

# Robust Visualization of Navigation Experiments with Mobile Robots over the Internet

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## Abstract

*Visualization is an important precondition for successful tele-operation of instructable mobile robots. Data connections with varying and limited bandwidth such as the Internet, however, prohibit the continuous transmission of video signals. In this paper we propose a predictive simulation technique which is designed to permit the reliable visualization of the robot's actions over the Internet. It differs from previous approaches in that it includes an odometry and sensor simulation. This simulation of the robot allows the integration of a complete robot control system to reliably predict complex actions of the robot even if large transmission gaps of several seconds occur. We describe an application of the predictive simulation technique to navigation experiments with mobile robots. We present different experiments carried out with a real robot illustrating that the predictive simulation technique provides accurate visualizations of the robot's actions even if transmission gaps of more than ten seconds occur.*

## 1. Introduction

Due to the increased costs of laboratory equipment such as mobile robots and due to the increased specialization of research on the other hand, there is a growing need for cooperation between research groups. Visualization over the Internet will become an important means for the collaboration of research groups, for example during the development and the testing of control systems or for the demonstration of new systems.

Unfortunately the Internet does only provide a restricted bandwidth and arbitrary large transmission gaps can occur so that video streams cannot be used for the visualization of the robot's actions. Obviously, accurate visualizations are important for the observation of experiments and during demonstrations. Furthermore, with the development of web-operated robots, for example tele-operated museum

tour-guide robots, there is a growing need for tele-operation interfaces which can be used even by untrained people. In this context, accurate visualizations of the robot's actions become more and more important.

In this paper we describe a predictive simulation scheme (PSS) which provides a basis for smooth and reliable real-time 3D visualizations of the movements of an autonomous mobile robot based on an object-oriented 3D CAD environment model. Predictive simulations are employed to synchronize the visualization with the current state of the robot even during larger transmission gaps of several seconds.

The long term behavior of an autonomous robot is usually determined by the planning component of the robot's control system. Thus, to make long term predictions, it is necessary to include this planner into the predictive simulation. The PSS therefore provides a robot simulator and appropriate interfaces to integrate a control system. It furthermore is able to exploit a 3D model of the environment for the visualization of the robot's actions as well as for the simulation of proximity sensors.

We built a prototypical implementation of PSS for our mobile robot Rhino. In the current system, the path planning component and the collision avoidance of Rhino's control system are integrated into the PSS. The experiments we carried out with our system show that the PSS-based visualization is highly accurate even in situations in which transmission gaps of over ten seconds occur. We believe that such techniques are a basic precondition for a robust visualization of navigation experiments over the Internet. This will allow distributed research groups to carry out and observe joint experiments with expensive laboratory equipments such as mobile robots.

The remainder of this paper is organized as follows. After discussing related work in the next section, Section 3 introduces the PSS framework. Section 4 briefly describes the parts of the Rhino system, which have been integrated into our system. Finally, Section 5 presents experimental results which illustrate the strength of the approach.



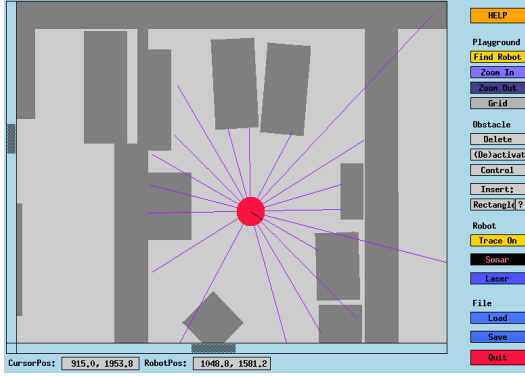


Figure 2. The simulator provides a 2D visualization of the robot and the computed sonar measurements.

simulation in real-time, the PSS applies a spatial indexing technique based on the rectangular tiling of the scene [13].

To establish a realistic simulation of proximity sensors the PSS takes sensor specific measuring errors into account. For example, ultrasound is subject to specular reflection. In case of a reflection the sensor does not perceive an echo and thus erroneously indicates free space. According to experiments carried out with the ultrasound sensors of our mobile robot Rhino, the probability of such a reflection increases with the angle  $\alpha$  between the surface normal and the acoustic axis of the beam and also depends on the distance  $d$  to the obstacle. We therefore approximate the probability  $P(r | \alpha, d)$  of a specular reflection by

$$P(r | \alpha, d) = \begin{cases} 0 & \alpha < \theta(d) \\ (\alpha - \theta(d))/\beta & \theta(d) \leq \alpha < \theta(d) + \beta \\ 1 & \alpha \geq \theta(d) + \beta \end{cases}$$

where  $\beta$  denotes the angle range in which the failure probability increases linearly from 0 to certainty, and  $\theta(d)$  is a decreasing linear function. The values of  $\beta$  and  $\theta(d)$  depend on the material the obstacle is made of. An example of a typical scan generated in an office environment is shown in Figure 2. For the more reliable laser-range finder we use the distance to the next obstacle in the sensing direction and add an appropriate Gaussian noise to model the small measuring errors.

### 3.2. Network Synchronization

In order to synchronize the visualization with the real robot, the PSS-server sends synchronization messages via the Internet to the PSS-client. Since the Internet is subject to packet loss, the use of a reliable protocol like TCP causes arbitrary long transmission delays, because the retransmission of lost messages prevents the arrival of new information. In several experiments carried out with typical

long distance connections, we frequently observed packet loss rates of up to 30 percent. In contrast to that, the transmission time of a single packet rarely exceeded 0.3 seconds, and the accuracy of the re-synchronization of the PSS-client solely depends on the transmission time of the latest synchronization message. To minimize the time required to obtain the latest packet, the PSS uses the unreliable UDP protocol. Each synchronization message therefore includes a state vector completely describing the state of the robot at time  $t$  as well as the time-stamp  $t$  when this vector was sent. The PSS-client extrapolates the state of the robot at message arrival time and warns the user if a packet needed more than 0.4 seconds for the transmission. The system relies on the “Network Time Protocol” [12] to synchronize the clocks of the computers involved for this purpose.

After receiving a synchronization message the PSS-client transmits it to the robot control system, which itself uses the PSS-simulation to compute the next actions of the robot. In return, the PSS-client receives the state of the robot in the simulation. Since this predictive simulation runs within a local network, state messages can be delivered at high frequency which is the basis for the smooth visualizations.

## 4. A Predictive Simulation for the Rhino System

Using the PSS, we implemented a prototype of a visualization tool for our mobile robot Rhino [2, 18]. Rhino is an RWI B21 synchro-drive robot equipped with 2 laser range finders, a ring of 24 ultrasonic sensors as well as with several tactile and IR sensors. In this prototype, the PSS uses the reactive collision avoidance component and the path planner of Rhino’s control system for the predictive simulation. All components including the network interface of the PSS communicate via local socket connections using TCX [5] as the communication server. In the following we briefly introduce the components of the Rhino control system.

**Path Planning:** Rhino’s path planner uses value iteration [18] to determine the shortest path from the robot’s position to its goal location. Path planning takes place in a grid map representation of the environment, which is computed from the 3D model through projection. Value iteration determines the optimal path towards the target point for every position in the environment. After that, depending on the robot’s position, the optimal path to the goal position is extracted. The path planner of the Rhino system computes a sequence of intermediate “target points” which are transmitted to the collision avoidance system

**Collision Avoidance:** Rhino uses the dynamic window approach [6] for reactive collision avoidance. The collision

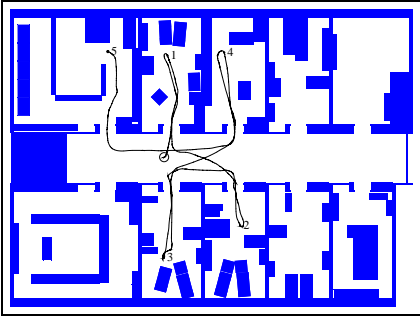


Figure 3. Trajectory of the robot during the office delivery task.

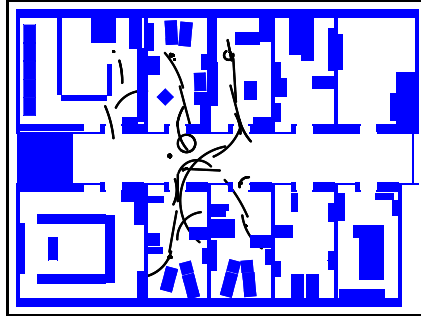


Figure 4. Trajectory estimated by extrapolation.

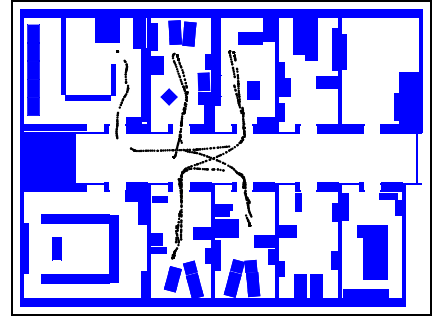


Figure 5. Trajectory predicted by PSS.

avoidance controls the velocities of the robot based on sensor input. Its task is to move the robot to a “target location” prescribed by the path planner. To avoid collisions with obstacles it takes the dynamics of the robot into account.

Given these components it suffices to transfer the robot’s current position, its current velocities and accelerations, as well as the current target point of the path planner to the PSS-client in order to realize the visualization.

## 5. Experimental Results

To demonstrate the prediction accuracy of the PSS, we performed several navigation experiments with our mobile robot Rhino. The goal of these experiments is to demonstrate the advantages of the PSS over a visualization technique which extrapolates the most recent state information received from the PSS-server.

In the first experiment, Rhino started in the corridor of our department and visited five different offices in the order which is depicted in Figure 3. The length of the trajectory is 80.8 m and the robot needed 320 seconds to complete this task. The numbers in the offices correspond to the target-points sent to the path planning module.

To evaluate the capabilities of the PSS, we manually decreased the packet transmission rate to approximately 10 packets per minute. We used a constant transmission interval, so that the time gap between subsequent packets was approximately 6 seconds. Since packets sometimes get lost, the effective time-gap between subsequent packets in several cases was  $n \times 6$  seconds. Figure 4 shows the trajectory obtained if the robot’s movements are extrapolated based on the most recent packet. Obviously the resulting trajectory differs largely from the true trajectory of the robot. It furthermore contains several long gaps of more than 1 m illustrating the limited quality of the standard extrapolation approach. The PSS, however, provides a trajectory which is much closer to the robot’s actual trajectory (see Figure 5). Thus, the PSS provides a better estimation of the robot’s position than the extrapolation approach.

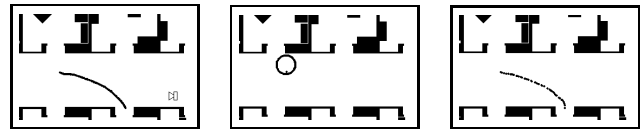


Figure 6. Trajectory of the robot taken after leaving room 1 (left), circular trajectory obtained by extrapolation (center), and trajectory predicted by PSS (right).

To illustrate the improvements in the visualization we now consider a small fraction of the trajectory of the robot after it left room 1. Figure 6 shows the corresponding trajectory of the robot (left image), the trajectory obtained by extrapolation (center image), and the trajectory computed by the PSS (right image). In this particular case one packet was lost so that the system had to predict the robot’s trajectory for a period of 12.5 seconds. Since the extrapolation does not change the velocities of the robot during a transmission gap, the robot moves on a circular trajectory. In contrast, the PSS uses the path planner and the collision avoidance modules to compute intermediate velocities. Therefore, the resulting trajectory is much closer to that of the real robot.

The corresponding sequences of computed images for the 3D visualization are shown in Figure 7. The time delay between consecutive frames is 2 seconds. The first row shows the images obtained using the correct position of the robot. The second row contains the images computed by the extrapolation, and the third row includes the images obtained using the PSS. Obviously, the PSS significantly improves the quality of the visualization.

We repeated this experiment several times given the data recorded during this run. In each experiment we randomly selected the packets which were not transmitted. Figure 8 shows the average positioning error – the distance between the predicted position and the position of the real robot – as a function of transmission gap. This shows, that the PSS is able to significantly reduce the average positioning error compared to the extrapolation technique after transmission gaps of at least 2.5 seconds. Since these differences depend

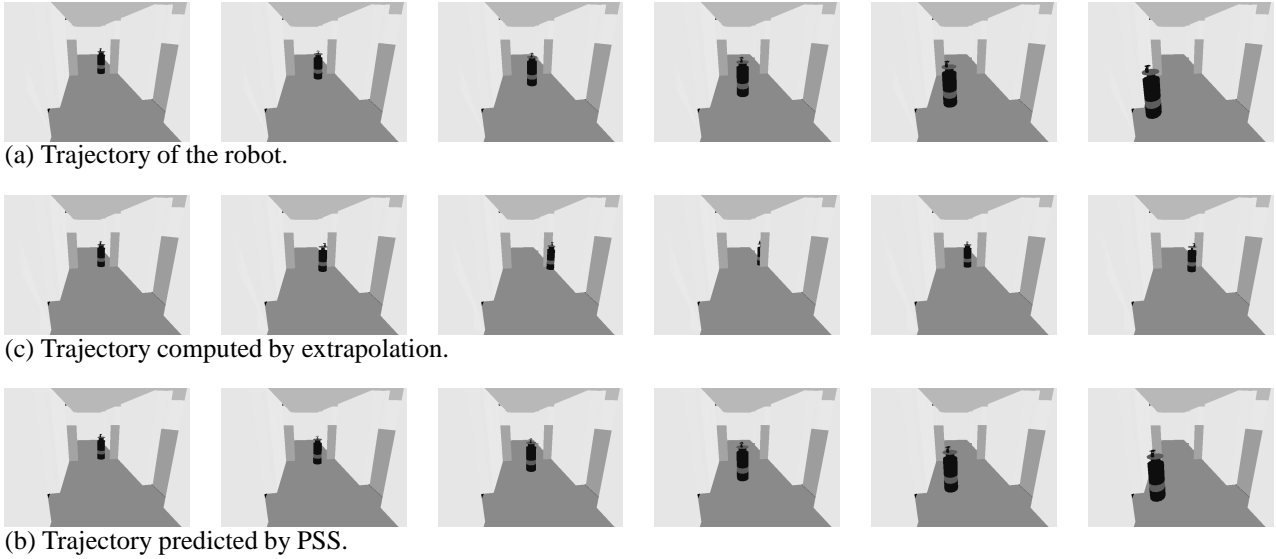


Figure 7. A sequence of computed images showing Rhino moving through the corridor of our department. The time-difference between consecutive images is approximately 2 seconds. The camera position is illustrated in the left image of Figure 6.

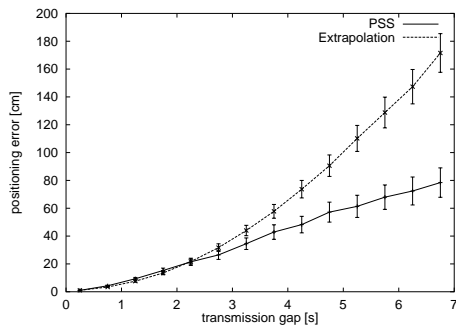


Figure 8. Average displacement depending on the length of the transmission gap.

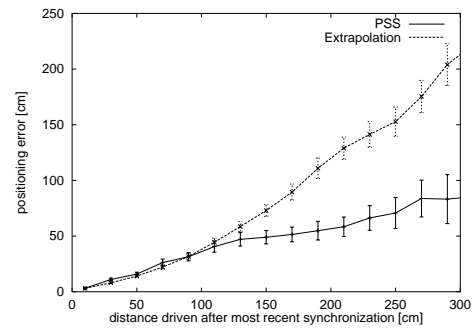


Figure 9. Average displacement depending on the distance traveled after the last synchronization.

on the speed of the robot, which was  $34.5 \text{ cm/s}$  on average in this experiment, we additionally computed the average displacement depending on the distance traveled after the latest synchronization packet. The resulting plots are shown in Figure 9. Thus, at least after  $1 \text{ m}$  of travel, PSS provides a significantly better prediction than extrapolation. In both figures, the error bars indicate the 95% confidence interval of the average mean.

Recently, we used parts of the PSS during the deployment of two mobile robots as interactive museum tour-guides which also possessed Web interfaces allowing to remotely control them over the Internet [3, 17]. Both Web-Interfaces (Figure 10 illustrates Rhino's interface) included a Java-applet for a smooth animation of the robots movements in a 2D-projection of the environment. During the 19 days of the deployments of the two robots more than 4000

virtual visitors used this applet to monitor the activities of the robots.

## 6. Summary and Conclusions

In this paper we presented the PSS, a predictive simulation system for the accurate visualization of navigation actions of autonomous mobile robots over the Internet. The PSS has a client-server architecture. The server is linked to the robot control system and broadcasts the status of the robot to all its clients. The clients use the PSS-simulator and a copy of the robot control system to predict the actions of the robot after receiving a status message. This way, the PSS can reliably visualize the robot's action even if transmission gaps of over 10 seconds occur.

The PSS has been implemented and tested in a typical office environment using the mobile robot Rhino. Extensive

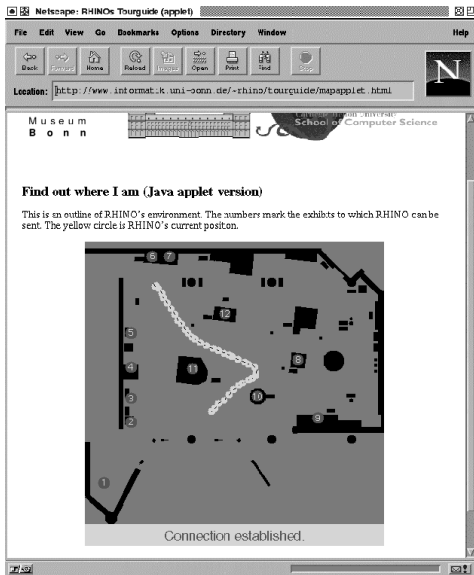


Figure 10. Java-applet based on the PSS displaying smooth trajectories of the robot Rhino

experiments showed that PSS is robust against transmission gaps of up to several seconds and that it provides smooth and realistic visualizations even in such situations. Parts of the PSS have furthermore been used during the deployment of mobile robots Rhino and Minerva as interactive museum tour-guides to visualize the movements of the robot over the Internet.

Despite these encouraging results there are several warrants for future research. The most important topic concerns the extension to dynamic environments and the visualization of manipulation tasks. This requires a reliable model update mechanism based on the sensor interpretation capabilities provided by the robot system.

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