Personalized Guided Tour by Multiple Robots through Semantic Profile Definition and Dynamic Redistribution of Participants

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Abstract

Existing robot guides are able to offer a tour of a building, such as a museum, bank, science center, to a single person or to a group of participants. Usually the tours are predefined and there is no support for dynamic interactions between multiple robots.

This paper focuses on distributed collaboration between several robot guides providing a building tour to groups of participants. Semantic techniques are adopted in order to formally define the tour topics, available content on a specific topic, and the robot and human profiles including their interests and content knowledge. The robot guides select different topics depending on their participants' interests and prior knowledge. Optimization of the topics of interests is achieved through exchange of participants between the robot guides whenever in each others neighborhood. Evaluation of the implemented algorithms presents a 90% content coverage of relevant topics for the individual participants.

Introduction

Applications supporting multiple robots require the simultaneous achievement of complex interdependent tasks. Such systems focus on techniques related to distributed robot coordination and task allocation. The individual robots should be able to execute several tasks independently and optimize the task execution through seamless collaboration with other robots. These autonomous robot interactions require exchange of context between the robots. The robot context is defined as the dialog between the robot and its participants such as visited places and personal details.

Emerging trend is the use of ontologies to define context in a formal way. The resulting semantic robot profile specifies a vocabulary that can be used during the robot interactions. Example of such profile is the Robot Ontology for Urban Search and Rescue (Schlenoff and Messina 2005) capturing relevant information on robots and their capabilities within a search and rescue emergency scenario. The ontology in (Amigoni and Neri 2005) focuses on exploiting models in the activities of a multi-robot system such as the possibility of a robot to pass through a door, rotate on the spot, and park depending on the described robot' capabilities and required tasks. A challenge is an optimal selection of the relevant information minimizing the amount of data exchanged between the robots.

The scenario of a robot tour guide requires one robot leading a group of participants. Mimicking a real person, the robot should be able to engage its public providing personalized content depending on the participants interests.

This paper focuses on the distributed collaboration between multiple robot guides providing a building tour for their participants. Several tour topics each having content on multiple locations are defined using semantic description languages such as ontologies. The ontologies enable definition of user (human and robot) profiles including interesting topics and acquired content knowledge on them. The robot guides select a specific topic to talk on depending on the participants' interests and their prior knowledge. Novelty of the paper is the focus on the optimal exchange of information between the robots. Ontologies define a common language for multi-robot interaction enabling a minimal selection of new information exchanged between the robots. The content delivery is optimized through the autonomous transfer of participants by the robots whenever they are in each others neighborhood. In this way the robots can but are not required to possess the same knowledge and are able to learn from one another. Evaluation of the implemented content delivery and optimization algorithms presents a 90% content coverage of topics of interests for the individual participants.

Related Work

The concept of a robot tour guide is not a new one. The Minerva tour guide (Thrun et al. 1999) was successfully exhibited in a Smithsonian museum focusing on safe navigation in unmodified and dynamic environments, and short-term human-robot interaction. In (Rosenthal and Veloso 2010) a companion robot (CoBot) escorts a visitor around a building and performs tasks such as schedule notifications, directions to locations, information on points of interest, fetching of water and coffee. Humanoid robots such as TOURBOT (Trahanias et al. 2005) and Robotinho (Faber et al. 2009) adopt the use of facial expressions. Robotinho interacts with people using multiple modalities such as speech, emotional expressions, eye-gaze, and human-like arm and head gestures. Similar to CoBot it supports omnidirectional walking, self-localization, mapping, obstacle avoidance, and path planning. In addition to on-site museum and exhibition tours, TOURBOT offers guided tours to Web visitors. Operating as the user's avatar, the robot accepts commands over the Web that direct it to visit specific exhibits communicating the imaged scenes.

The Santander Interactive Guest Assistants (SIGA) by YDreams (YDreams 2010) guide visitors to their destination. The bots use RFID tags, gyroscopes, and odometers to determine their position and 16 sonar sensors to locate objects (such as the human they are guiding) while they move. RFIDs and a wireless sensor network are adopted by (Chen 2007) supporting tours by multiple robot guides. The independent tour groups consist of a robot guide and several participants following their leader. A group guiding protocol uses sensor nodes to track leaders' locations and maintain paths from members to leaders. A member may ask where his/her leader is, and a leader may 'recall' his/her members.

A greater challenge is supporting robot interactions enabling the execution of common tasks. Several centralized approaches exist for selecting the best robot to execute a specific task. The network robot platform in (Nakamura et al. 2008) determines the most suitable robot for executing a specific service by comparing information on users, robots and services. An area management gateway controls the service execution by coordinating the robots in performing interdependent tasks. The approach in (Lundh, Karlsson, and Saffiotti 2008) automatically generates a functional configuration of a network robot system to perform a given task. The solution requires actual deployment of the configured application on the robotic network activating the necessary functionalities and setting up the channels between them.

Important aspect of the coordination of multiple robots is area partitioning. In (Ahmadi and Stone 2006) and (Jager and Nebel 2002) while the robots are performing continuous area sweeping respectively cleaning tasks, adaptive negotiation methods dynamically partition the area.

The proposed tour planning algorithm in this article partitions a building by optimizing the content delivery by multiple robots while minimizing the crossing of paths. The robots personalize the guided tour for their respective groups of participants. The constructed guided tour ontologies define user profiles including topic interests and prior knowledge that is updated during the tour. The robots optimize the delivery of content in order to engage as much of the participants as possible and at the same time show the building. The amount of received content is increased through the automatic exchange of participants between the robots whenever they are in each others neighborhood and decide that a different guide can provide for more interesting content to certain participants. We focus on a minimal selection of the relevant data to exchange, that is enough to reproduce the same information on the other robots.

Architectural Components of the Robot Guide

The main objective of this research is the design and implementation of strategies supporting a multi-robot guided tour for groups of participants. Through the distributed interactions between the robots, information on several topics (architecture, history, research, etc) of a building is provided. The discussed topics are selected depending on the participants' prior knowledge and interests covering as much building area as possible reducing the chances of meeting each other. During the tour, robots exchange context on their participants, the provided tours and if necessary swap participants if they can benefit from more interesting topics.

The developed algorithms are implemented on the CoBot (Licitra 2011). CoBot autonomously localizes and navigates in a multi-floor office environment while avoiding obstacles (Biswas and Veloso 2011). It carries a variety of sensing and computing devices, including a camera, a Kinect depth-camera, a Hokuyo LIDAR, a touch-screen tablet, microphones, speakers, and wireless communication.

The main building blocks of the proposed approach are presented by the layered design in Figure 1. At the lowest level resides the *Inference Engine*, capturing the robot and user profiles in an ontology and inferring new knowledge from their interactions. These semantic definitions are encapsulated by corresponding objects in the *Semantic Concepts* layer (locations, topics, robots and tour participants). This additional object layer on top enables switching between different ontologies modeling users, robots, tours which requires updating only these specific objects without affecting the rest of the implementation. The actual planning algorithm for the guided tour is implemented by the *Tour Planner* which invokes the *Robot Collaboration* component responsible for the communication between the different robots. The whole is enhanced with a *Robot Guide Interface* that visualizes the robot and participants' profile, and provided tours and enables the manual adaptation of the robot profile and the addition/deletion of participants.

Ontological Guided Tour Definition

As the guided tour is rather information intensive it requires capturing the gathered knowledge and interactions between the different parties in a machine-processable common vocabulary also known as an ontology. A typical ontology language is OWL (Web Ontology Language) (McGuinness, Van Harmelen, and others 2004), which is a well-defined vocabulary for describing a domain having a foundation in description logics. An OWL ontology is created using the Protégé Editor (Stanford 2011). This editor provides sup-

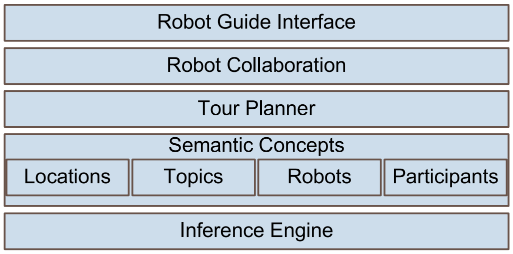

Figure 1: Main architectural components enabling the collaboration between multiple robot tour guides.

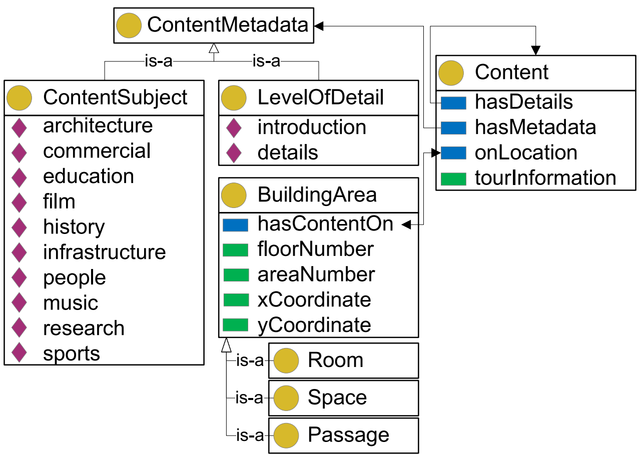

Figure 2: Semantic representation of content on a specific subject at a location with certain level of detail.

port for OWL, RDF (Resource Description Framework) and XML Schema making it possible to easily design ontologies through a graphical interface. Additional knowledge is captured using SWRL (Semantic Web Rule Language) expressions and built-ins (SWRLB) such as comparisons (equal, less/greater than), math functions (add, subtract, multiply, divide) (Horrocks et al. 2004). SWRL expressions are used for coding procedural relations in the form of rules.

Our approach captures the required guided tour concepts into a robotics OWL ontology. Figure 2 illustrates the definition of a *Content* concept at a *Location* on a specific *Subject* having certain *Level Of Detail* and possibly having additional details. The *Content Subject* covering topics such as architecture, history, and research, defines the robot's and person's interests. Based on the *Level Of Detail*, *introduction* or *details*, the robot provides new information whenever it passes through the same *Location* using the *hasDetails* property of the *Content*. The actual information as provided by the robot is defined by the *tourInformation* property.

The following example defines *introductory content* on the 'Robotics lab' having additional details on 'Robotics people' and 'Robotics projects'. It is classified as a *research subject* at *office* 'Office-7412'.

```
'Robotics lab'
        hasDetails 'Robotics people', 'Robotics projects'
        hasMetadata 'introduction'
        hasMetadata 'research'
        onLocation 'Office-7412'
        tourInformation "Research on the scientific and
        engineering challenges of creating teams of
        intelligent agents in complex, dynamic, and
        uncertain environments."
```

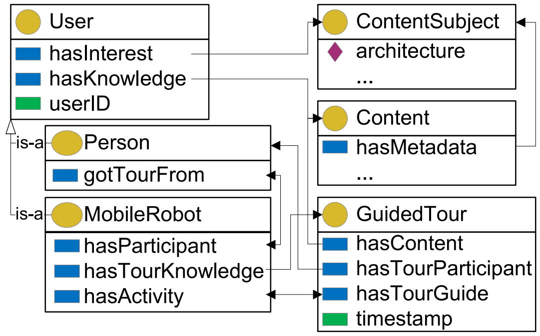

Figure 3: Relationships between tour guides, participants and a specific tour.

When a robot talks on a specific content, a *Guided Tour* concept is created (Figure 3), consisting of this *Content*, the robot *tour guide* and its *participants* and a *timestamp*. The example below defines a 'Robotics tour' on the 'Robotics lab' covered by 'CoBot 1' having 2 participants.

```
'Robotics tour'
        hasContent 'Robotics lab'
        hasTourGuide 'CoBot 1'
        hasTourParticipant 'Anna','Carlos'
        timestamp "2011-12-18T07:30:00"
```

Instead of explicitly specifying the tour guide and participants we define the tour's *hasTourGuide* property as an inverse property of the robot's *hasActivity*. The **Inference Engine** will automatically infer that if *hasActivity(CoBot 1, Tour A)* then *hasTourGuide(Tour A, CoBot 1)*. The tour's *hasTourParticipant* is inferred through the following SWRL rule stating that a tour participant is a participant of a robot giving tour on a specific topic.

```
MobileRobot(?robot), GuidedTour(?tour), User(?user),
hasActivity(?robot, ?tour),
hasParticipant(?robot, ?user)
-> hasTourParticipant(?tour, ?user)
```

As the robots provide content depending on their participants' knowledge, it should be possible to query for previously acquired data. In order to infer this information a rule stating that a tour participant has knowledge on the content of the tour is defined.

```
GuidedTour(?tour), User(?user), Content(?content),
hasTourParticipant(?tour, ?user),
hasContent(?tour, ?content)
-> hasKnowledge(?user, ?content)
```

Additionally, a property *hasTourKnowledge* is specified between a robot and a tour concept. It is used whenever robots need to exchange information on their participants' knowledge. For example 'CoBot 1' simply queries its data if 'CoBot 2' has knowledge on 'Tour A'. If that is not the

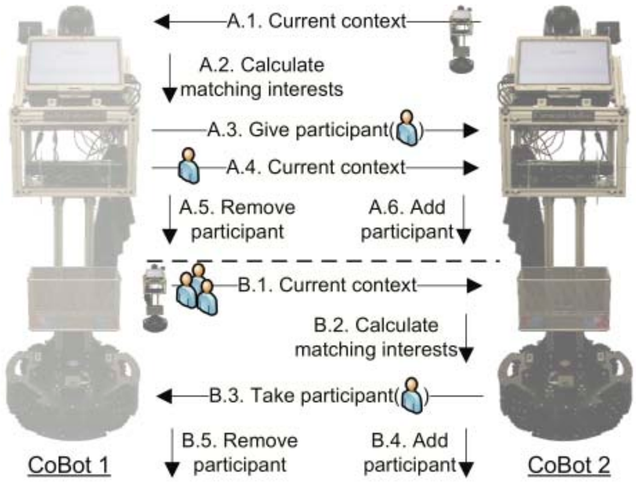

Figure 4: Robot interactions during participants' exchange.

case, it provides this information and adds the *hasTourKnowledge(CoBot 2,Tour A)* property. Extracting the participants and specific 'Tour A' content, 'CoBot 2' reproduces the knowledge of 'CoBot 1' useful whenever robot members are exchanged. This is detailed in the next section.

Exchange of Context Between Robots

In order not to pose any restrictions on the robots' configuration, the tour guides can have different knowledge simulating guides with diverse specialization and knowledge on their participants. The semantic definition of a participant includes his profile (name, age, picture, place of origin) that is collected by the robots. During a tour the participants are also exchanging this personal content with their guides, which in turn is transferred between the robots. This enables a dialog between a robot and his participant. If Robot A asked for a country of origin, Robot B can ask in which city of this country the person was born when the participant switches guides.

Therefore the intelligent exchange of context information between the robots is of utter importance as the guided tour is executed in a distributed manner. Context is defined as the dialog between the robot and its participants such as the provided content, visited places, personal details (country of origin, picture). It is supported by the **Robot Collaboration**.

Instead of sending each time all the participants' knowledge and interests, which are already known by the other robots, a selection should be made of the relevant new information. As mentioned before a robot will only send information on the new tours to the other robots (*hasTourKnowledge* property). As all the robots dispose of the same ontology and rules, the data residing on one robot is reproduced reducing the amount of sent information.

Vital for delivering an interesting selection of content by the robots is their knowledge on the participants. In the best case, if a robot is unable to deliver any more interesting information to a participant and another robot is, there should be an automatic transfer of this participant to the new robot.

Figure 4 presents two possible solutions (case A and B) depending on which robot triggers the transaction. Lets assume that a participant is transferred from 'CoBot 1' to 'CoBot 2', the next sections describe the two solutions, (A) giving participants and (B) taking over of participants.

Giving Participants (A)

If 'CoBot 1' decides that it can not provide enough new and interesting *content* to a specific person, it automatically gives the participant to another robot having better *interests* match. In order to do so, the robot needs information on the other robots' interests and knowledge. The robots exchange the following information:

1. 'CoBot 2' sends its current context consisting of its ID, topic interests and content knowledge it already provided to its participants.
2. 'CoBot 1' calculates which robot has a better interests fit with its participants.
3. 'CoBot 1' sends a *giveParticipant(userID)* message to 'CoBot 2' for each better matching participant.
4. 'CoBot 1' queries its data on the tour knowledge (*hasTourKnowledge* property) of 'CoBot 2' sending only the new tours to 'CoBot 2'. If the exchanged participant is not known by 'CoBot 2', 'CoBot 1' adds its profile to the exchanged context.
5. 'CoBot 1' deletes the participant from its list.
6. 'CoBot 2' adds the participant to its list.

The amount of data exchanged is the robot's profile, new tour data and optionally the new participant's profile.

Taking Over Participants (B)

If 'CoBot 2' would want to check if the other robots dispose of participants that better match its *interests* and *knowledge*, it needs information on the robots and their participants. The following transactions are performed:

1. 'CoBot 1' queries its data on the tour knowledge (*hasTourKnowledge* property) of 'CoBot 2' sending only the new tours to 'CoBot 2' as its current context. Additionally, any missing profile information on 'CoBot 1' and its participants is also exchanged.
2. 'CoBot 2' calculates which participants better fit its profile instead of the owner's.
3. 'CoBot 2' sends a *takeParticipant(userID)* message to 'CoBot 1' for each better matching participant.
4. 'CoBot 2' adds the participant to its list.
5. 'CoBot 1' deletes the participant from its list.

The amount of information exchanged is equal to new tour data and robot and participants' profiles. Advantage of this kind of exchange is the fact that more participants can be taken over without the need of extra context function calls.

Calculate Matching Interests

Calculation of the matching interests between a participant and a robot during participants' exchange is performed in various ways having different complexity and correctness:

- *Interests:* comparison of the two robots' interests and the participant's interests. The robot having more matching interests with the specific participant is selected.
- *Own Knowledge:* remove from the matching interests topics and content that are known by the three parties. This approach considers content already covered by the robots during their tours and prior participant's knowledge. It is possible that although the new robot has more matching interests, it will never talk about them after the participant's exchange as they were already discussed with its other participants.
- *Other Participants Knowledge:* remove content known by the rest of the robots' participants. This knowledge is taken into account as the providing of future content depends all the participants' profiles.

A trade-off should be made between the complexity and the correctness of the calculation of the matching interests between the robots and the participants as with each solution there is additional information to be considered.

Topic and Area Division Between the Robots

Each time a topic is finished the robot has to select a new one based on its participants, other robots and the building area in order to guarantee an optimal topic division and area coverage by the robots. Only one topic is covered at a time focusing on showing the building instead of standing too long at the same location. The robots dynamically change navigation paths in order to stay out of each others neighborhood. Especially for big groups even in real life scenarios with human guides it is always tedious when guides cross each other resulting in little space and too much noise to optimally enjoy the tour. The topic selection algorithm implemented by the **Tour Planner** is presented in Figure 5.

1. Starting from the topics known by the robot, only the union of interesting topics for the participants is retained.
2. Acquired content knowledge of the participants is removed using stored profiles from prior robot tours. The result is the removal of entire topics or specific content from a topic. Next two lists are created based on:
   (a) the number of interested participants per topic,
   (b) and the maximum number of content per topic.
3. Taking into account the number of interested participants (P) and the amount of available content for each topic (I+D) defined by the tour ontology, order the topics based on the *ContentGain (CG)* Equation (1) where I is the number of introductory content and D the number of additional content (*LevelOfDetail* concept in Figure 2). During the actual tour, the robot will provide detailed information on a specific location if more than 50% (flexible parameter) of the participants are interested resulting in the two parts of Equation (1). The resulting list reflects the amount of new knowledge for all participants acquired if the robot would select the specific topic. At this point the best topic (maximum *ContentGain*) is selected (step 7).

$$CG = \begin{cases} P \times (I + D), & \text{if } P \geq 50\% RobotGroup \\ P \times I, & \text{otherwise} \end{cases} \quad (1)$$

4. If there are several topics with the same *ContentGain*, the robot looks at the topics covered at this moment by the other robots. The list with equivalent topics is split into common topics and not common topics.
5. If there are only common topics, the list is ordered based on the minimum number of robots and the first one is selected. It is still possible that there are several equivalent topics which can be ordered based on the existence of empty floors or distance from other robots but as it is a dynamic environment this is not considered here.
6. If on the other hand there are topics, not overlapping with other robots, the topic with the closest location is selected.
7. Select the best/resulting topic (maximum *ContentGain*).

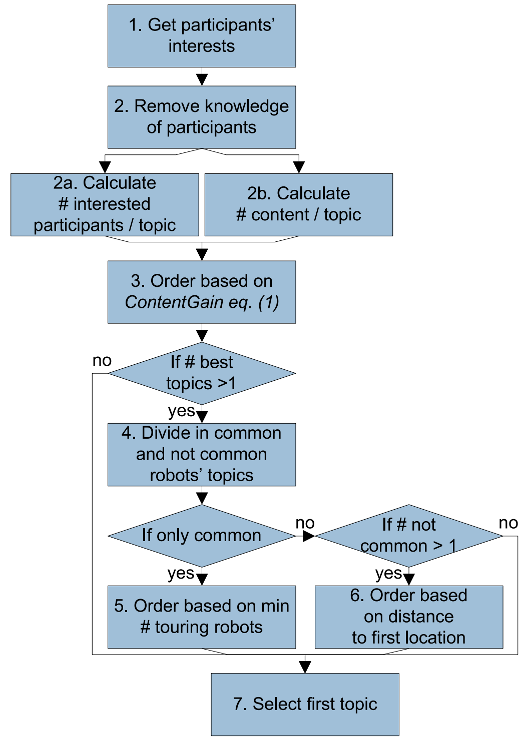

Figure 5: Topic selection based on the number of interested participants, new locations and content, common topics with other robots and the distance to the first location of a topic.

Once a topic is selected the robot uses a simplified algorithm to organize the content delivery in order to optimize performance. If a topic is selected common to other robots, the starting point is not necessarily the closest location, but the farthest point (elevator, floor) from the rest. This prevents robots from following the same tour path. During the guided tour, the robots exchange location information and adapt their next location in case of possible overlap. Robots with low id (string comparison) keep their current path while higher id recalculate their next point. As mentioned, if at a specific location more than half of the participants are interested in the selected topic, the robot not only provides basic introduction but also additional details if available.

The basic example below clarifies the described algorithm in Figure 5 for 'CoBot 1' having 5 participants.

1. Retained interesting topics (amount of available content): *research* (9), *architecture* (7), *people* (11), *history* (10).
2. Removal of prior participants knowledge result in: *research* (7), *architecture* (6), *people* (6).
   (a) Order based on the number of interested participants: *architecture* (P=3), *people* (P=3), *research* (P=2).
   (b) Order based on the amount of content per topic: *research* (7 with I=4, D=3), *architecture* (6 with I=4, D=2), *people* (6 with I=3, D=3).
3. Order based on the *ContentGain*: *architecture* (18), *people* (18), *research* (8). *Research* is removed from the list.
4. Common topics to other robots: *architecture* (covered by 'CoBot 2'); not common: *people*.
7. Select topic on *people*.

Experimental Results

A major challenge of the distributed tour guides is to provide a personalized selection of interesting content to several groups of participants depending on their prior knowledge. In order to measure the actual content delivery by the robots one should compare the provided content by the robots and the amount of relevant content for the participants.

In order to provide for more extensive results, the actual evaluation is carried out in simulation where the program is executed reproducing the robot movements. An ontology generator is developed that taking into account parameters such as number of robots, number of participants per robot and content distribution generates content for all the possible rooms in a building and a list of the robot and participant's interests. During the actual evaluation, 2 robots are defined, each having 5 participants. The robot and participant's interests are selected randomly out of a predefined list of topics. Using the same list of topics, the offices of a 9 storey building are automatically enriched with content. Each office has 50% chance of having a specific content with 50% chance of details and another 50% chance of having additional content on another topic with possible details. In total 10 test sets are generated in order to obtain average results.

For each of the 10 test sets, the following 5 experiments are executed measuring the optimization of the content delivery, the *ContentGain*, by the robots to their participants:

- *Random*: topics are randomly (alphabetically) selected.
- *Ordered*: topics are selected using the *ContentGain* optimization algorithm (Equation (1)) in the previous section.
- *Exchange* of participants between the robots:

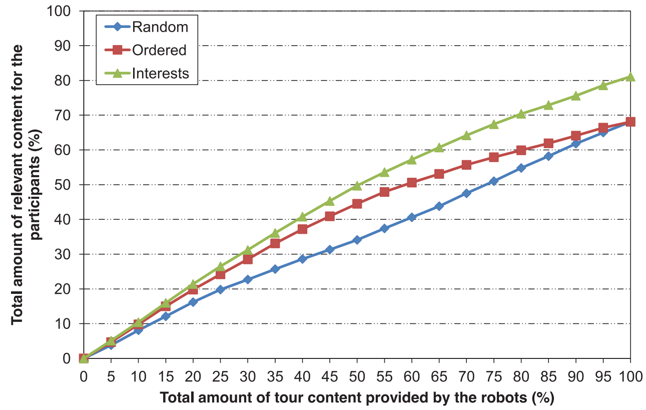

Figure 6: Comparison between random, ordered based on people's interests topic selection and exchange of participants optimizing robot-participant interests match.

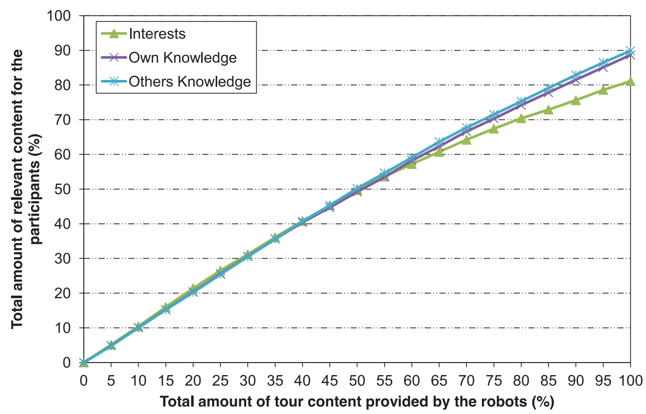

Figure 7: Comparison of amount of content delivery during participants exchange based on matching interests, known content and robot group knowledge.

- *Interests*: once during the start of a robot tour maximizing the number of matching interests with the robots.
- *Own knowledge*: each time the robots are on the same floor based on the amount of new knowledge that can be provided by both robots.
- *Others knowledge*: each time the robots are on the same floor based on the comparison of new knowledge provided by both robots taking into account the original robot group at the moment.

The results in Figure 6 and Figure 7 compare the *ContentGain* of the participants of both robots in respect to the total content knowledge of the robots. The evolution of the tour is measured in percentage of the provided content to the total amount of provided content at the end of the tour. Results are averages over the 10 test sets.

Figure 6 compares the amount of *ContentGain* between a *random* and *ordered* topic selection. Although both provide the same amount of content, the ordered solution engages as many participants as possible resulting in a curved line. A one time only exchange of participants based on the number of matching *interests* results in an additional 10% *ContentGain* compared to the solutions without exchange.

The different participants' exchange solutions are compared in Figure 7. Taking into account the individual's and the robot group's knowledge results in an additional *ContentGain* of 8 (*own knowledge*)-9 (*others knowledge*)%.

The evaluation of the *ContentGain* shows that robots are able to engage people into an interesting robot tour just like a real tour guide using a formal notion of interests and knowledge. Unlike standard tours, through an exchange of participants we propose a more personalized tour where robots not only interact with their group members but also with each other in order to optimize the distribution of people into common groups of interests. This solution supports robot groups starting at different times with a variety of participants converging into groups with similar interests.

Conclusion

This paper presents collaboration techniques between multiple robot guides providing a building tour to groups of participants. The definition of a tour ontology specifies the different topics, available content for a specific topic and the knowledge and interests of the robots and human participants. Depending on the participants' interests and their prior knowledge different topics are selected by the robots resulting in a personalized tour. Additionally the robot guides interact with each other exchanging profile and provided tour information. This cooperation enables the automatic exchange of group members in order to optimize the amount of interesting content each time the robots are in each others neighborhood. Evaluation of the deployed algorithms for two robot groups presents a 90% content coverage of the topics of interests for the individual participants.

Acknowledgments

A. Hristoskova would like to thank the Special Research Fund of Ghent University (BOF) for financial support through her PhD grant and the Computer Science group of prof. M. Veloso for hosting her at Carnegie Mellon University. This work is funded by a fellowship for a stay abroad of the Fund for Scientific Research, Flanders (FWO).

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