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Designing Information Gathering Robots for Human-Populated Environments

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Abstract— **Advances in mobile robotics have enabled robots that can autonomously operate in human-populated environments. Although primary tasks for such robots might be fetching, delivery, or escorting, they present an untapped potential as information gathering agents that can answer questions for the community of co-inhabitants. In this paper, we seek to better understand requirements for such information gathering robots (InfoBots) from the perspective of the user requesting the information. We present findings from two studies: (i) a user survey conducted in two office buildings and (ii) a 4-day long deployment in one of the buildings, during which inhabitants of the building could ask questions to an InfoBot through a web-based interface. These studies allow us to characterize the types of information that InfoBots can provide for their users.**

I. INTRODUCTION

Autonomous mobile robots are starting to enter human environments. The last decade has witnessed some of the early instances of long-term robotic autonomy, such as the CMU CoBot robots [1], [2], as well as the launch of commercial systems such as the SaviOne hotel delivery robot and Vecna hospital medication delivery robot, among others [3]–[5]. Even though these robots lack in manipulation capabilities, they provide services such as fetching and delivering items, providing tours as a museum guide [6], escorting people to unknown destinations [1], or giving directions in a shopping mall [7]. Despite the ability of autonomous mobile robots to continuously stream data from on-board sensors, the potential for using these robots as information gathering agents has not yet been thoroughly explored. In this paper we seek to understand the role of such information gathering robots ("InfoBots") and to gather requirements from potential users to inform the design of InfoBots.

The use of robots for information gathering is not a new idea. Outdoor mobile robots including ground, aerial, and underwater robots have been used for search and rescue missions [8], as well as space and oceanic frontier exploration [9], [10]. However, the use of indoor mobile robots for similar purposes has remained unexplored. Such robots could respond to questions (e.g. "Is my advisor in her office?") or requests (e.g. "Let me know when my advisor arrives in her office.") of building occupants. They could also monitor the state of building and report unusual events (e.g. open office door at 2am) or maintenance needs (e.g. broken lightbulbs).

One way to gather information without physically going to the locality of the information is to use a telepresence robot [11]. This solution does not provide strong productivity benefits, as it requires the user to actively control the robot. A different solution includes stationary cameras installed in the environment [12]; however, this requires modifications to the environment, cannot provide full coverage of the environment with high-density information, and presents greater privacy and security concerns than InfoBots. Moreover, InfoBots could carry out other tasks like fetch-and-delivery simultaneously with information gathering tasks.

Motivated by this potential, we seek to better understand the value proposition for InfoBots, characterize the types of information they can realistically provide, and gather requirements that would inform their design. To that end, this paper presents findings from two studies: (i) a user survey that was administered in two different office buildings, and (ii) a deployment of a semi-supervised InfoBot in one of those buildings.

II. RELATED WORK

The idea of gathering information with robots has been widely explored in domains where the locality of the information is difficult or dangerous to access by humans, such as space, underwater, and war or disaster zones. While most of this work focuses on enabling applications in challenging problem domains [8]–[10], [13], other work aims to develop general algorithms for information gathering [14]–[17]. Information gathering in human populated environments is largely unexplored.

Other related work is centered around mobile robots in human-populated environments. Researchers have explored social navigation algorithms that consider humans around the robot [18]–[20], following humans [21], escorting humans [1], and walking side-by-side with humans [22]. Some looked into exploiting human assistance as part of their tasks [2]. Others in the human-robot interaction community provided observations from studies involving a delivery robot in a hospital [23], a fetch-and-deliver robot assisting people with motor impairments [24], and social mobile robots assisting humans at a shopping mall [7], among others. Finally, the CMU Roboceptionist project involved a stationary robot that provides information from a database to visitors at a campus reception [25], [26].

A large body of work on mobile robots focuses on the object search problem in indoor settings [27]–[31]. Some researchers aim to give robots a human-like understanding of the environment to support active information acquisition [27], [29], [32]. Others focus on object detection and recognition in cluttered environments [31], possibly using the web to teach the mobile robot how to find objects

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[30]. While object search can be considered as an instance of information gathering in human environments, our work expands the definition of InfoBots, characterizes different types of information gathering tasks, and focuses on a particular type that is distinct from object search. Furthermore, unlike most previous work, our work approaches the problem from the end-user perspective by studying the value of and requirements for InfoBots.

Our work can also be compared with activity monitoring and surveillance research [33]–[37]. Surveillance systems can be effective when users are interested in monitoring a pre-determined set of locations. In contrast, mobile robots have ability to cover large spaces and observe the environments from viewpoints unavailable to fixed cameras, offering a richer and more adaptive information gathering service. In addition, their embodiment provide a natural way to address privacy concerns by potential users and bystanders [38].

III. Information Gathering in Human Environments

Human activity makes indoor environments dynamic. People constantly move around and change the state of the environment through their interactions with it. The more populated the environment, the more difficult it is to predict its state at a given time. Since many human tasks depend on accurate knowledge of the state of the environment, a large part of our daily tasks involve gathering information. The idea explored in this work is to design a service to which users can outsource information gathering tasks. We aim to provide that service with autonomous mobile robots.

A. Information Gathering Task Types

We categorize information gathering tasks into four types:

- *Checking* involves going to a particular location and reporting specific information about the current state of the world.
- *Searching* involves going to multiple candidate locations until a specific type of information is captured, and then reporting the location.
- *Monitoring* involves going to a particular location and waiting until a particular state change information is captured, and then reporting the time of occurrence of the event.
- *Summarizing* involves passively gathering information at an arbitrary location or while traveling along different locations for other tasks, and then providing an cumulative report of salient information (states or state change events).

Among the four task types that cover wide-range of services that InfoBots could provide, our work focuses on information *checking* tasks. Questions suitable for the checking tasks are primarily constrained by the locality of the answer and the robot's ability to capture the answer within its sensory horizon.

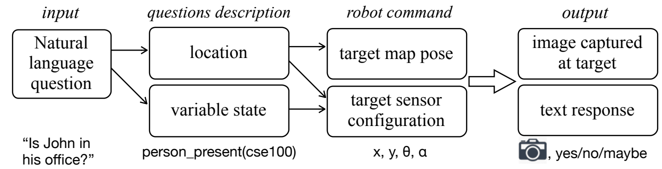

Fig. 1. Illustration of the information checking framework. The solid arrows represent the input processing steps the hollow arrow represent the step involving physical robot actions (e.g. navigation) that produces the outputs.

B. Information Checking Framework

We operationalize information checking tasks as answering questions about the environment (Fig. 1). We represent the environment (e.g. a building) as a collection of *locations* (e.g. cse100, cse101, ...) at some predefined level of abstraction (e.g. room). The locations have *location attributes* (e.g. John's office, seminar room 101) and *variable states* (e.g. person present/not present, room occupied/not occupied). The location attributes can be used to identify a corresponding location. The variable states are dynamic and their value at any given time is unknown to remote users; therefore, questions are assumed to be about the variable states of locations.

The input to the system is a user question and the output is an answer or a sensory recording that contains an answer. First, the location and the variable state that best describe the given question are identified by a set of location attributes. The identified location and variable state specify a target map pose and a target sensor configuration required to capture the requested information. The robot navigates to the target pose, configures sensors to the target configuration, and takes a sensor recording (e.g. an image). Finally, the system returns the sensor recording or inferred answer from the sensor recording to the user.

IV. Requirements for InfoBots

The primary stakeholders of InfoBots are the users requesting the information. Meeting their requirements is critical for the actual adoption of InfoBots. Hence, our requirement gathering efforts are focused on those users. Nonetheless, the views of the bystanders, particularly those about whom information might be requested, are also important. We come back to considerations about these secondary stakeholders in Sec. VI.

A. Survey Design

We created a survey with two aims: (i) determining the types of information that would be most useful and (ii) identifying constraints and requirements for how information would be requested and provided. To inform this survey with a list of questions that people might be interested in asking InfoBots, we conducted semi-structured interviews with 8 participants (4 M, 4 F, ages 24–70) from the Computer Science & Engineering building at our institution. The following information checking requests were most commonly mentioned in these interviews:

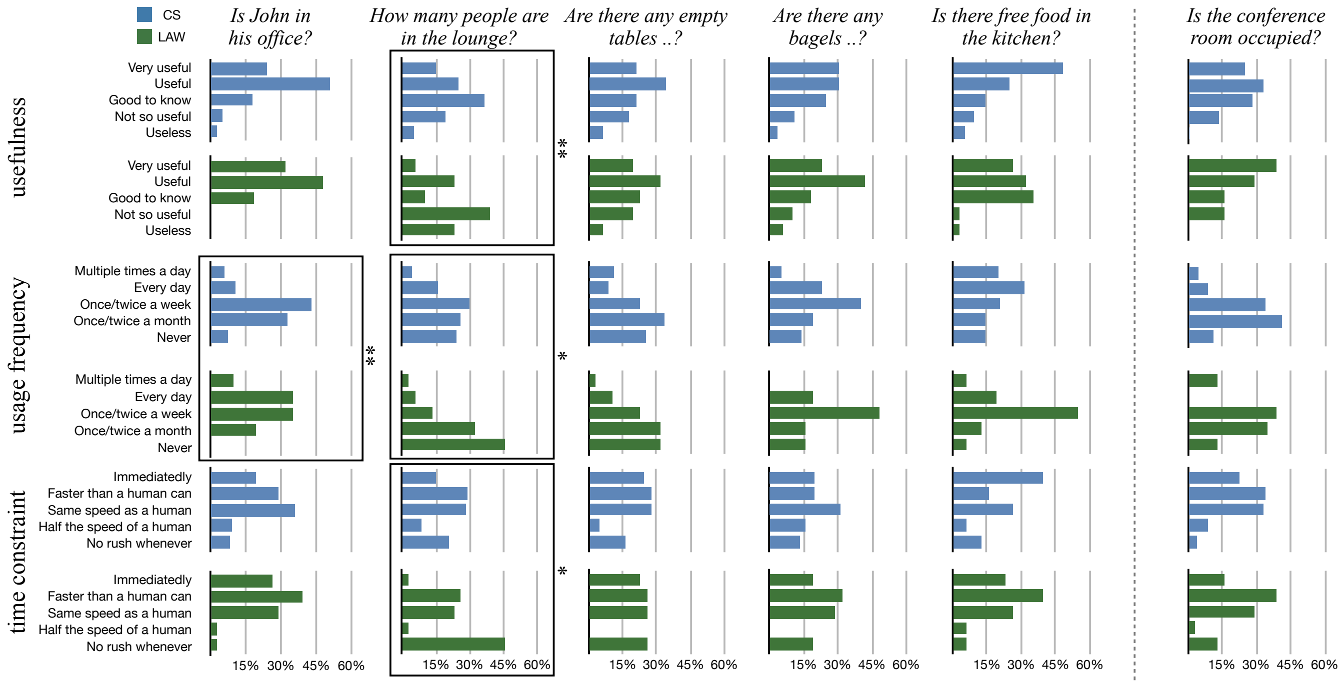

Fig. 2. Multiple choice survey results. The results are organized by example information check question (column), survey question type (row), and population (color). Each plot represents the response distribution of the corresponding survey question. Pairs of CS and Law results that are significantly different are marked with boxes; (*) and (**) denote $p < .05$ and $p < .01$, respectively.

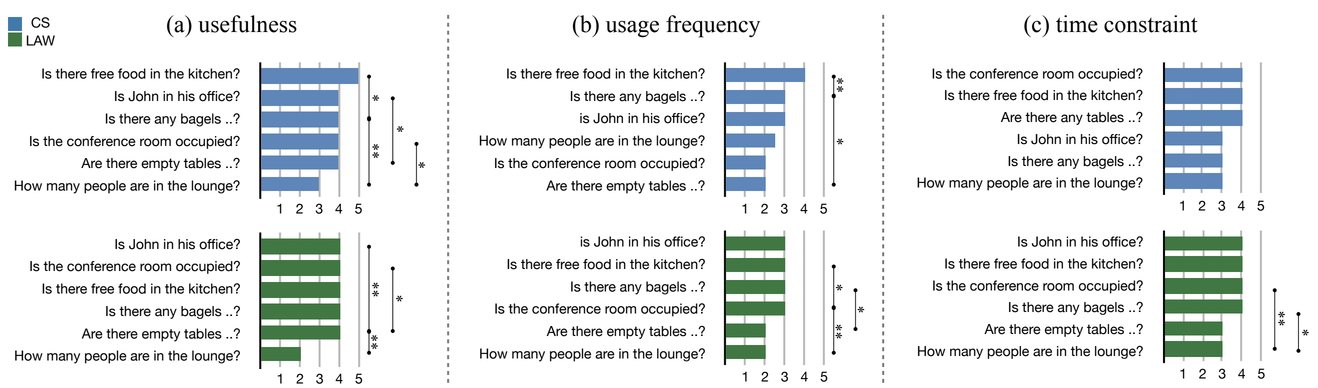

Fig. 3. Responses to sample information check questions sorted by median. The response distribution mean was used to break ties. (*) and (**) denote $p < .05$ and $p < .01$, respectively. The results are organized by survey question type (column), and population (color).

- *Is John in his office?*
- *How many people are in the lounge?*
- *Are there any empty tables in the study room?*
- *Are there any bagels at the coffeeshop?*
- *Is there free food in the kitchen?*
- *Is the conference room occupied?*

After introducing the idea of InfoBots, our survey presents these six information requests and asks the following multiple-choice questions regarding usefulness, usage frequency, and time constraints for each request:

- The ability to ask this type of question would be [5: Very useful, 1: Useless]
- I would ask this type of question [5: Multiple times a day, 4: Every day, 3: Once/twice a week, 2: Once/twice a month, 1: Never]
- I would require a response [5: Immediately, 4: Faster than human, 3: Same speed as human, 2: About half the time as human, 1: No rush]

The help text for each question indicates that the given question is just an example and that their response should address the category of questions similar to the particular example. In addition, an open-ended question asks for instances of other similar requests the users might have.

B. Findings

We administered our survey to occupants of two buildings at the University of Washington: Computer Science & Engineering (CS) and Law School (Law). We scouted both buildings before instantiating the example questions to make sure the questions are meaningful and accurate. We advertised the survey through mailing lists targeting undergraduate and graduate students, faculty, and staff. We received 80 responses from the CS (23 M, 25 F, 32 unspecified, age range 18–65 with mean 29.46 and standard deviation 11.64) and 31 responses from the Law (10 M, 11 F, 10 anonymous, age range 29–68 with mean 48.26 and standard deviation 12.42).

Fig. 2 summarizes the responses from the multiple choice part of the survey. To compare the differences between response distributions from CS and Law, we ran Wilcoxon-Mann-Whitney tests on 18 CS and Law response distribution pairs (three question types $\times$ six sample questions). We found four significantly different pairs (shown in Fig. 2). An analysis of differences among responses to different information request types is presented in Fig. 3. We make the following observations.

Usefulness. The results indicate that people think InfoBots can be useful. On average 84% of CS respondents and 79% of Law respondents thought that the answer to a state check question would be "Good to know" or better ("Useful," "Very useful"). Among the six questions, the one for checking the presence of a person and the one asking about the availability of food placed in the top three for both CS and Law (Fig. 3 (a)). The question that was rated as "Useless" the most times was the one asking about the number of people in a room.

Usage frequency. The usage frequency results were lower in scale than the usefulness results. Respondents considered the questions useful even though they anticipated asking them infrequently. For example, more people indicated that they would "Never" ask a question (CS: 16%, Law: 19%) than they indicated the question as being "Useless" (CS: 4%, Law: 6%). This is a positive finding as the robot serving a whole community of residents would not be able to handle high frequency requests from individual users.

Time constraints. Respondents had high expectations in terms of the response speed. 49% of CS respondents and 52% of Law respondents wanted a response "Immediately" or "Faster than a human can". 30% of CS respondents and 27% of Law respondents wanted a response at the "Same speed as a human". These requirements are currently unrealistic even if an InfoBot were serving a single user. Nonetheless, this shows that (i) there are some questions that people are okay with getting a response to in human-speed or slower, and (ii) some people are willing to wait longer for certain questions.

Variance across buildings. Responses from the two buildings were not significantly different for most questions. While this suggests that the role of InfoBots might not vary too much across different buildings, culture and workflow of different buildings might impact usage of InfoBots. For instance, our survey indicated that the ability to check whether someone is in their office would be used significantly more frequently in the Law building than the CS building.

V. Deployment of InfoBots

Our survey indicated that InfoBots might provide a useful service; however, what people say does not always match what they actually do. This is particularly true for robotic services since most people do not have experience with them [39]. To study the practical usage of InfoBots, we deployed a semi-supervised InfoBot in the computer science building where the survey was conducted.

A. Robot and Web Interface

Our InfoBot is based on MetraLabs Scitos G5 mobile base [40], expanded with a structure providing support for sensors and user interface devices. It is equipped with Allied Vision Manta G609 camera on a tilt unit for data collection, two Asus Xtion Pro depth cameras (one forward and one backward facing) and Hokuyo UTM-30LX laser range finder for navigation, and an LCD display and speakers for communicating its intent.

The front-end of our system is a web interface organized as a feed of questions posted by users (Fig. 4). To collect unconstrained natural questions, we let users post free-form questions using the text field. When a user submits a question, they could choose whether a question should be visible to all users ("public" mode), whether notification emails should be sent as status updates, and a timeout for when the answer would no longer be needed. Once a question is submitted, it is placed in the user's private feed with the service status, as well as in the public feed if the question was in the public mode. Public questions have a "comments" panel and a "Thank you robot" button.

The robot and the web interface are connected by a back-end system supervised by a human operator. This system monitors user activities and alerts the operator when a question is posted. The supervision interface allows the operator to accept or reject a questions, move the mobile base, play sound files, display messages on the LCD display, and post a response to the question. It also visualizes the data from the on-board sensors (e.g. images from a camera).

B. Experiment Procedure

Our system was deployed for four business days (9am to 5pm). We recruited users by emailing graduate student, undergraduate student, staff, and faculty mailing lists. In the recruitment email, we provided a brief introduction of the information gathering service and the service website address. In addition to the recruitment email, we displayed posters containing a picture of the robot and the service website address on multiple bulletin boards in the building. To prevent non-residents from signing up for the service, the system only allowed people with a valid computer science email account to sign up.

When a user asked a question on the website, the operator received a question and decided to accept or reject the question. The operator was instructed to only accept the checking type questions that could be answered by analyzing a static image from the robot visiting a location in the building. After the operator made an acceptance decision,

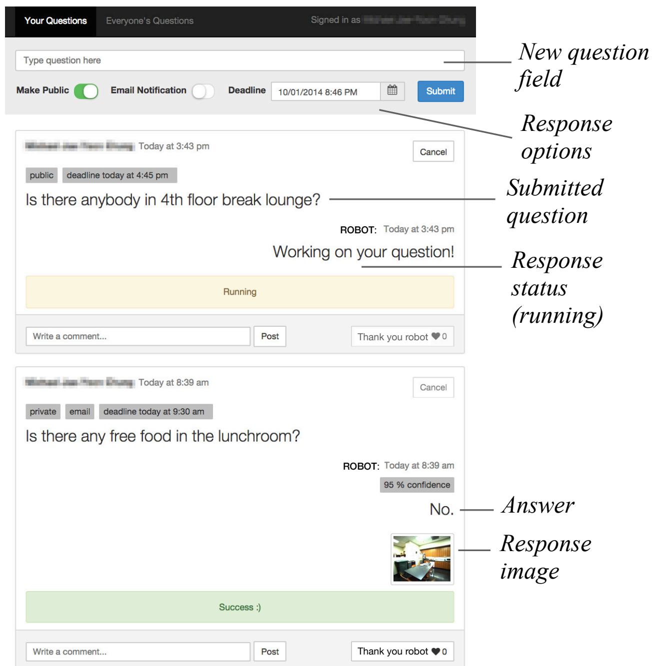

Fig. 4. InfoBot front-end web interface.

TABLE I

QUESTION TYPES

Information Gathering Task Types	deployment	post-survey
checking	70 (80%)	18 (78%)
non-checking	18 (20%)	5 (22%)
total	88	23
Checking Task Types ($\kappa = 0.89$)	**deployment**	**post-survey**
presence	53 (76%)	10 (56%)
state	17 (24%)	8 (46%)
total	70	18
Presence Targets ($\kappa = 0.93$)	**deployment**	**post-survey**
person	32 (60%)	4 (40%)
food	11 (21%)	5 (50%)
mail	4 (6%)	1 (10%)
other	7 (13%)	0
total	54	10

TABLE III

DEMOGRAPHICS

Job Titles	# of users	# of questions	avg. questions per user $\pm$ std.
faculty/staff	16	33	2.06 ± 0.93
graduate	20	44	2.20 ± 2.04
undergraduate	9	11	1.22 ± 0.67
total	45	88	1.95 ± 1.5

they supervised the robot to go to the target location in the building, position the camera, and save an image from the camera. Subsequently, they answered the question by only looking at the acquired image, and then updated the web interface with the answer and image. To communicate the robot's intent to bystanders, the operator displayed the message, "Working on behalf of {username} on question {question}" on the LCD display while the robot was navigating. Additionally, when the robot arrived at its destination, it verbalized the message through the on-board speaker using text-to-speech with a male voice.

At the end of the forth day, we sent a short questionnaire to users who asked at least one question. This questionnaire asked participants about their experience with the InfoBot service, their satisfaction with the service, and their likelihood of using the InfoBot when it becomes permanently installed in the building. In addition, the questionnaire asked for open-ended feedback.

C. Findings

Question types. Over the course of the four days when the service was available, a total of 88 questions were posted. The "deployment" column in Table I summarizes distributions of these questions. During the experiment, the operators categorized the questions into two groups, checking and non-checking (search, monitor and summarization questions or non-questions, Sec. III-A). 80% of the total questions were of the checking type, which the operator accepted, and the other 20% (non-checking questions) were rejected. In the latter case, the operator posted "This question is not for me" as a response.

Questions in the checking category were further grouped into two categories: *presence* (76%) and *state* (24%). Two authors coded 70 checking questions and measured inter-coder agreement using Cohen's κ (0.89). The most common presence type checking questions were "Is there anyone in {location}?" and "Is {person} in his/her office?" (Table II, 1–2). We further categorized presence by its target objects; two authors coded 53 questions and measured inter-coder agreement using Cohen's κ (0.93). Although there were more than 20 target object categories, only three objects (person, food, and mail) appeared more than once. We merged the other target object categories into a new category called "other." Out of all presence questions about objects, users asked most about the presence of food and mail, e.g. "Is there any food in the downstairs kitchen?" and "Is there anything in my mailbox?" (Table II, 3–4). For the state type checking questions, we observed a wide variety of questions ranging from checks about the accessibility of services (e.g. "Is the door to the conference room open?" and "Is the reception still open?") to noise conditions (e.g. "How noisy is it in the atrium right now?") or weather conditions (e.g. "Is it raining outside?") (Table II, 5–8).

The non-checking category included both search (Table II, 9–10) and monitoring (Table II, 11) type questions. Several questions in the *other* category were clearly submitted with the purpose of challenging the system (e.g. "What do you look like?" and "Are there any mirrors in the building?") or simply as jokes (e.g. "Who let the dogs out?") (Table II, 12–14). Such requests were rejected by the operator.

Demographics. Table III presents the general statistics of the service usage. We identified three groups of users based on their occupation: faculty/staff, graduate students, and undergraduate students. Although the number of graduate students

TABLE II
SAMPLED QUESTIONS FROM DEPLOYMENT EXPERIMENT

	questions	information gathering task type	checking task type	targets
1.	"Is there anyone in {location}?"	checking	presence	person
2.	"Is {person} in his/her office?"	checking	presence	person
3.	"Is there any food in the downstairs kitchen?"	checking	presence	food
4.	"Is there anything in my mailbox?"	checking	presence	mail
5.	"Is the door to the conference room open?"	checking	state	N/A
6.	"Is the reception still open?"	checking	state	N/A
7.	"How noisy is it in the atrium right now?"	checking	state	N/A
8.	"Is it raining outside?"	checking	state	N/A
9.	"Is there an empty conference room in the Computer Science building?"	other	N/A	N/A
10.	"Has {person} arrived yet today in the CS building?"	other	N/A	N/A
11.	"Which meeting room has the best visibility of the {landmark} today?"	other	N/A	N/A
12.	"What do you look like?"	other	N/A	N/A
13.	"Are there any mirrors in the building?"	other	N/A	N/A
14.	"Who let the dogs out? :)"	other	N/A	N/A

or faculty/staff is much smaller than that of undergraduate students, graduate students and faculty/staff used the service more often. This can be explained by the fact that users in these groups spend more time in the building and therefore were more likely to perform everyday tasks in the building.

Post-deployment survey. Among 45 users who asked at least one question on the website, 20 users participated in the post survey. 12 respondents reported the InfoBot actually answered their questions, and 7 respondents reported the answer returned by the InfoBot was actually useful. Two respondents reported that the InfoBot was not answering their questions because it replied with "This question is not for me.' This happened because they were not asking the checking type questions. Two respondents mentioned that while the InfoBot's text answer did not answer their question, they could extract the answer from the associated image.

We asked about the users' satisfaction with the Infobot's answers and its response speed (Fig. 5). In terms of satisfaction with the answer, the majority (84%) were "Neutral" or better ("Satisfied", or "Completely satisfied"). In terms of satisfaction with the response speed, only 5% of the users were "Not at all satisfied" despite their initial high expectation (Sec. IV-B). More than half of respondents (53%) were interested ("Interested" or "Definitely interested") in using the system if the InfoBot became permanently deployed (Fig. 5 (c)). In the last part of the survey, we asked what questions users would ask if the InfoBot were permanent. To compare questions listed in response to this survey and questions asked during the deployment, we categorized them in the same manner as we did with the deployment questions. The result is shown in Table I "post-survey" column. We observed that around 20% of the new questions were still non-checking questions. Among the new checking questions, the percentage of the *state* checks was almost doubled (from 24% to 46%) as compared to state check questions that were actually asked during the deployment.

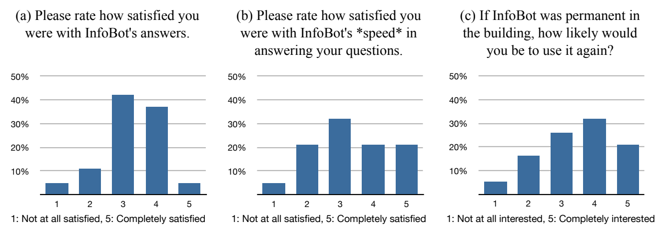

Fig. 5. Post survey results.

VI. DISCUSSION

A. Non-checking Information Gathering Types

Even though our study was focused on *checking* type questions, our studies indicated that other types of questions might be useful. During the deployment, despite the fact that non-checking type questions were rejected, users still asked those questions. For example, users made *search* requests such as "Is there an empty conference room in the Computer Science building?" and "Which meeting room has the best visibility of Mount Rainer today?". We also observed *monitoring* type questions, such as "Has {person} arrived yet today in the CS building?" One respondent described desired *summarization* capabilities:

> *I would love to be able to ask about current building statistics, such as what lights are on/off, which projectors are powered on/off, what the building internet up/down bandwidths currently are, current temperature(s) are, power usage, water usage, etc... Also, if the robot could do some kind of mood recognition whenever it saw a face, like "happy" or "sad", being able to ask about how the average mood in the building is today would be really cool.*

As in this example, many others wanted a system that combines the ability to check local state with other types of information that is already available through other sources, such as seminar schedules, weather, or nearby coffee shop.

B. Limitations

Although our studies indicated that building occupants found InfoBots to be useful, the influence of the novelty effect in these results cannot be disregarded. The duration of our deployment was not long enough for such effects to diminish.

During our deployment, the building occupants who were the subjects of the requested information seemed to be mostly amused. We consider these to be the result of the novelty effect. Some expressed they would rather be asked a question instead of their picture being taken. Besides these informal observations, our work did not systematically explore the attitudes of secondary stakeholders, including bystanders.

We have not explored any potential variations of the user interface for the primary users. We used a fixed user interface set up–our choice of using web interface consisted of free form text input and text and image response, as well as email notification–to conduct a consistent experiment. In the open-ended feedback on the post-deployment survey, some commented on interface elements and requested more feedback about the InfoBot's progress after submitting a question (current question queue or estimated time of response).

C. Comparison with Surveillance Systems

There were a total of 70 checking questions involving 39 unique locations. Considering this number, creation of a surveillance system by installing a camera at every unique location is not practical. Although it might be plausible to install a large number of cameras given the price of cameras today, this would present privacy concerns that are more serious than those associated with Infobots.

D. Privacy Concerns

During the deployment experiment, we aimed to make the information gathering service provided by the mobile robot as similar as possible to a human gathering the information themselves. We displayed the name of the person for whom the robot was gathering information (Sec. V-B) and announced the question before taking the picture. We plan to further explore the strategies for mitigating privacy concerns with using the robot's embodiment to communicate the primary user's intent.

E. Towards Autonomous InfoBots

A critical question is whether it would actually be realistic to build an autonomous InfoBot that can provide the information gathering service studied in this paper. We believe that recent advances in robot navigation, semantic mapping, natural language processing, and computer vision strongly support this possibility. Our follow up work beyond what is presented in this paper has demonstrated the feasibility of longer term deployments and our future work will further explore different information gathering tasks in human-populated environments with fully autonomous systems.

VII. Conclusion

This paper investigates the potential of autonomous mobile robots as information gathering ("InfoBots"). We present a survey that shows promise in terms of usefulness of InfoBots and identifies system requirements. We also present findings from a short-term deployment of an InfoBot indicating that the information gathering tasks requested by users are suitable for a mobile robot implementation and can be realized in practice despite the constraints of robotic systems. Our paper contributes a categorization of information gathering task types, a framework for information checking robots, survey findings on people's expected usage of InfoBots, and empirical findings of people's actual usage of InfoBots. These inform the design and implementation of future autonomous InfoBots.

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