2010 International Conference on Indoor Positioning and Indoor Navigation (IPIN), 15-17 September 2010, Zürich, Switzerland

Modeling and Simulating Assistive Environments in 3-D with the YAMAMOTO Toolkit

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***Abstract*—We present the map modeling toolkit YAMAMOTO, which allows to efficiently model and design assistive building environments in 3-D. We focus on the tool's ability to represent and simulate sensors and actuators, i.e. navigational beacons used for indoor positioning and navigation purposes. An interactive avatar can be used to simulate and evaluate location-based applications in the virtual model. Vice versa, the model can be used to visualize the state of the real world, including the location of the user and the content of public displays.**

***Keywords*—3-D Modeling, Mapping, Building, Indoor Navigation, Wayfinding, Intelligent Environments, Dual Reality**

I. INTRODUCTION

Modeling the physical environment is a basic requirement for the design and development of user assistance in intelligent environments, especially if navigational aid has to be conveyed to the user. Furthermore, any location-aware service may benefit from the ability to relate the location of users and devices to features of their surrounding space. During the development of navigational assistance systems for indoor environments we have faced many limitations of current off-the-shelf modeling tools for 3-D graphics (e.g. *Blender*[1] or Google's *SketchUp*[2]). Most importantly, these tools are focused on the manipulation and visualization of geometry and do not properly support additional semantic knowledge about the modeled objects that is needed for route finding, i.e. the passableness of spatial regions and doors. Other shortcomings regard the maintenance of geometric metadata for indoor positioning systems (sender and receiver devices) and the conversion between model- and geographic coordinate spaces. Furthermore, we are interested in the simulation and evaluation of assistive environments in virtual and mixed reality. Therefore we need some additional functionality to couple the environment model with real sensors and actuators.

In [1] we introduced the YAMAMOTO (**Y**et **A**nother **MA**p **MO**deling **TO**olkit) toolkit that we have developed to model multi-level buildings in a way that allows route finding in indoor spaces. In this paper, we present extensions of YAMAMOTO for a full 3-D visualization of buildings and show how we applied the toolkit to implement the VISTO (**VI**deos for **S**pa**T**ial **O**rientation) [2] kiosk system that presents indoor navigational aid. We further present how YAMAMOTO's can be used for the simulation and evaluation of instrumented environments in dual reality. Application domains comprise indoor positioning, home automation, and ambient assisted living. Our approach is to support the development of assistive environments during all stages of a user-centered development process, from requirements analysis and design to implementation and evaluation, through a graphical editor and XML-based file format, dedicated to the specific requirements of pedestrian navigation in instrumented indoor environments.

II. MODELING BUILDINGS IN YAMAMOTO

The typical workflow to create a building model with YAMAMOTO is to use a floor plan as backdrop image and to trace the outlines of rooms and corridors as spatial regions that are represented by vertices and edges. Optionally, vertex and polygon data can be imported from CAD systems through a minimalistic XML format that is fairly easy to create by scripting language.

In order to allow for a simpler and easier to learn user interface than existing 3-D modeling tools, we have reduced the degrees of freedom by half of a dimension to a so-called 2.5-D model. As already presented in [2], this means that rooms are represented as polygons in a 2-D plane, but they can also be vertically arranged according to multiple levels of a building. It is also possible to model stairs, ramps and slopes. The editor provides a layer controller that allows the user to view or hide different levels of a building.

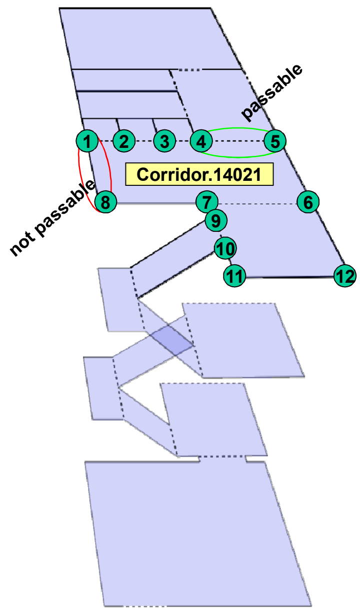

Figure 1. Modeling spatial regions as polygons in 2.5-D.

[1] http:/www.blender.org
[2] http://sketchup.google.com/

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Polygons are defined as ordered sequences of vertices with Euclidean (x, y, z) coordinates. E.g., polygon "*Corridor.14021*" in Figure 1. is defined as a sequence of vertices with index (1, 2, 3, .. , 8). In order to allow for route finding in the model, it is important to know the semantics of connections between polygons. Thus each edge between to vertices is attributed by their passableness: edges that represent walls or windows are set to "*not passable*", in our example the edge (8, 1) represents a wall. The edge (6, 7) however connects the corridor polygon with the adjacent staircase polygon (7, 6, 12, 11, 10, 9). Therefore this edge is annotated to be "*passable for pedestrians*".

By the shared use of vertices and edges, all polygons form a mesh-like data structure that avoids redundancy and contradicting attributes, since edges of adjacent polygons are represented only once. It further reduces the overall number of vertices that are needed, and if applied consequently, finally leads to a partitioning of floors. Thus each point within a floor belongs to exactly one polygon, so that we have a clear mapping between coordinates and rooms that allows to infer statements like "*Dominik is currently in room 1.06*".

Although the spatial regions of the building are represented in YAMAMOTO as "flat" shapes, they can be visualized in full 3-D from both an allocentric (bird's eye view) and egocentric (avatar view) perspective. Our tool automatically creates the necessary 3-D geometry using parametric objects "on-the-fly"; based on semantic annotation of regions and edges with information about their type and passableness, parametric objects automatically generate the geometry for walls and doors, as shown in Fig. 2. Edges can be rendered as walls, doors, walls with window, handrail, or just open space. The vertical dimensions of the elements are parameterized by the three base-lines that define the height of walls, windows, and doors. Furthermore, it is possible to customize the color and width of door- and window-frames. Walls that are represented by edges have no thickness. If thick walls have to be represented, they can be modeled as spatial regions with type set to solid.

The visualization of the room's interior is important for two practical applications of the YAMAMOTO toolkit, namely the visualization of route descriptions and the modeling and simulation of interaction in instrumented environments. We have implemented a set of frequently-used parametric objects, such as boxes, shelves, and tables. All objects share the same basic properties of position, orientation, depth, width, and height. Image textures can be mapped to the surfaces of the object in order to give it a more realistic visual look, e.g. like an oven, as shown in Fig. 2. Finally, parametric box objects can be grouped together to form complex objects like a kitchen block.

All objects can be labeled with symbolic identifiers in order to refer to an external, symbolic representation in a database or ontology. YAMAMOTO provides integrated support for the Web-based UBISWORLD ontology by Heckmann [3] that can be interactively explored within the editor's user interface to assign instances from the ontology to spatial regions and furnishing objects. The ontology can be edited using the UBISWORLD tool set [4].

III. WAYFINDING AND NAVIGATIONAL AID

Seamless route-finding is supported in indoor and outdoor environments without the need for explicit modeling of path networks. The YAMAMOTO toolkit includes the PATHFINDER component that has been implemented to find shortest paths in multi-level building models. The semantic annotation of edges (doors or walls) allows the algorithm to perform a heuristic *A** search directly on the spatial regions without the need for an additional route network model. Figure 3. shows an example route from the first- to ground floor. For dynamic re-routing, an incremental search strategy (e.g. *D* lite* [5]) would be more efficient; this remains future work.

The unique combination of route finding and visualization capabilities of YAMAMOTO suggests its use for the generation of route descriptions and wayfinding assistance. VISTO is an information kiosk system that we have developed to support pedestrians in their wayfinding tasks in built environments. In the scope of the VISTO project, YAMAMOTO has been used to generate graphical route descriptions that visualize indoor routes as 3-D animations showing a walkthrough the building from the pedestrian's perspective.

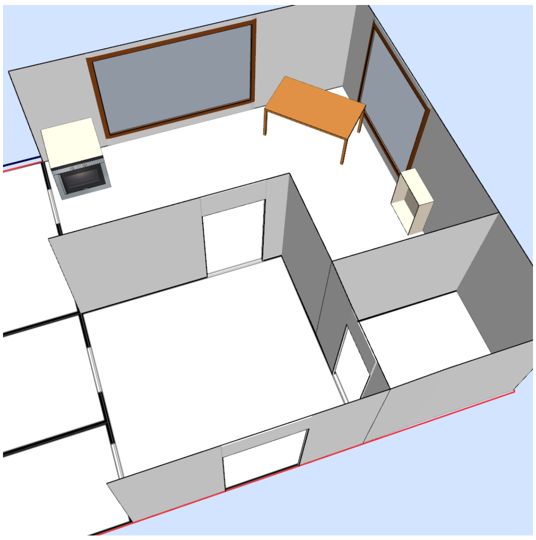

Figure 2. Defining the edge attributes creates geometry for walls, doors, and windows. The example also shows some furniture.

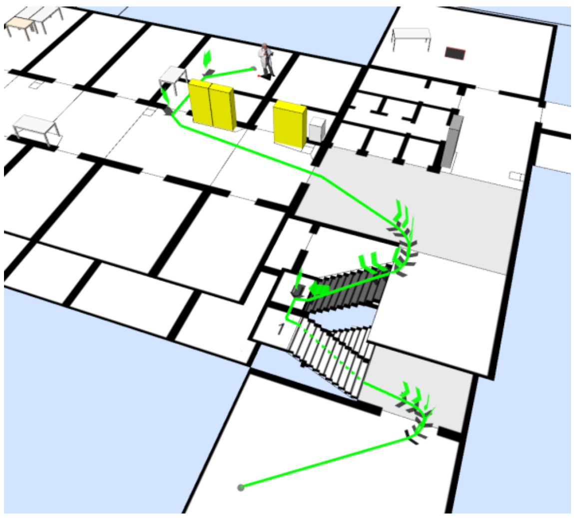

Figure 3. The shortest path between the current avatar's position and the exit has been calculated and is displayed as green line. Arrows indicate turning points.

A. Computing a Route Knowledge Database

Considering the structure of buildings, one can find out that there are only a limited number of possible routes between two rooms. In the case of VISTO, there are even less routes to consider, since we only need route segments that begin at an infopoint display and end at another display or room in the vicinity. The route descriptions for these segments do not change unless the building is renovated in a way that walls are moved.

Hence it seems reasonable to pre-compute and store all route descriptions for a building in a route catalogue. This approach saves any computation at runtime, reduces delays for the user and simplifies the system implementation. We use the YAMAMOTO toolkit for the modeling of the building and the PATHFINDER module for the route finding between all displays and destinations.

Figure 4. shows all required route segments for our lab, where VISTO has been deployed. In order to access the route knowledge at runtime, we store the route catalogue in a relational database that contains one table per infopoint. Each table has at least one record per destination that stores the length between start and destination, and directional information that describes in which way the user should move when they are standing in front of the display. This direction is indicated by VISTO as a simple arrow. Each record also refers to a visual route description (flash movie) that can be played in VISTO's user interface.

B. Automated Rendering of Visual Route Descriptions

We use the egocentric avatar perspective of YAMAMOTO to visualize and export each route segment as 3-D animation, as shown in Fig. 5. Basically, the motion of the avatar already encodes all information that is necessary for the user to follow the presented route. Still we have added meta-graphical elements to make the presentation more concise. The route itself is marked as a green line on the floor, and we inserted arrows at turning points along the route. The turning points are directly derived from the geometric course of the path, which automatically includes all decision points where the user needs additional information on how to continue. The arrows are placed in green color at approximately breast height into the building, pointing to the direction to turn. The flat, vertical geometry of the arrows is supplemented by a shadow-like projection to the ground that helps the user estimate the position and size of the arrow.

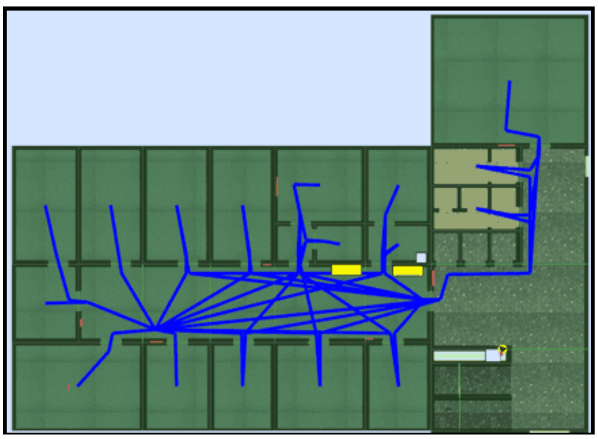

Figure 4. Overview of all route segments in our lab environment.

Figure 5. The route is shown from the user's (egocentric) perspective. The green line visualizes the path and an arrow indicates a left turn. Landmark objects, such as the posters and yellow column, help the user to memorize and recognize the setting.

However, the described procedure of arrow insertion fails in situations with too many turning points, with the result that the arrows will overlap. We have also experienced that 180° turns are hardly recognizable as the route directly leaves the user's field of view. Hence we have introduced an arrow sequence as a new graphical style for curved route segments, similar to road-signs at sharp turns. We also use B-spline interpolation in order to smooth the original path geometry.

C. Empirical Studies on Wayfinding

Our work towards visual route descriptions sparked extensive interdisciplinary research together with psychologists in the field of wayfinding and spatial cognition. We were interested if our animations from the egocentric perspective were better suited to convey route knowledge to pedestrians than traditional paper maps. An empirical field study with 48 subjects showed that subjects who had seen the animations made considerably less critical wayfinding errors than the others who received floor maps [6]. The advantage of the animated condition might be explained with the form of information transmission about complex turns. Turning movements on stairs, turns immediate after leaving the stairs, as well as U-turns were critical points at which errors were likely to occur. The animation transmits turning information through the movement of the virtual camera.

Another current research question is whether different exploration strategies can explain spatial learning with a virtual model of a building. In a new set of experiments we are using YAMAMOTO as a desktop VR (Virtual Reality) environment to study individual differences in spatial learning. Subjects can use a reduced viewer-only version of the UI to virtually explore an unfamiliar multi-level building from allocentric and egocentric perspectives. The viewer measures the navigational behavior of the subjects by a set of parameters, such as the relative times spend in each perspective as well as the number of perspective changes and rotations of the building model by the user. Analyses of individual differences suggest that visual-spatial abilities, self-reported spatial strategies and playing computer games can explain variance in spatial learning with a virtual model.

IV. Modeling Instrumented Environments

Indoor positioning typically requires an arrangement of sensors and actuators to measure distances (directly by time of flight or indirectly by signal strength) or angles in order to estimate the location of the user by trilateration or triangulation, respectively. Therefore the location of some of the devices must be known to the positioning system.

A. Navigational Beacons

Figure 6. shows the instrumentation of our lab with active RFID tags and infrared beacons, which are sending from fixed positions. Their signals are received by a mobile terminal that computes its position based on the known position of the tags and infrared beacons by Bayesian networks, refer to [2] for more details. In order to model the different signal characteristics, the YAMAMOTO editor supports three basic primitives: i) *Point (x, y)*; ii) *Circle (x, y, radius)*; and iii) *Section (x, y, radius, beam angle, orientation)*. They can be given a symbolic name and an additional ID that is typically broadcasted by the beacon. *Point* primitives for example can be used to map the position and MAC-address of WLAN access points without considering their range. Short-range signals can be modeled as *circle* primitives with an approximated reception range. Directional signals, like infrared lights, can be defined as *section* primitives with angle and orientation. As future work, attenuation models for radio signals, considering obstacles and materials, might be added to support the planning of positioning systems.

B. Display Objects

Digital signage is becoming an essential medium to convey advertisement and local information, e.g. the schedule of a conference, to the visitors of a building. Likewise, information kiosk systems also require large touch screens. Particularly in case of route directions, the visibility and orientation of the display matters. Hence the placement of displays needs to be planned carefully. The opportunity to evaluate the visibility of displays from the avatar's perspective might be helpful for the designer of such systems. YAMAMOTO accommodates the modeling of displays with a dedicated object type, as shown in Figure 7. The size and format of the display object can be defined to match any real display regarding its diagonal measure, aspect ratio (4:3 or 16:9), and orientation.

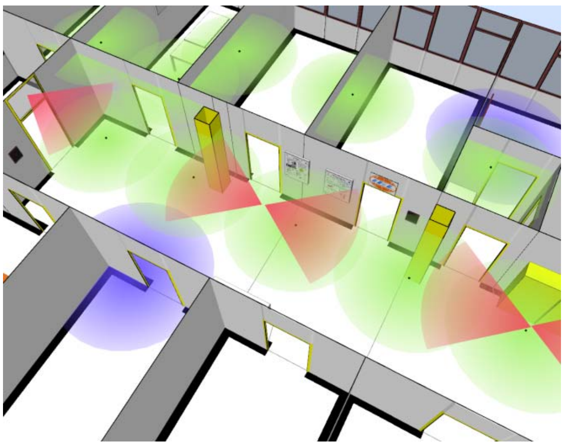

Figure 6. To estimate the position of the user, our lab has been instrumented with active RFID tags (green), directional infrared beacons (red), and Bluetooth access points (blue) to recognize users by their mobile phones.

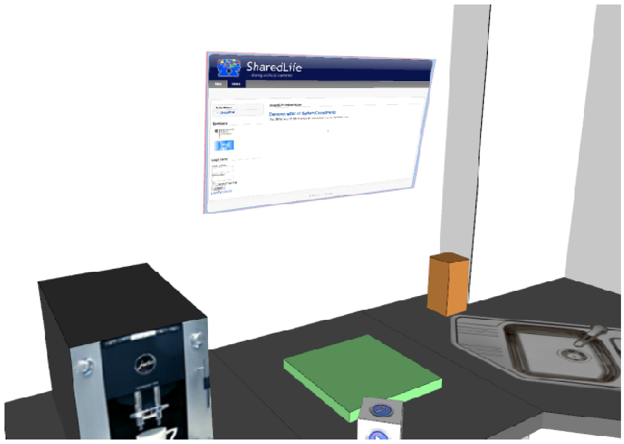

Figure 7. The Smart Kitchen at DFKI utilizes a TFT display to assist its users with the presentation of cooking recipes (movie clips).

Any screenshot can be mapped to the display as static image texture. The interesting aspect of virtual displays in YAMAMOTO is however their ability to connect to a VNC (Virtual Network Computing) server so that any content from an external application can be shown in real-time in the 3-D world. VNC has been originally developed at the ORL (Olivetti & Oracle Research Lab) to remotely control another computer (server) on a local machine (client) using mouse and keyboard. The content of the graphical display of the remote machine is captured and transferred via network to the local computer, based on the RFB protocol [7]. In the case of YAMAMOTO, the content is mapped as image texture on the virtual display. Section V gives an actual use case for this feature.

C. Geo-referenced Location Models

The YAMAMOTO toolkit further allows to geo-reference the model according to known points or aerial photographs (by manual alignment), so that local (model) coordinates can be converted to geographic (Longitude/Latitude) coordinates for a seamless transition between indoor and outdoor (GPS) positioning systems. Modeling buildings in 3-D allows to visually identify obstacles between sender and receiver units, and to represent geometrically challenging situations, such as staircases.

Modeling the interior of buildings on a high level of detail further helps the designer to plan the coverage and precision of the positioning infrastructure according to the users' activities. For fingerprint-based indoor positioning, e.g. based on WLAN networks, a simulation of signal strengths within a building would be desirable. This could be realized in the future by adding semantic knowledge about the materials of a building's structure and its furnishing and the proper attenuation coefficients.

V. Simulation and Evaluation of Assistive Environments

In this section we will give a concrete use case of how YAMAMOTO can be used for the simulation and evaluation of assistive environments in a desktop virtual-reality environment. Our example shows how the avatar can be used to simulate an indoor positioning system, and how virtual displays can mirror the content of real displays in real time.

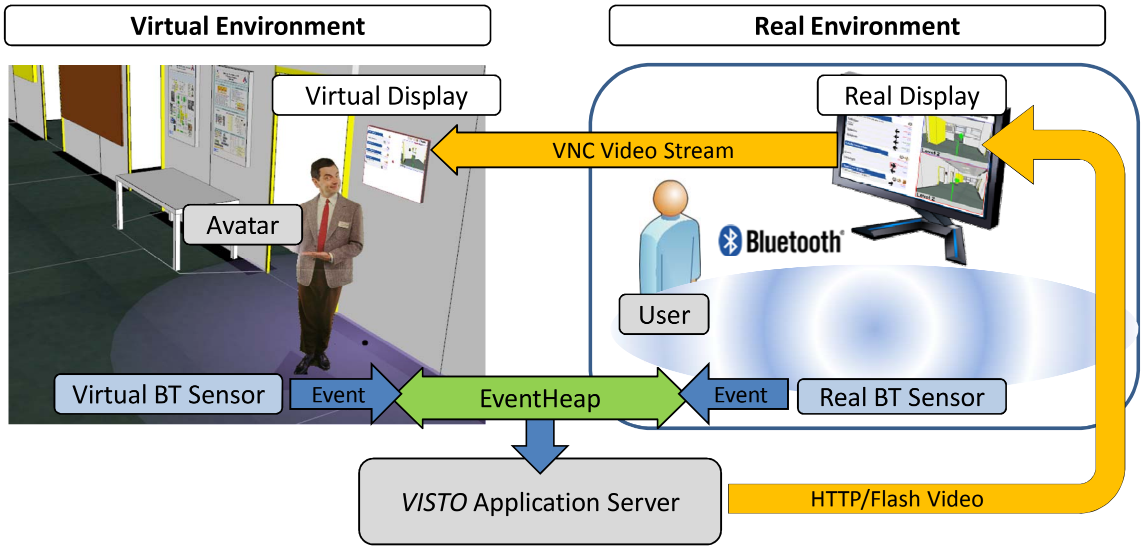

Figure 8. Visto system architecture with real components (right) and their virtual counterparts (left).

A. *Evaluating the Visto Kiosk System in Virtual Reality*

VISTO provides navigational assistance for pedestrians in built environments. VISTO has a user-adaptive graphical user interface that automatically adapts the selection of possible destinations according to the external, Web-based task planner application Ubidoo (**UBI**quitous to-**DO** **O**rganizer) [8]. Ubidoo allows its users to manage tasks similar to a to-do list, but also integrates time and location information for each task. Hence the system is able to automatically suggest destinations that are likely to be relevant for the user at the current time and place.

VISTO has been designed with the goal to reduce the necessary interaction between the user and the kiosk to a minimum. Instead of a manual login procedure, VISTO identifies registered users by their mobile devices, such as mobile phones, with Bluetooth connectivity. Similar to MAC addresses in the Ethernet, each Bluetooth adapter has a unique hard-coded address that is given by the manufacturer and cannot be changed by the user (no coupling between the devices is necessary, and no data is transmitted).

As shown on the right hand side of Figure 8. the kiosk system uses a Bluetooth dongle that continuously scans for nearby devices. If a known device is discovered, the kiosk sends an event containing the ID to the application that runs on a server. The application retrieves the user's profile and tasks and creates personalized web content (html and flash) that is pushed to the kiosk that runs a Web browser.

The same process can also be triggered and experienced in YAMAMOTO as desktop virtual reality environment, as shown on the left hand side of Figure 8. Instead of a real sensor, a virtual proximity sensor responds to the location of the avatar. The sensors are modeled as sphere items with their type set to Bluetooth. The sphere's radius determines their range. As the avatar enters the activation radius, the virtual sensor sends exactly the same event to the application as the real sensor does. Hence it is transparent for the application's implementation whether a real user approaches the kiosk or if the avatar approaches the virtual kiosk. Consequently, the VISTO application creates web content that is pushed to and displayed on the real kiosk. The kiosk's public display is modeled as a virtual display object that is able to stream the content of the real display via VNC, as explained in Section IV. As a result, the user-adaptive interface of VISTO can be completely experienced and tested in the virtual environment. This option could be useful in cases where the building has not yet been built, or in order to evaluate digital signage systems prior to their actual deployment.

B. *Interactive wheelchair driving simulation in BAALL*

Another use case for the simulation of assisted environments has been the planning of the Bremen Ambient Assisted Living Lab[3] (BAALL) [9], as reported in [10]. BAALL is an apartment of 60 m² suitable for the elderly and people with physical or cognitive impairments. The goal of the project is to investigate how the living environments of seniors to-be can be instrumented with infrastructures for user assistance systems. The Intelligent Wheelchair Rolland is a mobility assistant that is able to autonomously operate within the BAALL. It is equipped with two laser range scanner, wheel encoders, and an onboard computer.

User-adaptable furniture and automated sliding doors have been installed to allow a wheelchair-dependent user to stay together with their non-impaired partner in the same living environment. Concerning the furnishing, we aimed to maximize the storage space of shelves without compromising the maneuverability of the wheelchair. In order to figure out the best configuration, we used the YAMAMOTO toolkit to model the building structure and the furnishing items in 3D, as shown in Fig. 9. Then we exported the model to SIMROBOT, a robot simulator which is able to simulate arbitrary user-defined robots based on rigid body dynamics in three-dimensional space [11]. Thereby, a realistic evaluation of the physical configuration becomes possible, e. g. by interactively driving the wheelchair through the environment.

[3] http://baall.net

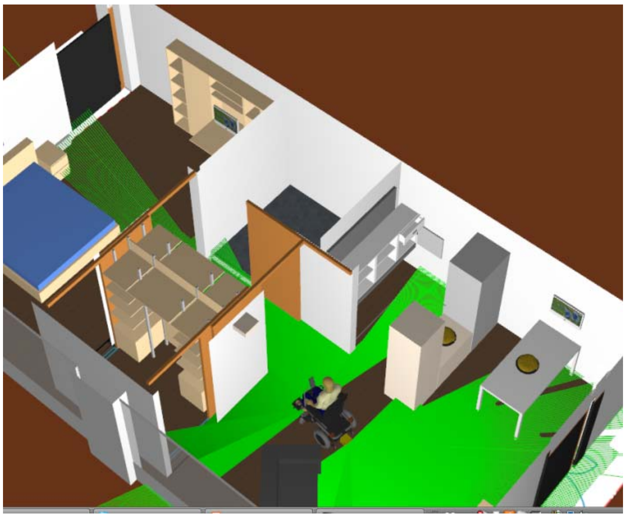

Figure 9. Interactive simulation of a robotic wheelchair with laser range scanners in the Bremen Ambient Assisted Living Lab (BAALL).

C. External Interface for 3rd Party Applications

The YAMAMOTO toolkit provides an external interface to get and set the state of all modeled objects through 3^{rd} party applications, hence it is possible to visualize the measured position of the user by the avatar in the virtual model. Vice versa, the avatar can be controlled by the user to simulate a precise indoor positioning system in VR to evaluate location-based applications.

VI. CONCLUSION AND OUTLOOK

YAMAMOTO has been designed as an easy to learn and efficient map modeling toolkit for buildings. In contrast to off-the-shelf computer graphics tools, semantic annotation of spatial entities allows for route finding in indoor spaces and for the automated generation of 3-D geometry for walls and furnishing objects. We have demonstrated how these capabilities can be applied to the development of navigational aid in case of the VISTO kiosk system. We have further outlined how YAMAMOTO supports the simulation and evaluation of assistance systems like VISTO in a dual reality setting that mixes virtual reality with actual sensor data and the content of real displays. In case of the assisted living lab BAALL we have shown how an autonomous robotic wheelchair can be simulated in VR.

Concerning future work, we have already mentioned important points throughout the paper. Firstly, the PathFinder search component could be optimized with an incremental search strategy (D*) to support dynamic re-routing and to adapt the route knowledge to changes in the environment. Secondly, the integration of physical signal attenuation models could contribute to a better planning and prediction of indoor positioning systems that are based on signal strength measurements, e.g. WLAN-based positioning. Therefore, the current semantic annotation has to be supplemented with material properties for walls and furnishing objects.

The lack of suitable semantic annotation in computer graphics tools motivated us to create our own, proprietary YML file format. Recently, new standards for building information systems have emerged from the fields of geographical science, architecture, and facility management. The *Geographic Markup Language* has been enhanced by the CityGML[4] profile that allows the geometric representation of buildings and their interior in 3-D based on the *Keyhole Markup Language* (KML). KML has been standardized in 2008 by the Open Geospatial Consortium[5] (OGC) for the exchange of geographic information and is used by *Google Earth*. The *Industry Foundation Classes*[6] (IFC, ISO 16739) provide an extensive semantic data model for buildings and their components that is supported by several commercial and academic tools. For the future, we consider adding import and export support for the CityGML and IFC standards. It might also seem reasonable to adopt IFC as internal data model. However, since the IFC addresses the needs of architects, it is quite extensive. The complexity of IFC might conflict with YAMAMOTO's intended goal to be easy to learn and use for computer scientists working on intelligent environments and psychologists in the field of spatial cognition. YAMAMOTO aims to represent buildings from a cognitive (user, designer) rather than a technical (construction engineer) perspective.

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