The State-of-the-Art in Autonomous Wheelchairs Controlled through Natural Language: A Survey

Tom Williams[a,*], Matthias Scheutz[a]

[a] *Human-Robot Interaction Laboratory, Tufts University*
200 Boston Avenue
Medford, MA USA

Abstract

Natural language is a flexible and powerful control modality which can transform a wheelchair from a vehicle into a genuine helper. While autonomous wheelchairs are increasingly designed to use natural language for control, most of them only handle a small number of rigid commands. To establish the state-of-the-art in language-enabled wheelchairs and determine how to improve natural language capabilities, we introduce a framework for analyzing and classifying properties of language-enabled wheelchairs. We then apply the framework to the twenty-four most recent natural language-enabled wheelchair projects, in order to compare their achievements and identify areas for improvement.

Keywords: Intelligent wheelchairs, Natural language, Assistive technologies, Human-robot interaction

---

1. Introduction

Many societies are faced with a growing elderly population. Over the next fifteen years, the number of elderly citizens in the United States alone is expected to increase by over 50% [1]. Hence, *assistive technologies* that can support the elderly in their daily lives and help them retain some level of autonomy are becoming increasingly important. In fact, independent mobility technologies such as wheelchairs, for example, have been shown to substantially benefit the elderly [2]. Even though electric wheelchairs are not uncommon among the disabled and elderly, about 40% of wheelchair users find it difficult or impossible to maneuver using a joystick [3], often due to tremors, limited range of motion, or spastic rigidity [4]. In addition, power wheelchair use can be physically and cognitively burdensome, even for those able to manipulate a joystick [5].

To make electric wheelchairs more accessible, researchers have designed control interfaces that use a variety of additional modalities such as eye tracking, gesture recognition, brain monitoring, and natural language (NL). NL is particularly well-suited for

---

[*] Corresponding author

Email addresses: `williams@cs.tufts.edu` (Tom Williams), `matthias.scheutz@tufts.edu` (Matthias Scheutz)

Preprint submitted to Robotics and Autonomous Systems *July 28, 2017*

wheelchair control as it (1) allows for flexible communication of a wide array of commands (compared to gestures, for example), and (2) does not require instrumentation of the wheelchair user (as in the case of eye tracking or brain-computer interfaces). Not suprisingly, NL-enabled wheelchairs have been developed since the late seventies [6]. However, only since the mid 2000s do we witness significant advances in functionality, allowing NL-enabled wheelchairs to identify landmarks, travel between multiple floors, ask and answer questions, and map their environments. Capabilities such allowing users to specify target locations to which the wheelchair subsequently will navigate automonously – compared to having to provide moment-by-moment joystick control inputs to the wheelchair – can signifcantly reduce users' cognitive workload and required motor skills.

Yet, while the linguistic and navigational capabilities of wheelchairs have come a long way, they are still far from those of human helpers. Human assistants pushing a wheelchair can do more than just move in certain directions or travel to named locations: they can follow directions given by a wheelchair's user regardless of whether they have previously visited the destination. They have no problem traveling outside or using an elevator to travel between floors. They can learn about locations through visual observations or through descriptions (e.g., "This is my favorite cafe"). They can use memories of events and trends in behavior to follow requests such as "Let's go to the park we visited last week" or "Bring me to my barbershop." They can ask questions, make suggestions, make conversation, and can temporarily separate themselves from their companions (e.g., to fetch items for the wheelchair user).

Fortunately, autonomous wheelchairs do not have to achieve human-like performance in order to be become *genuine helpers* that support their users' autonomy and mobility and do so in a way that establishes trust in the technology. As we will argue, two key synergistic elements will critically figure in transforming today's wheelchairs into tomorrow's helpers: *mnemonic* and *linguistic* capabilities. A genuinely helpful wheelchair should remember the objects and locations discussed and encountered in both the recent and distant past, requiring various mnemonic capabilities (e.g., episodic and working memory). And it should be able to leverage those memories through descriptions, questions, and commands, requiring various linguistic capabilities. By properly integrating these two capabilities, important synergies can be obtained that will improve interactions with the user: Mnemonic capabilities are necessary so that full linguistic specification is not needed during every interaction; and linguistic capabilities are necessary for a user to successfully leverage mnemonic capabilities.

The main aim of this survey is to (1) take stock of research on natural-language enabled wheelchairs, (2) present a comprehensive summary of the capabilities of current NL-enabled wheelchairs, and (3) propose a set of directions for future developments based on the summary. To this end, we present a framework for comparing NL-enabled wheelchairs, from the most basic wheelchairs whose speech interfaces mirror joystick control, to wheelchairs that act as genuine helpers. We then apply this framework in our analysis of all twenty-four NL-enabled wheelchair projects (including our own) published in the past twelve years. Following the analysis, we propose a list of eleven research topics that need further exploration and development in order for NL-enable autonomous wheelchairs to become genuine helpers to humans.

2. Framework Definition

The proposed framework for comparing autonomous language-enabled wheelchairs consists of the following four parts which we will motivate subsequently:

Hardware Configuration: the physical properties of the wheelchair.
Non-linguistic Capabilities and Behaviors: The wheelchair's high-level perceptual or mnemonic capabilities, and the types of navigational tasks facilitated by those capabilities.
Linguistic Capabilities and Behaviors: The wheelchair's high-level linguistic capabilities, and the types of dialogue acts facilitated by the wheelchair's capabilities.
User Evaluation: the way the wheelchair was evaluated.

Since NL capabilities must be reflected in the wheelchair's behavioral capabilities (otherwise they would be superfluous), it is most natural to compare NL-enabled wheelchairs by their executable behaviors. For example, there is an obvious behavioral difference between a wheelchair only able to accept metric commands (e.g., "Go forward") and a wheelchair able to accept commands such as "Go faster," "Follow Jim," "Go to the third door on the right," or "Go to the breakroom." Similarly, one can distinguish between a wheelchair that is only able to accept commands and a wheelchair able to interpret statements such as "This room is called the Atrium" or "I could use a glass of water." In addition to the types of utterances a wheelchair can interpret or use, it is important to differentiate between the types of dialogue acts a wheelchair can interpret or use. Although most of the examined wheelchairs only accept commands, some respond with simple acknowledgments such as "Okay." or "Please repeat your command", and a few are capable of richer dialogue exchanges (e.g., asking or answering questions).

Behaviors alone are not, however, sufficient metrics for comparison. A wheelchair may be able to execute a wide range of behaviors, but due to limited functional capabilities may only be able to do so at a rudimentary level. One may be able to tell a wheelchair to go to the breakroom, but this does not reveal much about that wheelchair's capabilities. The wheelchair may be able to follow the command because it has hardcoded knowledge that following a line on the floor will bring it to the breakroom. Alternatively, it may be able to follow the command because the user said "that's the breakroom" while driving past an open door on the previous day, and because the wheelchair's mapping system can find a route to that location. It follows that the wide range of functional capabilities that facilitate executable behaviors must also be compared. A wheelchair's functional capabilities also tend to indicate its robustness or flexibility. For example, *perceptual* capabilities such as object and gesture recognition may allow a wheelchair to better interpret utterances that refer to objects or locations, such as "that's the microwave," "bring me over there," or "that one." *Mnemonic* capabilities such as belief modeling and episodic memory may allow for better disambiguation of utterances such as "let's go to the cafeteria" by determining locations known to or frequented by the wheelchair's user. Spatially-oriented mnemonic capabilities for mapping or outdoor navigation may allow the wheelchair to be used in unmapped environments. *Linguistic* capabilities such as listening in on conversations may facilitate disambiguation by providing more information to the wheelchair, and capabilities such as dialogue management and robustness to disfluency, ungrammaticality, and ambiguity make the wheelchair more natural to converse with, and easier to use for those with speech impairments.

In this paper, we consider *Non-linguistic Capabilities and Behaviors* separately from *Linguistic Capabilities and Behaviors*: these represent the two primary dimensions within our framework for evaluating NL-enabled wheelchairs. While these two dimensions allow for easy comparison between wheelchair projects, we also include two dimensions which provide additional, practical information to wheelchair designers.

First, we have chosen to include *Hardware Configuration*. Just as capabilities determine the sophistication of behaviors, the physical properties of a wheelchair (i.e., its body, sensors and input modalities) limit the sophistication of its capabilities. Although a wheelchair's body (e.g., a powered wheelchair versus a motorized camping chair) affects the way the wheelchair will be perceived, and the addition of control modalities (e.g., a brain control interface) reflects the goals of the wheelchair's developers, a wheelchair's sensors affect what the wheelchair can actually do. A wheelchair without sensors cannot map its environment or avoid obstacles, and a wheelchair without a camera will have a hard time recognizing objects in the environment. The inclusion of this framework dimension will allow developers of new wheelchairs to assess what hardware features may be needed to enable particular capabilities and behaviors.

Finally, we have chosen to include *User Evaluation*. The majority of the examined wheelchairs had only limited evaluations, producing little to no evidence that they would be usable in daily life by their target populations. The inclusion of this framework dimension will allow developers of new wheelchairs to assess the capabilities of previously developed wheelchairs, and the hardware configurations which can be used to enable those capabilities, with greater confidence and a more critical eye.

Having motivated our framework, we next introduce the subcategories within our broader framework categories.

2.1. Hardware Configuration

A wheelchair's sensors dictate its capabilities, its base affects how it is perceived by users, and its control modalities determine its level of accessibility.

Wheelchair Base: The examined wheelchairs varied widely in structure, from camping chairs to sophisticated powered wheelchairs. Wheelchair users will certainly differentiate between modified manual wheelchairs and fully developed power wheelchairs, due to differences in comfort, control, safety and price effectiveness.

Sensors: Many of the capabilities of an intelligent wheelchair that is a genuine helper require some means of perception. The wheelchairs we examined were fairly evenly distributed between those having no sensors whatsoever, those having a single means of perception, and those having two or more types of sensors.

Control Modalities: Many of the examined wheelchairs can be controlled by one or more modalities other than NL. We thus classify control modalities into three categories: verbal (control by NL), manual (control by physical movement) or mental (control by thought).

2.2. Non-Linguistic Capabilities and Behaviors

The functional capabilities of a wheelchair necessarily constrain the types of behaviors the wheelchair is capable of executing, and determine the power, robustness and flexibility of these behaviors. We separate non-linguistic functional capabilities into two categories: *perceptual* (pertaining to the types of entities a wheelchair can detect or identify), and *mnemonic* (pertaining to the types of information the wheelchair can store in long-term memory).

2.2.1. Perceptual Capabilities

Detection: A wheelchair may be able to detect features of its environment, obstacles in its path, or the positions of nearby agents. Detecting and avoiding obstacles is necessary for any significant level of navigation.

Identification: A wheelchair able to detect people or objects may also be able to identify them.

Gesture or Action Recognition: A wheelchair may be able to interpret gestures made by its user or other agents. And, monitoring the actions performed by other agents, may allow a wheelchair to model their intentions.

2.2.2. Mnemonic Capabilities

Belief and Intention Modeling: Modeling the spatial knowledge of its user and other agents may allow a wheelchair to resolve referential ambiguities or to better answer queries.

Episodic Memory: If a wheelchair can recall particular events, it may be able to predict the referent of an ambiguous instruction based on patterns of past behavior.

Working Memory: If a wheelchair maintains information about what entities are "salient" or "in focus" within the environment or discourse structure, it may be better able to resolve referring, deictic, and anaphoric expressions.

Mapping Style: The maps used by wheelchairs may be metric, topological, or hybrid in nature, which will affect the granularity of the wheelchair's knowledge of its environment. At a broad level, we classify systems based on whether or not they use maps at all. At a more granular level, we classify systems as to whether they use metric and/or topological maps, and whether they create those maps.

Environmental Flexibility: Most NL-enabled wheelchairs can only navigate indoor environments due to limitations of their sensors or assumptions imposed by their navigation systems, such as the types of paths the wheelchair is restricted to or the ways paths are expected to intersect.

We will now discuss the types of non-linguistic *behaviors* facilitated by these non-linguistic *capabilities*. We divide these into behaviors that do and do not require any mapping capabilities.

2.2.3. Mapless Navigation Behaviors

A wheelchair may be able to carry out a variety of commands which do not require any mapping abilities:

Metric Commands: All examined wheelchairs can execute metric commands such as “Go Forward” and “Turn Left.”

Speed Adjustment: A wheelchair may be able to speed up or slow down on request.

Following of Static Entities: A wheelchair may be able to follow walls, lines on the ground, or other static features of its environment.

Following of Dynamic Entities: A wheelchair may be able to follow a human or another robot.

Following Route Descriptions: A wheelchair may be able to follow route descriptions from its current location without using a map.

2.2.4. Map-based Navigation Behaviors

Many of the behaviors of an intelligent wheelchair that is a genuine helper require the ability to build or use a map.

Traveling to Named Locations: If a wheelchair can assign labels to locations in a topological or metric map, it may be able to visit them without needing a route description.

Traveling to Objects: A wheelchair may be able to travel to named objects.

Traveling to Unknown Locations: A wheelchair may be able to visit places it hasn’t been to before if their locations are sufficiently described. The wheelchair may then be able to follow directions *relative* to the described place (e.g.,“Go to the room two doors past the break room”).

Traveling to Unknown Objects: A wheelchair may be able to visit objects it hasn’t been to before if their locations are sufficiently described (e.g.,“Go to the kitchen table” where the kitchen is known, but unexplored).

Traveling to Implied Locations: A wheelchair may be able to visit implied destinations (e.g., the kitchen for “Let’s cook some eggs.”).

2.3. Linguistic Capabilities and Behaviors

Most NL-enabled wheelchairs only follow simple orders. An intelligent wheelchair that is a genuine helper could engage in robust dialogue, and could follow the conversations of others to facilitate mnemonic capabilities such as belief and intention modeling.

Dialogue Management: A wheelchair may have dialogue capabilities such as turn taking or topic tracking.

Robustness: A wheelchair may be robust to speech disfluencies, ungrammatical utterances, or ambiguous references.

Listening in on Conversations: A wheelchair may be able to gain information by listening to commands and descriptions in the conversations of nearby agents.

But the most important features of a wheelchair are the behaviors it can perform. An intelligent wheelchair that is a genuine helper could engage in a wide variety of dialogue behaviors:

Accepts Commands: A wheelchair may only accept *commands* (expressed grammatically through imperatives as opposed to more indirect forms of commands, see below).

Accepts Descriptions: A wheelchair may understand statements such as "The door to the lab is locked" or indirect speech acts such as "It'd be great if you could get me a coffee."

Acknowledgment: The simplest speaking behavior is providing acknowledgment that a command or description has been received.

Answers Questions: A wheelchair may be able to answer queries, such as how to get to a certain room, where a meeting is being held, or what the weather will be like.

Asks Questions: If a wheelchair can ask questions, it may better resolve ambiguities, gain additional knowledge of its environment, or dispute conflicting information.

Offers Suggestions: A wheelchair may be more helpful if it suggests ways it might be of service, or reminds its user of appointments they may have forgotten.

2.4. User Evaluation

Wheelchair evaluation should be holistic, task-based, large-scale and long-term. As we later discuss, the evaluations of existing wheelchairs have been much less rigorous in these categories than would be desirable.

Style: Wheelchairs were evaluated either by capability (e.g., only speech recognition has been evaluated), holistically (e.g., by measuring task performance), or not at all.

Size: We categorize holistically evaluated wheelchairs as having fewer than, or greater than or equal to ten participants, based on the subject pool of the publication with the most holistic evaluation.

2.5. Further divisions

To better compare current wheelchairs with different capabilities, we first divide the wheelchairs by the highest scope of command they can execute. Out of twenty-four examined wheelchairs, fifteen only execute metric-level commands, three also execute commands to follow locally observable features, such as "follow the wall" or "enter the elevator," and six execute commands to go to named locations. This division, while unbalanced, emphasizes how far most current wheelchairs are from attaining the linguistic capabilities we desire. We further divide the two larger categories to produce groups of more manageable sizes.

The fifteen wheelchairs only capable of executing metric commands are further divided based on their hardware configuration: three have a microphone but no other sensors or control modalities, seven have some additional control modality or sensor but no way of autonomously avoiding obstacles, and the remaining five have additional sensors and control modalities, and can autonomously avoid obstacles.

The six wheelchairs capable of executing commands to visit specific locations are further divided based on mapping style: four use *prebuilt* topological maps of their environment, and the other two build their own.

These divisions separate the wheelchairs into groups of three to seven wheelchairs each, facilitating easier comparison. In the following pages, we present two tables: (1) Table 1 assigns an identifier to each wheelchair projects analyzed in this survey paper, used in all subsequent tables; (2) Table 2 applies the framework to these projects. For the sake of space, some framework dimensions are only applied at a high level in Table 2. For example, Table 2 only indicates *number* of sensors, and not *which* sensors were used. For such framework dimensions, a more granular analysis is provided later on.

3. How to Use This Survey

In this section we provide a brief guide explaining how the presented survey and framework can be used to achieve two basic tasks: finding information on a particular project, and finding information on a subset of projects with a particular capability or behavior[1].

---

[1] There are of course other ways of gleaning information using this survey and framework. We would also note that there is information that can be extracted from this survey which could be easily accessed if this framework were digitized. For example, we have elected to include specifics of hardware configuration in subsection tables rather than in Table 2 in order to fit the table on a single page. It would be valuable in future work for this information to be made available in a digital form, so that researchers can more easily determine what capabilities and behaviors have been previously enabled using particular hardware configurations.

ID	Year	Author	Affiliation
1	2010	Qidwai	Qatar University
2	2009	Qadri	Sir Syed University of Engineering and Technology
3	2007	Suk	National Institute of Advanced Industrial Science and Technology
4	2013	McMurrough	University of Texas at Arlington
5	2011	Maskeliunas	Kaunas University of Technology
6	2011	Berjon	Universidad Pontificia de Salamanca
7	2007	Asakawa	Kanagawa Institute of Technology
8	2015	Wang	WuYi University
9	2013	Ruiz-Serrano	Instituto Tecnologico de Orizaba
10	2015	Linh	HCMC University of Technical Education
11	2011	Wallam	Sir Syed University of Engineering and Technology
12	2012	Babri	University of the Punjab
13	2010	Liu	Nanchang University
14	2015	Sheikh	Nagpur University
15	2015	Skraba	University of Maribor
16	2007	Hockey	UC Santa Cruz
17	2010	Pineau	McGill University
18	2009	Murai	Tottori University
19	2011	Megalingam	Amrita Vishwa Vidyapeetham
20	2009	Tao	Beijing University of Aeronautics and Astronautics
21	2015	Faria	Instituto Politecnico do Porto
22	2016	Williams	Tufts University
23	2016	Hemachandra	Massachusetts Institute of Technology
24	2005	Ross	University of Bremen

Table 1: Legend of Examined Wheelchairs: The identifier for each project (to be used in subsequent tables), and the year of publication, first author, and first author's affiliation, for the most recent work on each project.

3.1. Finding Information on a Particular Project

A researcher interested in learning more about a particular NL-enabled wheelchair and wheelchairs with similar capabilities should perform the following steps.

1. Locate the project of interest in Table 1, and note its associated *Project ID*.
2. Locate the *Project* row in Table 2, and identify the column containing the desired Project ID.
3. Consult the rows (*below* the Project row) containing a black dot in that column in order to briefly assess the hardware configuration, capabilities, behaviors, and evaluation of the project of interest.
4. Identify the column label(s) immediately *above* the Project row to identify the section of the survey paper in which more detailed information is provided.
5. Find the associated subsection of Section 4 to learn more about the project of interest and its relationship to other projects with the same level of navigation behavior.
6. In the Table contained in that section, find the column containing the project ID of interest.

	NL-enabled Wheelchairs: Navigation Behaviors:																							
	Metric Commands Only															**Local Feature Following**			**Place Navigation**					
	Mic Alone			**Extra HW No OA**							**Extra HW With OA**								**Prebuilt Maps**				**OTF Maps**	
Project	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Hardware Configuration																								
Base: Manual	●	●			●	●	●			●	●	●		●					●	●				
Powered			●	●				●	●				●		●	●	●	●			●	●	●	●
Sensors: None	●	●	●	●	●	●		●	●															
One							●			●	●	●	●	●		●	●					●	●	
Several															●			●	●	●	●			●
Control Modalities: Verbal	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Manual				●	●	●		●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●
Mental				●																				●
Non-Linguistic Capabilities and Behaviors																								
Perceptual Capabilities																								
Detection											●	●	●	●	●	●	●	●	●	●	●	●	●	●
Identification																						●	●	●
Gesture or Action Recognition																								
Mnemonic Capabilities																								
Belief or Intention Modeling																	●					●		
Episodic Memory																								
Working Memory																						●		
Mapping																			●	●	●	●	●	●
Environmental Flexibility																							●	
Mapless Navigation Behaviors																								
Metric Commands	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Any Other Local Commands				●													●	●			●		●	●
Map-Based Navigation Behaviors																								
Travels to Named Places																			●	●	●	●	●	●
... to Objects																●						●	●	●
... to Unknown Places or Objects																●						●	●	
... to Implied Objects or Locations																						●		
Accepts New Place Names																							●	
Linguistic Capabilities and Behaviors																								
Linguistic Capabilities																								
Dialogue Management																●	●					●		
Listening in																								
Robustness			●																			●	●	
Linguistic Behaviors																								
Accepts Commands	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Accepts Descriptions																						●	●	
Acknowledgment																●		●		●		●	●	●
Answers Questions						●														●	●			
Asks Questions																●						●		
Offers Suggestions																								
User Evaluation																								
None		●		●	●	●					●		●	●		●								
By Capability	●		●					●		●		●							●			●		●
Holistic: n < 10							●		●									●		●	●			
Holistic: n >= 10															●		●						●	

Table 2: Framework applied to all wheelchairs

7. For each row in the "Hardware Configuration" section containing a black dot in that column, note what hardware was used in the design of the project.

8. For each row in the "User Evaluation" section containing a black dot in that column, note the type of evaluation, if any, the project received.

For example, to learn more about the NL-enabled wheelchair research we have performed at Tufts University, one would (1) see that we are listed in Row 22 of Table 1; (2) find Column 22 of Table 2; (3) scan down Column 22 for black-dotted cells and consult the row-label for such cells; (4) observe that the labels above Column 22 are "Place Navigation" and "Prebuilt Maps", (5) locate Section 3.3.1 ("Wheelchairs Capable of Navigating to Specified Locations, that Require a Prebuilt Map"), (6) identify Column 22 in Table 7, (7) note that this project involved a powered wheelchair base equipped with an LRF and a joystick, and (8) note that the capabilities of the project were individually evaluated, and a holistic evaluation of the project has yet to be performed.

3.2. Finding Information on Projects with a Particular Capability or Behavior

A researcher interested in learning more about previously developed wheelchairs with a particular capability or behavior should perform the following steps.

1. Locate the capability or behavior of interest in the first column of Table 2.

2. For each column containing a black dot in that row, identify the Project ID in the same column of the Project row.

3. For each such project ID:

    (a) identify the column label(s) immediately *above* the Project row to identify the section of the survey paper in which more detailed information is provided.

    (b) Find the associated subsection of Section 4 to learn more about the project of interest and its relationship to other projects with the same level of navigation behavior.

    (c) In the Table contained in that section, find the column containing the project ID of interest.

    (d) For each row in the "Hardware Configuration" section containing a black dot in that column, note what hardware was used in the design of the project.

    (e) For each row in the "User Evaluation" section containing a black dot in that column, note the type of evaluation, if any, the project received.

For example, to learn more about wheelchairs capable of belief or intention modeling, one would (1) locate this capability in the "Mnemonic Capabilities" section of Table 2, (2) identify projects 17 and 22 as the set of projects with this capability,

(3) identify associated column labels “Local Feature Following” and “Place Navigation”/”Prebuilt maps”, (4) locate Sections 4.2 (“Wheelchairs Capable of Following Local Features”) and 3.3.1 (“Wheelchairs Capable of Navigating to Specified Locations, that Require a Prebuilt Map”), (5) identify Column 17 in Table 6 and Column 22 in Table 7, (6) observe that both wheelchairs used Powered Bases with Laser Range Finders, and that Project 17 made additional use of a Touch Screen, and (7) note that Project 17 received a holistic evaluation with greater than ten participants, and Project 22’s individual capabilities were evaluated outside the context of the wheelchair system.

4. Analysis of Projects

We will now use the presented framework to compare the wheelchairs shown in Table 1. In this paper, we will examine twenty-four distinct wheelchair projects. These represent, to the best of our knowledge, all NL-enabled wheelchairs presented within the past twelve years. Many of the projects we will examine represent the work of a large number of researchers, and resulted in a large number of distinct publications; in most cases, we will refer only to the most recent publication in each project, and make note of the first author on that most recent publication.

4.1. Wheelchairs Limited to Metric Commands

Nearly two thirds of recent NL-enabled wheelchairs can only follow verbal commands to go forward, turn or stop. We first examine the wheelchairs in this category that have no hardware additions other than the microphone necessary for speech input.

4.1.1. Wheelchairs Limited to Metric Commands with No Hardware Additions

Project	1	2	3
Hardware Configuration			
Manual Base	●	●	
Powered Base			●
Linguistic Capabilities			
Robust to Disfluencies			●
User Evaluation			
Style:None		●	
By Capability	●		●
Size: N/A		●	
< 10 Participants	●		
>= 10 Participants			●

Table 3: Wheelchairs allowing only metric level commands with no sensors other than a microphone

Since the published aspects of the wheelchairs in this category ([7, 8, 9]; 1-3 in Table 3) were solely related to aspects of speech recognition, it is understandable that the set of commands executable by these wheelchairs is limited in scope. The wheelchair presented by Suk et al., for example, was presented with respect to a voice-control algorithm designed to be robust to speech disfluencies[9].

Two of these projects used augmented manual wheelchairs instead of powered wheelchairs, due to their limited needs. Experimental validation differed between projects; one analyzed about 2000 samples collected from 12 participants [9], one analyzed 250 commands collected from five participants [7], and one did not indicate whether their wheelchair had been empirically evaluated [8].

4.1.2. Wheelchairs Limited to Metric Commands with Hardware Additions but without Obstacle Avoidance

Project	4	5	6	7	8	9	10
Hardware Configuration							
Manual Base		●	●	●			●
Powered Base	●				●	●	
RF Reader				●			
Eye Tracking	●	●					
Head Tracking			●				
BCI	●						
Magnetic Control						●	
Keyboard and Mouse					●		●
Touch Screen		●	●				●
Keypad				●		●	
Joystick	●			●	●	●	●
Non-Linguistic Behaviors							
Speed Adjustment	●						
Linguistic Behaviors							
Answers Other Questions			●				
User Evaluation							
Style: None	●	●	●				
By Capability					●		●
Holistic				●		●	
Size: N/A	●	●	●				●
<10 Participants				●	●	●	

Table 4: Wheelchairs allowing only metric level commands with sensors that do not provide obstacle avoidance

Of the wheelchairs with hardware additions but without obstacle avoidance ([10, 11, 12, 13, 14, 15, 16]; 4-10 in Table 4) only those presented by McMurrough et al. and Linh et al. used powered wheelchair bases [10, 16] . All seven wheelchairs in this category used a manual control modality such as a standard joystick [10, 13, 14, 15, 16], or a touch screen [11, 12]. Most of these projects focused on the use of multiple control modalities. In addition to voice and touch control, McMurrough et al. used BCI and eye-tracking control [10]; Maskeliunas et al. used eye-tracking control[11]; Berjon et al. used head-tracking control [12]; Ruiz et al. used tongue-based magnetic control [15]; and both Want et al. and Linh et al. used a keyboard and mouse [14, 16].

Asakawa and Nishihara, on the other hand, used no additional control modalities, but used a Radio Frequency (RF) tag reader along with RF tags embedded into the floor to allow their wheelchair to autonomously round corners [13]. Other capabilities of these wheelchairs were limited. The wheelchair presented by McMurrough et al. could accept voice commands to adjust its speed of movement (but could not accept commands to turn) [10]; the wheelchair presented by Berjon et al. could use a smartphone to answer questions about the weather and news [12].

Evaluations of the wheelchairs in this category were limited. McMurrough et al. do not appear to evaluate their wheelchair at all [10], and Berjon et al. and Maskeliunas et al. only state that their wheelchairs work fine [12, 11]. Wang et al. and Linh et al. evaluate the accuracy of their speech recognition systems [14, 16], with Wang et al. stating that five participants were used, and Linh et al. not providing any information about who provided their training and testing data. Asakawa and Nishihara contrast the time taken for three subjects to navigate a hallway when using voice, button pad or joystick control [13]. Ruiz et al. had five participants navigate an environment with obstacles, measuring the time taken to complete the task [15].

4.1.3. Wheelchairs Limited to Metric Commands with Hardware Additions Allowing for Obstacle Avoidance

Project	11	12	13	14	15
Hardware Configuration					
Manual Base	●	●		●	
Powered Base			●		●
Ultrasound	●			●	
Camera		●	●		●
IR				●	
Finger Motion Sensor	●				
Touch Screen					●
Remote Control				●	
Joystick	●	●	●	●	
User Evaluation					
Style: None	●		●	●	
By Capability		●			
Holistic					●
Size: N/A	●		●	●	
<10 Participants		●			
>=10 Participants					●

Table 5: Wheelchairs allowing only metric level commands with sensors that provide obstacle avoidance

We will now discuss the five remaining wheelchairs restricted to metric commands ([17, 18, 19, 20, 21]; 11-15 in Table 5). Three of these wheelchairs used manual bases [17, 18, 20] and two used powered bases [19, 21]. Unlike the wheelchairs examined thus far, all wheelchairs in this category used sensors to avoid obstacles: Wallam and Asif and Sheikh et al. used ultrasound sensors ([20] also used an IR sensor) [17, 20], and Babri et al., Liu et al., and Škraba et al. used a camera [18, 19, 21]. All wheelchairs could be controlled with a joystick except that presented by Škraba et al, who replaced theirs with a touch screen [21]. In addition, Wallam and Asif used a finger motion sensing glove [17], while Sheikh et al. used a remote controller [20].

The wheelchair presented by Škraba et al. was evaluated by twelve participants [21], including two patients from a rehabilitation institute. Experimental validation of the other wheelchairs was minimal; Babri et al. state that two people tested their wheelchair's speech recognition; the rest are only described as working fine, if their performance is described at all [18].

Thus far, we have examined 15 wheelchairs, most of which could only understand five commands: Go forward, Go backwards, Turn left, Turn right, and Stop. This is clearly well-trod ground, and yet many of these projects do not significantly predate the projects found in latter categories: some were published on as recently as 2015. Future wheelchair developers should focus not on these basic capabilities, but rather on enabling more sophisticated linguistic and mnemonic capabilities, as do the developers of the projects we will now discuss.

4.2. Wheelchairs Capable of Following Local Features

Project	16	17	18
Hardware Configuration			
Powered Base	●	●	●
LRF		●	
Ultrasound	●		●
IR			●
Touch Screen		●	
Joystick	●	●	●
Non-Linguistic Capabilities and Behaviors			
Intention Modeling		●	
Metric Mapping		●	
Speed Adjustment			●
Wall Following		●	
Elevator Entering			●
Travels to Objects	●		
Travels to Unknown Objects or Locations	●		
Linguistic Capabilities and Behaviors			
Dialogue Management	●	●	
Acknowledgment	●	●	
Ask Questions	●		
User Evaluation			
Style: None	●		
Holistic		●	●
N/A	●		
<10 Participants			●
>=10 Participants		●	

Table 6: Wheelchairs able to issue NL commands not requiring perception

The next group of wheelchairs are those that can navigate relative to local environmental features such as walls and elevators. All projects in this category ([22, 23, 24]; 16-18 in Table 6) use powered wheelchair bases controllable by joystick. In addition, the wheelchair presented by Pineau et al. can be controlled by a touch screen [23]. All wheelchairs in this category have at least one sensor used to avoid obstacles: Hockey and Miller use an ultrasound sensor [22], Pineau et al. use an Laser Range Finder (LRF) [23], and Murai et al. use both ultrasound and IR sensors [24]. Unlike the previous wheelchairs, those in this category all have an array of capabilities and behaviors.

The wheelchair presented by Hockey and Miller appears to have been used as a proof-of-concept demonstration within a limited domain [22]. As such, it has not been empirically evaluated, and there are scarce details about how it works algorithmically. Hockey and Miller do, however, provide a sample dialogue handled by their wheelchair, suggesting some interesting capabilities, such as dialogue management, which it uses to provide acknowledgment and ask questions, and the ability to travel to described objects even if it has never seen them before – a capability of interest in current research (c.f. [25, 26]).

The SmartWheeler wheelchair [23] uses an LRF to detect and avoid obstacles and to map its environment, which allows the wheelchair to easily follow walls. When the SmartWheeler receives a command, it can ask for feedback regarding its interpretation using a touchscreen. Recent work on this project has included modeling of the wheelchair user's intentions when issuing commands [27]. For evaluation, the wheelchair was first run through the Wheelchair Skills Test [28]. Then, 23 subjects, both able-bodied and disabled, evaluated the wheelchair.

Finally, Murai et al. present a wheelchair that uses ultrasound and infrared sensors to detect and avoid obstacles and to get in and out of elevators [24]. Their wheelchair does not use a dialogue manager, but prompts the user after every command to ensure it understood them correctly. This wheelchair was validated using five able bodied participants in a series of experiments.

In this category, we see for the first time wheelchairs with substantial linguistic capabilities. But while some wheelchairs in this category (i.e., those of Pineau et al. and Murai et al.) have begun to allow more sophisticated navigational behaviors such as wall following and elevator entering, more sophisticated linguistic capabilities are still lacking; only Hockey et al.'s wheelchair may have come close to the goal of *genuine helper*, but it was not truly evaluated.

4.3. Wheelchairs Capable of Navigating to Specified Locations

The final group is comprised of wheelchairs that use a topological map to navigate. We split these into those that are given maps, and those that create their own.

4.3.1. Wheelchairs Capable of Navigating to Specified Locations, that Require a Prebuilt Map

Four projects used wheelchairs preloaded with topological maps ([29, 30, 31]; 19-21 in Table 7), and our own wheelchair [32], 22 in Table 7). Hardware varied greatly between these projects. Megalingam et al. used a camping chair attached to a platform with sonar sensors and an RF reader [29]. Tao et al. use a manual wheelchair base outfitted with ultrasound sensors, an RF reader, a touch screen and a joystick [30]. The IntellWheels project [33, 34, 31] uses a powered wheelchair with both sonar and infrared sensors. They focus in part on mapping multi-modal input sequences to desired actions; their wheelchair can be controlled by touchscreen, joystick, gamepad, keyboard, or head movement. Our own wheelchair uses a powered wheelchair base, can be manipulated with a joystick, and is equipped with two LRFs. We will next discuss the three previously published wheelchairs in this category, and then discuss our own research efforts.

Despite the wide variance in hardware, the three previously published wheelchairs can perform roughly the same behaviors; all three can go to a pre-labeled room, and Faria et al.'s wheelchair can follow walls [31]. All three avoid obstacles, and Tao et al.'s wheelchair can provide acknowledgments and answer questions about the weather

Project	19	20	21	22
Hardware Configuration				
Manual base	●	●		
Powered base			●	●
Sonar	●			
RF Reader	●	●		
Ultrasound		●	●	
IR			●	
Camera			●	
LRF				●
Joystick		●	●	●
Touch Screen		●	●	
Gamepad			●	
Keyboard and Mouse			●	
Head Tracking			●	
Non-Linguistic Capabilities and Behaviors				
Intention Modeling				●
Working Memory				●
Metric Mapping				●
Wall Following			●	
Travels to Named Places	●	●	●	●
Travels to Objects				●
Travels to Unknown Objects				●
Linguistic Capabilities and Behaviors				
Dialogue Management				●
Robust to Ambiguity				●
Accepts Descriptions				●
Acknowledgments		●		●
Answers Questions		●		●
Asks Questions		●		●
User Evaluation				
Style: By Capability	●			●
Holistic		●	●	
Size: N/A	●			●
<10 Participants		●	●	

Table 7: Wheelchairs able to issue NL commands requiring mapping based on preloaded topological maps

and upcoming events [30]. Megalingam et al. tested wheelchair response time [29], while the other two groups performed a battery of tests on a small number of subjects (five [30] or eight [34]), yielding qualitative results about the wheelchair's performance. These wheelchairs used preloaded maps either because they expected that the wheelchair would be used in a preknown home environment [29, 30], or because they used a mixed reality system requiring a simulated environment representation[34].

Designed as a successor to the Vulcan wheelchair in collaboration with the University of Michigan [35], our own wheelchair [32] can avoid obstacles and dynamically create a *metric* map of its environment using the Hybrid Spatial Semantic Hierarchy (HSSH) [36]. We are currently integrating prior work on topological maps built through both observation and dialogue interactions [25]. Unlike the other wheelchairs examined thus far, our wheelchair can posit new hypothetical locations based on dialogue (even though it can only travel to them in some contexts) and can travel in search of previously unknown objects. For example, a reference to "the medkit in the breakroom" will allow it to travel to the breakroom in search of the medkit as long as it knows where the breakroom is. These capabilities are afforded by our use of the POWER framework [37, 38, 39], which makes the wheelchair robust to referential ambiguity and uncertain and open worlds. In recent work, we have extended this framework using the *Givenness Hierarchy* [40], which models working memory, attention, and discourse context, to better resolve anaphoric and deictic expressions [38]. This approach also differs from previous approaches in that it does not only accept commands to travel to locations denoted by a *rigid designator* (i.e., by "name"), but rather accepts commands to travel to places matching *descriptions* such as "the room at the end of the hall down on the right", a strictly larger class of referring expression.

Another key feature of our wheelchair is its robust dialogue system (provided by the ADE implementation of the DIARC architecture [41]), which can infer goals and intentions from indirect speech acts under contextual uncertainty or ignorance [42, 43]. For example, if the user says "Could you bring me to the kitchen?" the robot will understand that this is probably not meant as a literal yes-or-no question, and will bring the user to the kitchen. This dialogue system also allows the wheelchair to ask and answer some questions [44], provide appropriate acknowledgments, and track turn-taking. A video of our wheelchair acting on indirect language can be viewed at `https://www.youtube.com/watch?v=eSU1YWdSfpk`. While we have evaluated many such capabilities in previous work, and have informally demonstrated many of them on our wheelchair, we have not yet holistically evaluated our wheelchair – this will be a topic for future work as our research efforts progress.

4.3.2. Wheelchairs Capable of Navigating to Specified Locations and of Dynamically Building Topological Maps

Finally, we discuss the two wheelchairs capable of building topological maps dynamically ([45, 46]; 23 and 24 in Table 8). Both use powered wheelchair bases with laser scanners for detecting and avoiding obstacles, and allow for joystick control.

The first is the MIT Intelligent Wheelchair Project [47]. This wheelchair builds a metric map from which topological structures can be extracted. Not only can this system travel to named objects and places, but it can receive new labels on-the-fly during guided tours while following a guide [48]. More recent papers also describe the

Project	23	24
Hardware Configuration		
Powered Base	●	●
Sensors: LIDAR	●	
LRF		●
Camera		●
Joystick	●	●
Head Joystick		●
BCI		●
Non-Linguistic Capabilities and Behaviors		
Metric Mapping	●	●
Topologic Mapping	●	●
Multi-floor Mapping	●	
Follows Route Descriptions		●
Wall Following		●
Person Following	●	
Elevator Entering	●	
Travels to Named Places	●	●
Accepts New Place Names	●	
Travels to Objects	●	
Travels to Unknown Objects	●	
Linguistic Capabilities and Behaviors		
Robust to Ambiguity	●	
Accepts Descriptions	●	
Acknowledgment	●	●
User Evaluation		
Style: By Capability		●
Holistic	●	
Size: >=10 Participants	●	●

Table 8: Wheelchairs able to issue NL commands requiring dynamic mapping

wheelchair's ability to accept descriptions such as "The kitchen is down the hall" [49] and references to previously unknown entities, such as "the cone behind the hydrant" [26]. This system can also provide acknowledgments, travel outdoors to some extent [49], enter elevators to traverse multiple floors, and is robust to referential ambiguity through the use of the G^3 framework.

There have been many publications on this project: in addition to evaluation of individual capabilities, it has also undergone holistic evaluation with a larger number of subjects than most other systems examined (e.g., fifteen participants were used to test the social acceptability of the wheelchair's following behavior).

The second wheelchair in this category is that presented by Röfer et al. [46]. This wheelchair can be controlled with a head joystick or with a brain-computer interface, and can follow route descriptions, such as "Go down the corridor and take the second door to the left" [46]. Previous work on this project explored map creation, but so far as we can tell route descriptions are used solely in conjunction with prebuilt maps. As the target environment for this wheelchair is an assisted living center, its layout would presumably already be known. Work on this project has also attempted to deal with some ambiguous situations, such as determining what is meant by "right" when it could mean "correct," "veer right," "turn right here" or some other meaning [50]. There has been extensive of research on this project in the past two decades, involving many studies with detailed quantitative analysis (e.g., [51]). Much of this work has been focused on evaluating individual parts of the system and on Wizard-of-Oz studies, however, and to the best of our knowledge there has been no holistic evaluation of their wheelchair.

In this and the previous section, we have finally seen significant developments in the mnemonic and linguistic capabilities and behaviors necessary for an intelligent wheelchair to become an genuine helper. Of these systems, the MIT Intelligent Wheelchair Project stands out as the state-of-the-art, as it is capable of a wide range of non-linguistic and linguistic behaviors, and has been holistically evaluated by a (comparatively) large number of participants, but this project has not focused on developing the mnemonic capabilities necessary for an intelligent wheelchair to be genuinely helpful. In our own work, in contrast, we have broken new ground in developing such mnemonic and linguistic capabilities – but our approach is as yet a work in progress, and is in need of both autonomous topological mapping and a holistic evaluation.

5. Discussion

Many of the examined wheelchairs, especially those that dynamically map their environments ([45, 46]), show promising progress towards the development of an intelligent wheelchair that genuinely helps them in their daily lives. Yet, the creation of such an genuine helper requires solutions to many challenging problems, as evidenced by the fact that most of the examined wheelchairs either focus on a particular subproblem (e.g., accurate speech recognition) or are unevaluated proofs-of-concept. Most importantly, there are many desirable properties of an ideal wheelchair that have not even been addressed yet, such as independence of environmental structure, modeling of interlocutors' beliefs, episodic memory, and the ability to engage in truly natural dialogues. We will discuss some of these capabilities in more detail and sketch necessary steps to achieving them.

5.1. Environmental Constraints

Although a number of wheelchairs allow their users to give commands pertaining to shared environmental features such as walls, rooms, or objects, the majority of these wheelchairs are constrained to preknown environments. What is more, these wheelchairs are almost entirely constrained to indoor environments, either due to assumptions about the structure of the environment, or sensors that cannot accurately function outdoors.

In fact, only two wheelchairs [12, 49] seem to have even been used outdoors, and to the best of our knowledge none of the examined wheelchairs can cope with fully outdoor navigation. This is due in part to a lack of appropriate sensors: only five of the examined wheelchairs were equipped with cameras, and other types of sensors may be ill-suited for outdoor navigation. Although this problem has not been addressed by NL-enabled wheelchairs, other intelligent wheelchairs *do* navigate outdoors (e.g., [52, 53]). Future NL-enabled wheelchairs should robustly cope with unknown environments, both indoor and outdoor.

To travel outdoors, wheelchairs will likely need to be equipped with cameras, if not more advanced multi-modal perceptual systems. Not only are cameras useful for recognizing objects, landmarks, and signs, but stereo cameras can rapidly generate 3-D point clouds which can be used for outdoor navigation in a way that is resilient against the illumination changes which plague outdoor navigation [54]. NL-enabled wheelchairs should also use GPS for navigation (as other wheelchairs have, e.g., [55]): it is a useful navigation technique, and could allow continued localization while a wheelchair user is transported by vehicle. Of course, it may be most advantageous to use an array of different types of sensors whose data may be fused to achieve greater accuracy.

In addition, wheelchairs must break from the assumption of straight hallways and room-and-hall networks within a single floor, and move towards handling not only multi-floor buildings, multi-building complexes and networks of outdoor paths, but anomalous environments with oddly shaped rooms, rooms which flow into each other, and doors which are wider than average or made of glass.

Finally, NL-enabled wheelchairs should accept commands to go to objects and locations they have not already visited; a feature exhibited only by Duvallet et al. [26], Hockey and Miller [22], and ourselves [32], and must use belief modeling and episodic memory for the better resolution of ambiguous references.

5.2. Linguistic and Mnemonic Capabilities and Behaviors

An advantage of using NL to interact with wheelchairs (and robots in general) is that NL can be used for *communication*, which in turn can be used for teaching and for explanation. Unfortunately, most of the examined wheelchairs fail to take advantage of this in any way, using voice input as just another way to obtain joystick functionality; fewer than half of all wheelchairs allow for additional linguistc input. Of those that do, only the wheelchairs presented by Hemachandra et al. [45] and ourselves allow a user to *inform* the wheelchair about features of the environment, such as the names or locations of rooms, and only a few attain any degree of conversation through dialogue management. It would be useful in many cases for an intelligent wheelchair to be capable of sustained dialogue interactions: the wheelchair may need to engage with dialogue with its rider as to what route to take. We envision future wheelchairs handling interaction patterns such as the following dialogue, which requires dialogue tracking, intent recognition, indirect speech act handling, question asking and answering, and other linguistic capabilities and behaviors, as well as episodic, working, belief, and intention modeling, among other mnemonic capabilities and behaviors.

User: Alright, let's go to my barbershop.

Wheelchair: *Drives off, takes a left*

User: I said my *barbershop*, wheelchair.

Wheelchair: *Stops*. We can go this way to get to your barbershop. If we took the other path we would have to cross Boston Avenue. You told me you'd rather not have to do that anymore.

User: I remember. How do we get there this way?

Wheelchair: We can just drive down Medford Street, and then take Somerville Avenue. We should be there in fifteen minutes. Is that alright?

User: Yes, that's alright wheelchair, let's go.

Wheelchair: Alright. *Drives off*

A wheelchair with sufficient linguistic capabilities could assume the role of helping the wheelchair's user fulfill his or her needs, in the same way a human companion would if they were pushing the wheelchair. To be perceived in this manner, it is important that the wheelchair achieve all of the capabilities we laid out when describing a genuinely helpful wheelchair, including those reflected in the dialogue above. Although the prototype wheelchair we presented is under development, it represents a step forward in addressing our concerns about the perception of NL-enabled wheelchairs, as it can interact in a more conversational manner than its predecessors, and takes a more *cognitive* approach than the other wheelchairs developed to date.

As mentioned before, our desiderata lie along the path to a wheelchair that is a *genuine helper*, and not one that has all the capabilities of a human helper. As we previously mentioned, the full set of human capabilities are well beyond the scope of current intelligent wheelchairs, and lie far beyond the current research horizon. We have also chosen to focus on *task oriented* capabilities and behaviors. While robot wheelchairs may be endowed with non-task-oriented capabilities such as the ability to make smalltalk, to empathize, or to manifest its own personality and desires, such capabilities from the domain of *social robotics* are not necessary for the robot to be a *genuine helper*. And in fact there are ethical concerns associated with developing an intelligent wheelchair that is a *companion* with whom users should form social or emotional bonds [56]. The benefits and consequences of such a decision are well beyond the scope of this paper.

5.3. Experimental Validation

The purpose of a wheelchair is to provide continuous, long-term mobility assistance to its user; a highly user-centered requirement. And yet, the majority of wheelchair evaluations were anything but user-centered. The ideal evaluation for an autonomous robotic wheelchair controllable by NL would be *task-oriented*, *long-term*, *large-scale*, and *using the wheelchair's target population*. In this section we describe why each of these aspects is both important and insufficiently addressed in current wheelchair evaluations.

5.3.1. Task-Oriented

A wheelchair is an important part of its user's day-to-day life. Testing whether the wheelchair can navigate around corners or respond quickly to commands is not enough; experiments should require subjects to accomplish tasks that actual wheelchair users might encounter: navigating to particular locations, retrieving objects, going through doorways, pulling up to tables, and so forth. It will be important to evaluate how easy these tasks are to achieve, how long it takes to achieve them, and the level of trust the wheelchair maintains. Does the wheelchair move in ways that make its user uncomfortable or nervous? Does the user trust the wheelchair to carry out high-level commands, or does the user fall back on metric commands?

Few of the examined wheelchairs had evaluations of this sort. Only one third of the wheelchairs were holistically evaluated: the rest were either presented as proofs of concept, or only evaluated specific features such as speech recognition rates. Of the eight wheelchairs with holistic evaluations, the three capable of only metric commands were evaluated with respect to time taken to complete various navigation tasks; of the two capable of local feature following, one was evaluated based on user satisfaction, the other based on ability to complete the navigation tasks of the Wheelchair Skills Task; of the three capable of place navigation, one was evaluated based on preference, comfort, efficiency, and mapping accuracy, after receiving a guided tour, while the other two were evaluated on navigation tasks. Although some of the evaluations described above were indeed task-based in nature, we would argue that the tasks used for evaluating future wheelchairs should be more "everyday" in nature.

5.3.2. Long-Term

Robotic wheelchairs may be continuously used every day for several years. But the evaluations of the examined wheelchairs tended to be short, likely due to unwillingness to invest the time and money, or due to a lack of robustness of the wheelchairs themselves. It would be useful to see how a wheelchair user feels about their wheelchair after an entire day of using it: the user could better adapt to the wheelchair, allowing them to provide better feedback as to difficulties of use, and provide insight into what types of commands actually get used after the first hour or so of operation. A user may become more frustrated with their wheelchair after a longer period of time, and may become more or less likely to use high level navigational commands. It will also be important to see how the wheelchair handles navigation in larger environments, many additional interlocutors engaging in conversation with its user, and other issues that may not come up in a half hour evaluation of navigation through one or two hallways.

Long term evaluations will also reveal everyday tasks the wheelchair has trouble with that its designers may not have considered, such as pulling up to a table, going to the restroom, or driving through an automatic doorway.

5.3.3. Large-Scale

A long term evaluation may only be possible with a small number of subjects, but short term evaluations should be performed with a large number of subjects, or at least more subjects than are currently being used. Few of the examined wheelchairs used even ten subjects. And it is at best questionable how useful an evaluation by only two or three people is, especially when those two or three people designed the wheelchair themselves, and are familiar with its quirks and idiosyncrasies.

5.3.4. Using Target Population

Few projects were validated using members of the wheelchair's target population. The nature and focus of an individual project may excuse this, but future projects should make an effort to demonstrate successful use of their wheelchair by those who would use it on a daily basis, as such users will have their own unique needs and concerns which must be addressed for the wheelchair to be usable by them.

5.4. Future Work

From our survey of recent NL-enabled wheelchair project it is obvious that there is a long road ahead for NL-enabled wheelchairs; many of the capabilities and behaviors necessary for a wheelchair to be genuinely helpful are missing from even the most state-of-the-art NL-enabled wheelchairs. And many other features are handled by only one or two wheelchairs. The first step towards a genuinely helpful wheelchair will be developing a wheelchair that achieves *all* capabilities previously achieved by previous wheelchairs, including multi-floor mapping, speed changing, entity following, route description following, memory modeling, dialogue management, and traveling to unknown places.

Researchers might then take a number of future directions to improve the functionality and interaction capabilities of NL-enabled wheelchairs:

- **Belief Modeling:** Some wheelchairs already have means for representing the topological structure of their own spatial knowledge; these structures should be adapted to represent the likely spatial knowledge of other agents, including but not limited to their users. This would be useful if a wheelchair is used by multiple people who may be familiar with different spatial regions, or if the robot needs to interpret directions given to the wheelchair's current user by a third party.

- **Intention Modeling:** Research on modeling the intentions and goals of agents should be applied to intelligent wheelchairs for them to make better decisions when following instructions which require them to reason about other agents, including but not limited to their users. This would allow a wheelchair to more accurately predict the intended destinations of its user, and would allow a wheelchair to follow commands such as "Let's go find Lisa", where Lisa's location may depend on her own daily routine.

- **Episodic Memory:** Such intention modeling would be greatly facilitated by the integration of episodic memory models. If a robot can recall what it saw where, what locations it visited when, and so forth, it can better model its user's intentions when driving down a familiar hallway, or when processing an utterance like "Let's go to *my usual* barbershop."
- **Action and Intent Recognition:** There has been much recent research on recognizing actions [57], but researchers must develop action and intention recognition systems that will work from the perspective of, and on data generated by, intelligent wheelchairs. This is necessary to store information in aforementioned episodic memory structures, in order, in turn, to facilitate the aforementioned intention modeling processes.
- **Working Memory:** Integration of working memory models similar to those employed by us in recent work [38] will allow wheelchair users to more easily communicate with their wheelchairs through deictic and anaphoric expressions. When wheelchair users use expressions like "it", or "that big kitchen", the use of pronouns like "it" and "that" give hints as to where in the listener's memory the speaker believes the relevant memory trace to reside. The more accurately a wheelchair can model what would be in each of its memory structures were it human (and how salient each entity would be in memory), the more accurately it can understand these types of expressions.
- **Dialogue Modeling:** Research on general spoken dialogue systems [58] should be put to use on intelligent wheelchairs so as to facilitate more robust question asking and question answering behaviors, as well as to allow wheelchairs to better provide justifications for their behaviors.
- **Pragmatic Reasoning:** Integration of pragmatic reasoning capabilities similar to those employed by us in recent work [43] can be further exploited to better allow intelligent wheelchairs to understand and generate task-based utterances beyond direct commands. Wheelchairs should not be restricted to understanding commands (e.g., "Go to the breakroom") and using similarly direct language itself (e.g., "Tell me where to go"), as people will frequently use, and expect robots to use, indirect speech acts (e.g., "Could you go to the breakroom?; "Where would you like to go?") for reasons such as politeness. There is, in addition, an opportunity for empirical research in this area, to investigate what types of utterance forms wheelchair users specifically are likely to use.
- **Disfluency Handling:** Few NL-enabled wheelchairs attempt to handle disfluencies resulting from speech impairments. One of the primary motivations for developing NL-enabled wheelchairs is to aid the 40% of wheelchair users who cannot easily manipulate a joystick; but many wheelchair users also suffer from speech impairments, a fact only addressed by Suk et al. [9]. Researchers should attempt to address disfluencies to be accessible to a greater number of people.
- **Outdoor Navigation:** Researchers must develop mapping systems flexible enough to allow for autonomous navigation in outdoor environments, in order for wheelchairs to be used outside of indoor environments such as private homes.

- **Gesture Recognition:** There has been much recent work on gesture recognition [59]; but researchers must develop gesture recognition systems that allow for interpretation of simultaneous speech and gesture issued from the perspective of wheelchair users. This will be necessary so as to accurately interpret utterances such as “Drive closer to that *(*points*)* table” or “Can you go over that way? *(*points*)*”.
- **Suggestion Generation:** Researchers must develop systems that leverage episodic memory and intention modeling for robots to autonomously generate timely suggestions for their users. A wheelchair may need to make suggestions like “Isn’t it time for your appointment?”, “Didn’t you want to go see Lisa?” or “It’s time for your medication” – utterances which are not typically used in response to utterances made by the user, but are instead spontaneously generated.

6. Conclusions

We have presented a framework for evaluating the abilities of both existing and future NL-enabled wheelchairs. We have identified several areas in which NL-enabled wheelchairs can be advanced, focusing on navigability of outdoor environments, thoroughness of experimental validation, and treatment of the wheelchair as an intelligent agent through capabilities such as dialogue, belief modeling and episodic memory. And while great strides have been made in recent years, we believe that progress may be best accelerated through two choices. First, research is needed on understanding and carrying out natural language instructions that go *beyond* simple directional commands. Second, research is needed on higher-level mnemonic and cognitive functions such as belief, intention, dialogue and memory modeling, as these will not only facilitate more advanced executable behaviors for intelligent wheelchairs, but also bring wheelchairs closer to being, and being perceived as, genuine helpers for their users.

Acknowledgements

This work was funded in part by grants N00014-14-1-0149 and N00014-11-1-0493 from the United States Office of Naval Research, and by grant 111323 from the United States National Science Foundation.

[1] J. M. Ortman, V. A. Velkoff, H. Hogan, et al., An aging nation: the older population in the united states, Washington, DC: US Census Bureau (2014) 25–1140.

[2] E. Trefler, S. G. Fitzgerald, D. A. Hobson, T. Bursick, R. Joseph, Outcomes of wheelchair systems intervention with residents of long-term care facilities., Assistive Technology 16 (2004) 18–27.

[3] L. Fehr, W. E. Langbein, S. B. Skaar, Adequacy of power wheelchair control i terfaces for persons with severe disabilities: A clinical survey, Development 37 (2000) 353–360.

[4] R. A. Cooper, Rehabilitation engineering applied to mobility and manipulation, CRC Press, 1995.

[5] L. I. Iezzoni, E. P. McCarthy, R. B. Davis, H. Siebens, Mobility difficulties are not only a problem of old age, Journal of General Internal Medicine 16 (2001) 235–243.

[6] J. A. Clark, R. B. Roemer, Voice controlled wheelchair., Archives of Physical Medicine and Rehabilitation 58 (1977) 169–175.

[7] U. Qidwai, F. Ibrahim, Arabic speech-controlled wheelchair: A fuzzy scenario, in: Proceedings of the Tenth International Conference on Information Sciences Signal Processing and their Applications (ISSPA), 2010, pp. 153 –156.

[8] M. Qadri, S. Ahmed, Voice controlled wheelchair using dsk tms320c6711, in: Proceedings of the International Conference on Signal Acquisition and Processing (ICSAP), IEEE, 2009, pp. 217–220.

[9] S.-Y. Suk, H.-Y. Chung, H. Kojima, Voice/non-voice classification using reliable fundamental frequency estimator for voice activated powered wheelchair control, in: Y.-H. Lee, H.-N. Kim, J. Kim, Y. Park, L. Yang, S. Kim (Eds.), Embedded Software and Systems, volume 4523 of *Lecture Notes in Computer Science*, Springer Berlin / Heidelberg, 2007, pp. 347–357.

[10] C. McMurrough, I. Ranatunga, A. Papangelis, D. O. Popa, F. Makedon, A development and evaluation platform for non-tactile power wheelchair controls, in: Proceedings of the Sixth International Conference on PErvasive Technologies Related to Assistive Environments (PETRA), ACM, 2013, p. 4.

[11] R. Maskeliunas, R. Simutis, Multimodal wheelchair control for the paralyzed people, Elektronika ir Elektrotechnika (2011) 81–84.

[12] R. Berjon, M. Mateos, A. Barriuso, I. Muriel, G. Villarrubia, Alternative human-machine interface system for powered wheelchairs, in: Proceedings of the First IEEE International Conference on Serious Games and Applications for Health (SeGAH), IEEE, 2011, pp. 1–5.

[13] T. Asakawa, K. Nishihara, Operation assistance of a voice-controlled electric wheelchair, in: Proceedings of the International Workshop and Conference on Photonics and Nanotechnology, International Society for Optics and Photonics, 2007, pp. 67942W–67942W.

[14] H. Wang, T. Li, F. Zheng, A wheelchair platform controlled by a multimodal interface, in: Proceedings of the Second International Conference on Information Science and Control Engineering, 2015, pp. 587–590.

[15] A. Ruíz-Serrano, R. Posada-Gómez, A. M. Sibaja, G. A. Rodríguez, B. Gonzalez-Sanchez, O. Sandoval-Gonzalez, Development of a dual control system applied to a smart wheelchair, using magnetic and speech control, Procedia Technology 7 (2013) 158–165.

[16] L. H. Linh, N. T. Hai, N. Van Thuyen, T. T. Mai, V. Van Toi, MFCC-DTW algorithm for speech recognition in an intelligent wheelchair, in: Proceedings of the fifth International Conference on Biomedical Engineering in Vietnam, Springer International Publishing, Cham, 2015, pp. 417–421.

[17] F. Wallam, M. Asif, Dynamic finger movement tracking and voice commands based smart wheelchair, International Journal of Computer and Electrical Engineering 3 (2011) 497.

[18] O. Babri, S. Malik, T. Ibrahim, Z. Ahmed, Voice controlled motorized wheelchair with real time obstacle avoidance, in: Proceedings of the Third International Conference on Communications and Information Technology (ICCIT), IEEE, 2012.

[19] J. Liu, H. Zhang, B. Fan, G. Wang, J. Wu, A novel economical embedded multimode intelligent control system for powered wheelchair, in: Proceedings of the International Conference on Computing, Control and Industrial Engineering (CCIE), volume 1, IEEE, 2010, pp. 156–159.

[20] S. A. M. S. Sheikh, D. R. Rotake, An evolutionary approach for smart wheelchair system, in: Proceedings of the International Conference on Communications and Signal Processing (ICCSP), 2015, pp. 1811–1815.

[21] A. Škraba, R. Stojanović, A. Zupan, A. Koložvari, D. Kofjač, Speech-controlled cloud-based wheelchair platform for disabled persons, Microprocessors and Microsystems 39 (2015) 819–828.

[22] B. A. Hockey, D. P. Miller, A demonstration of a converstionally guided smart wheelchair, in: Proceedings of the SIGACCESS Conference on Computers and Accessibility (ASSETS), 2007, pp. 243–244.

[23] J. Pineau, A. Atrash, R. Kaplow, J. Villemure, On the design and validation of an intelligent powered wheelchair: Lessons from the smartwheeler project, in: J. Angeles, B. Boulet, J. Clark, J. KÃűvecses, K. Siddiqi (Eds.), Brain, Body and Machine, volume 83 of *Advances in Intelligent and Soft Computing*, Springer Berlin / Heidelberg, 2010, pp. 259–268.

[24] A. Murai, M. Mizuguchi, T. Saitoh, T. Osaki, R. Konishi, Elevator avilable voice activated wheelchair, in: Proceedings of The Eighteenth IEEE International Symposium on Robot and Human Interactive Communication(RO-MAN), 2009, pp. 730 –735.

[25] T. Williams, R. Cantrell, G. Briggs, P. Schermerhorn, M. Scheutz, Grounding natural language references to unvisited and hypothetical locations, in: Proceedings of the Twenty-Seventh AAAI Conference on Artificial Intelligence, 2013.

[26] F. Duvallet, M. R. Walter, T. Howard, S. Hemachandra, J. Oh, S. Teller, N. Roy, A. Stentz, Inferring maps and behaviors from natural language instructions, in: Proceedings of the International Symposium on Experimental Robotics (ISER), 2014, pp. 373–388.

[27] S. Png, J. Pineau, Bayesian reinforcement learning for pomdp-based dialogue systems, in: Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2011, pp. 2156 –2159.

[28] F. Routhier, C. Vincent, J. Desrosiers, S. Nadeau, C. Guerette, Development of an obstacle course assessment of wheelchair user performance (OCAWUP): a content validity study, Technology and Disability 16 (2004) 19–31.

[29] R. Megalingam, R. Nair, S. Prakhya, Automated voice based home navigation system for the elderly and the physically challenged, in: Proceedings of the Second International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace Electronic Systems Technology (Wireless VITAE), 2011, pp. 1 –5.

[30] Y. Tao, T. Wang, H. Wei, D. Chen, A behavior control method based on hierarchical pomdp for intelligent wheelchair, in: Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), 2009, pp. 893–898.

[31] B. M. Faria, L. P. Reis, N. Lau, A Methodology for Creating an Adapted Command Language for Driving an Intelligent Wheelchair, Journal of Intelligent Robot Systems (2015) 609–623.

[32] T. Williams, C. Johnson, M. Scheutz, B. Kuipers, A tale of two architectures: A dual-citizenship integration of natural language and the cognitive map, in: Proceedings of the Sixteenth International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS), 2017.

[33] R. Braga, M. Petry, L. Reis, A. Moreira, Intellwheels: modular development platform for intelligent wheelchairs., Journal of Rehabilitation Research and Development 48 (2011) 1061–1076.

[34] M. R. Petry, A. P. Moreira, B. M. Faria, L. P. Reis, Intellwheels: intelligent wheelchair with user-centered design, in: Proceedings of the Fifteenth IEEE International Conference on e-Health Networking, Applications & Services (Healthcom), 2013, pp. 414–418.

[35] A. Murarka, S. Gulati, P. Beeson, B. Kuipers, Towards a safe, low-cost, intelligent wheelchair, in: Proceedings of the Workshop on Planning, Perception and Navigation for Intelligent Vehicles (PPNIV), 2009, pp. 42–50.

[36] B. Kuipers, An intellectual history of the spatial semantic hierarchy, in: M. Jefferies, W.-K. Yeap (Eds.), Robotics and Cognitive Approaches to Spatial Mapping, volume 38 of *Springer Tracts in Advanced Robotics*, Springer Berlin / Heidelberg, 2008, pp. 243–264.

[37] T. Williams, M. Scheutz, POWER: A domain-independent algorithm for probabilistic, open-world entity resolution, in: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2015.

[38] T. Williams, S. Acharya, S. Schreitter, M. Scheutz, Situated open world reference resolution for human-robot dialogue, in: Proceedings of the Eleventh ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2016.

[39] T. Williams, M. Scheutz, A framework for resolving open-world referential expressions in distributed heterogeneous knowledge bases, in: Proceedings of the Thirtieth AAAI Conference on Artificial Intelligence, 2016, pp. 3598–3964.

[40] J. Gundel, N. Hedberg, R. Zacharski, Cognitive status and the form of referring expressions in discourse, Language (1993).

[41] M. Scheutz, G. Briggs, R. Cantrell, E. Krause, T. Williams, R. Veale, Novel mechanisms for natural human-robot interactions in the DIARC architecture, in: Proceedings of AAAI Workshop on Intelligent Robotic Systems, 2013.

[42] G. Briggs, M. Scheutz, A hybrid architectural approach to understanding and appropriately generating indirect speech acts, in: Proceedings of the Twenty-Seventh AAAI Conference on Artificial Intelligence, 2013.

[43] T. Williams, G. Briggs, B. Oosterveld, M. Scheutz, Going beyond literal command-based instructions: Extending robotic natural language interaction capabilities, in: Proceedings of the Twenty-Ninth AAAI Conference on Artificial Intelligence, 2015.

[44] T. Williams, M. Scheutz, Resolution of referential ambiguity in human-robot dialogue using dempster-shafer theoretic pragmatics, in: Proceedings of Robotics: Science and Systems (RSS), 2017.

[45] S. Hemachandra, T. Kollar, N. Roy, S. Teller, Following and interpreting narrated guided tours, in: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), Shanghai, China, 2011.

[46] T. Röfer, C. Mandel, A. Lankenau, B. Gersdorf, U. Frese, 15 years of rolland, in: Festschrift Dedicated to Bernd Krieg-BrÃijckner on the Occasion of his 60th Birthday, 2009, pp. 255–272.

[47] N. Roy, S. Teller, B. Reimer, Y. Battat, F. Doshi, S. Hemachandra, W. Li, J. Velez, The MIT intelligent wheelchair project: Developing a voice-commandable robotic wheelchair, 2011. URL: `rvsn.csail.mit.edu/wheelchair`.

[48] S. M. Hemachandra, Narrated Guided Tour Following and Interpretation by an Autonomous Wheelchair, Master's thesis, Massachusetts Institute of Technology, 2010.

[49] M. R. Walter, S. Hemachandra, B. Homberg, S. Tellex, S. Teller, Learning semantic maps from natural language descriptions, in: Proceedings of Robotics: Science and Systems (RSS), Berlin, Germany, 2013.

[50] R. Ross, H. Shi, T. Vierhuff, B. Krieg-Brückner, J. Bateman, Towards dialogue based shared control of navigating robots, Spatial Cognition IV. Reasoning, Action, Interaction (2005) 478–499.

[51] T. Tenbrink, R. Ross, K. Thomas, N. Dethlefs, E. Andonova, Route instructions in map-based human–human and human–computer dialogue: A comparative analysis, Journal of Visual Languages & Computing 21 (2010) 292–309.

[52] H. A. Yanco, Development and testing of a robotic wheelchair system for outdoor navigation, in: Proceedings of the conference of the rehabilitation engineering and assistive technology society of North America, 2001, pp. 588–603.

[53] M. Tabuse, T. Kitaoka, D. Nakai, Outdoor autonomous navigation using surf features, Artificial Life and Robotics 16 (2011) 356–360.

[54] K. Irie, T. Yoshida, M. Tomono, Outdoor localization using stereo vision under various illumination conditions, Advanced Robotics 26 (2012) 327–348.

[55] W. M. Y. W. Bejuri, W. M. N. W. M. Saidin, M. M. B. Mohamad, M. Sapri, K. S. Lim, Ubiquitous positioning: integrated gps/wireless lan positioning for wheelchair navigation system, in: Intelligent Information and Database Systems, Springer, 2013, pp. 394–403.

[56] M. Scheutz, The inherent dangers of unidirectional emotional bonds between huma ns and social robots, Robot Ethics: The Ethical and Social Implications of Robotics (2011) 205.

[57] R. Poppe, A survey on vision-based human action recognition, Image and vision computing 28 (2010) 976–990.

[58] C. Lee, S. Jung, K. Kim, D. Lee, G. G. Lee, Recent approaches to dialog management for spoken dialog systems, Journal of Computing Science and Engineering 4 (2010) 1–22.

[59] Y. Zhang, J. Zhang, Y. Luo, A novel intelligent wheelchair control system based on hand gesture recognition, in: Proceedings of the IEEE/ICME International Conference on Complex Medical Engineering (CME), IEEE, 2011, pp. 334–339.