a new one was started:

Searcher: *so to my* -I'm just like next to the door frame like right in front of it and there's a desk to my left

Although lexical insertions and abandoned utterances can seem similar, insertions tend to be similar to the following phrase, whereas abandoned utterances tend to be followed by a completely separate thought.

In somewhat rarer cases, an entirely wrong word is used:

Director: and then there should have been a blue box by the cardboard box at the end of the hallway but you said there wasn't so that's the misplacement that they spoke of earlier

Searcher: I didn't see one at the end of that *hardware*

Director: yeah there definitely wasn't blue one at the end of that hallway with the cardboard box

Surrounding context clearly indicates that *hardware* referred to a *hallway*, yet the misspeak is never acknowledged (and possibly never noticed) by either participant.

Rule-based algorithms for each of these disfluency types have shown some success. However, these methods are typically targeted at offline NLP, and rely on transcription features that are not usually provided by real-time speech recognizers, such as identifying aborted words by looking for those that end with hyphens. Our method, given a possibly disfluent utterance, is to produce only a partial parse with whatever can be made sense of, similar to other robotic systems we have described. Having been trained on correct (that is, nondisfluent) utterances, the parser, when faced with disfluent utterances, may do any of several things in order to discard such disfluences:

Attach Extra Nodes to the Root

Each root node is viewed as a separate phrase; attaching disfluent words to the root creates semantically incomplete phrases that are subsequently discarded. In *to go to go into a room*, the disfluent initial nodes *to go* were both left unconnected to the rest of the graph, leaving only the relevant parts of the utterance. This is shown in figure 1a.

Attach Extra Nodes to a Nearby Node

Given the connection rules, this will often result in correct semantic output. For example, *you are um at a closed um door* should, regardless of the nonlexical fillers, result in $at(listener, x)$ where x is known to be a door that is closed. Figure 1b shows how this works for the first occurrence of *um*: the

parser connected *at* as a *pred* child of *um*, which in turn was listed as a *pred* child of *are*. The definition of *are* indicated that it should take a predicate and a subject, and attach the subject to the predicate. The system created an empty definition for *um* that allowed it to attach the subject it was handed by *are* to its own predicate child *at*, resulting in the correct definition.

Leave Extra Nodes Unattached

In figure 1b the second *um*, between *a* and *closed*, was simply not attached to any node and was thus discarded.

Note that in none of these cases is it necessary to explicitly identify the disfluency. Instead, these actions are chosen by the parser as it attempts to incrementally parse the input. With well-formed input, the same rules lead to correct parse trees, whereas disfluencies end up “falling out” of the parse as a side effect of the parsing process, as just described.

Handling Multimodal Natural Spoken Dialogues

The next example is an interaction that takes place between an autonomous mobile robot with a humanoid torso and a human interlocutor. They engage in a simple dialogue that explores the robot’s perceptual capabilities (such as its ability for perspective taking). In this case, it is important that acknowledgments include both verbal and nonverbal components, because the robot’s humanoid features trigger expectations that it will behave in a humanlike way, using multiple channels to convey information (for example, producing head motions in conjunction with utterances to indicate agreement or disagreement).

Human: Hello robot.

Robot: Hello.

Human: Come over here.

The robot uses sound source localization to determine the location of the human speaker to resolve the indexical *here* as part of the action *move-to(here)* (that is, the meaning of *here* in this context is the location of the speaker).

Human: Do you see a green, no, red box?

Robot: (shakes head) No, I don’t see anything red.

The robot handles the repair *green, no, red* correctly and searches for a red box. Since it does not see a red box, and, in fact, sees nothing red, it generates a head motion together with an utterance stating as much.

Human: Look to the left.

Robot: (looks to its left)

Human: Now do you see it?

Robot: (nods head) Yes, I see a red one.

The robot takes the instruction to look to the *left* to

mean *left from its perspective* and turns its head in that direction.² It ignores the word *now* at the beginning of the following sentence and resolves the pronoun reference of *it* to refer to the *red box* from the previous sentence. Upon noting the red box now in its visual field, it nods and generates its own anaphoric reference using *one* instead of *box*.

Human: Is the red box to the left of the blue box?

Robot: (nods head) Yes, it is.

Human: Well, ah, is it to the right of the blue box?

Robot: (shakes head) No, it is not.

Again, the robot handles anaphoric reference correctly and also handles fillers (*well*) and disfluencies (*ah*).

Human: Point to the blue box.

Robot: (points to the blue box) It’s over there.

Human: (moves out of robot’s visual field) Look at me.

Robot: (looks at the human)

Human: Thank you.

Robot: (smiles) You’re welcome.

The robot accompanies its pointing action with verbal feedback using the indexical *there*, which in this case indicates the location of the pointing action. Moreover, it resolves the indexical reference of *me* in *look at me* and uses sound localization again to resolve the destination of the *look* command (that is, the location of the speaker, who has moved out of the robot’s field of vision — had the speaker remained within the robot’s visual field, the robot could have used vision to orient its head to face the speaker).³

Handling Dialogues with Task-Based Knowledge

The next example also builds on the search task (Scheutz and Eberhard 2008) and demonstrates the kinds of natural task-based dialogues found in the human experiments. In particular, the example shows how the robot can determine what objects to look out for and what facts about the environment to report based on its knowledge of the task. It also demonstrates how the robot can quickly react to a given instruction by changing its behavior based on a tight integration between natural language understanding and action execution (Brick, Schermerhorn, and Scheutz 2007) while providing the necessary feedback to the human commander. At this point in the interaction, the robot has been going down one corridor and has stopped outside of a doorway:

Human: Is there a hallway?

Robot: I see a hallway.

Human: Okay, go down there.

Robot: Okay.

The robot drives down the newly encountered

hallway. As it is driving down it notices a doorway, which it reports to the team leader, also acknowledging its position:

Robot: Okay, I'm now in the hallway. There is a doorway on the left.

Human: Good, go through that doorway.

Robot: Okay.

The robot enters the room and notices several yellow blocks, some of which are in boxes. Since these are task-relevant, it reports them to the team leader:

Robot: I'm now inside the room. There are yellow blocks in boxes.

Human: Get a yellow block from a blue box.

Robot: Okay.

The robot verifies that there is a yellow block in a blue box, approaches it, and gets it from the box.⁴

Discussion

While the previous examples demonstrate some encouraging progress, there is still a long road ahead with many obstacles that need to be overcome before robots will be able to engage in humanlike natural language dialogues. Some of the obstacles such as speech recognition have been known for a long time. After years of significant efforts and great progress, there is unfortunately still no speech recognizer that can provide sufficiently high recognition rates in typical human environments that are not carefully controlled for background noise. Similarly, most current parsers need large amounts of training data to be able to perform well on novel problems. However, such training data is usually not available for HRI domains and collecting it is often not feasible (and even when it is feasible, it is unclear how much of the data will transfer to different tasks in different environments). There are also open questions about dialogue systems that are currently not fully understood, for example, the different types of dialogue moves in task-based dialogues and the resultant interaction schemes that humans will naturally follow. Moreover, it is currently unclear to what extent robots will have to build and maintain mental models of their human interlocutors to be able to reach humanlike dialogue competence. Beyond the linguistic issues, there are other important open questions related to a robot's physical appearance and capabilities. It is, for example, unclear whether people will even seriously engage in humanlike dialogues with robots that have very different physical forms (for example, wheels, no heads, and others) and very different physical capabilities. And it is an open question how super-human capabilities (for example, being able to follow tens of conversations at the same time) would be received should those become possible at some

point. Clearly, additional HRI experiments will be needed to stake out the territory of human-robot dialogue, human receptivity to it, and the best ways for robots to meet human expectations.

Conclusion

In this article, we demonstrated the challenges faced by a robotic natural language understanding system that is intended for natural humanlike dialogue interactions with the robot in HRI contexts. And we briefly introduced our DIARC architecture which is starting to address some of these challenges. Specifically, we reported results of several simple natural dialogues that DIARC can handle together with a brief high-level description of the processes involved in handling them. Clearly, this is only a start and there is a great deal of work ahead of us before we can claim to have reached *natural* humanlike spoken language interactions. However, by starting with limited domains and tasks (such as instruction tasks), it is possible to make progress right now toward a not-too-distant future point where the resultant architecture will be ready for transition into real-world application domains.

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Notes

1. The CReST corpus, including transcriptions of all interactions coded for disfluencies and dialogue moves, together with POS tags and dependency and CCG parse annotations, will be made available for research purposes free of charge.
2. Of course, it is possible that the interlocutor had a different perspective in mind; the same is possible, of course, in human-human interactions, and may require subsequent synchronization of the two agents' assumptions.
3. See www.youtube.com/watch?v=NinDDNc7sCM.
4. See the video at www.youtube.com/watch?v=Lr3pNDJ3XIA.

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