AR-Bot, a Centralized AR-based System for Relocalization and Home Robot Navigation

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Abstract: We describe a system enabling to assign navigation tasks to a self-moving robot in a domestic environment, using an Augmented Reality application running on a consumer-grade mobile phone. The system is composed of a robot, one or several mobile phones, a robot controller and a central server. The server embeds automatic processing modules for 3D scene modeling and for device relocalization. The user points at a target location in the phone camera view and the robot automatically moves to the designated point. The user is assisted with AR-based visual feedback all along the experience. The novelty of the system lies in the automatic relocalization of both the robot and the phone: they are independently located in the 3D space thanks to registration methods running on the server, hence they do not need to be explicitly spatially registered to each other nor in direct line of sight. In the paper we provide details on the general architecture and the different modules that are needed to get a fully functional prototype. The proposed solution was designed to be easily extended and may be seen as a general architecture supporting intuitive AR interfaces for in home devices interactions.

1 INTRODUCTION

Augmented Reality (AR) technology is evolving very rapidly. It has become very present in the industry, and AR-based consumer applications are more and more popular (gaming, interior design, virtual try-on, etc.). AR consists in adding virtual content in a live view of the real-world environment and enables to design intuitive user interfaces for interacting with surrounding objects.

We are living in an era where a large number of devices communicate with each other or access services hosted in the cloud. A recent related trend is the development of the Internet of Things (IoT), which illustrates the need to establish an end-to-end communication structure, from low-level but power efficient wireless exchanges to higher level protocols managed by one or more servers. As a side effect, it is common to get system architectures with many protocol layers, each one having a specific role in the final applications and services. Using AR technology and such protocols, it is possible to visually select and control connected objects in a natural manner, like turning on a light for instance, using either a phone or a headset (Heun, 2017; Zaki et al., 2019; Becker et al., 2019; Jo and Kim, 2019).

In this paper, we focus on the use of AR for controlling a moving robot. In robotics, AR can act as a user-friendly interface for exchanging information between the user and autonomous systems, increasing the efficiency of Human-Robot Interactions (HRI). As robots become more and more prevalent in our professional and private life, it becomes vital to find an easy and intuitive way to control them. We propose a fully automatic multisensory solution called AR-Bot, which enables to easily move an autonomous robot (typically a vacuum cleaner) towards a target point, thanks to the use of an AR-based mobile interface and automatic 2D/3D registration methods. Instead of typically using a 2D floor map representation to indicate to the robot where it should go to, the user simply points at the target location in the camera view of the phone. The user is assisted with AR-based visual feedback which enables a better precision in the location selection. After validation the system summons the robot to move to the selected location. An overview of the solution is depicted in Figure 1. The system leverages several communication protocols to manage heterogeneous data whilst keeping high efficiency. Unlike other similar solutions, the initial position of the robot relatively to the phone does not need to be explicitly determined. Instead, a reference 3D

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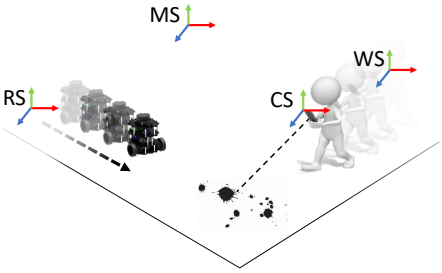
model of the scene is stored on a server and used for the respective relocalization of the robot and the phone with respect to the environment.



(a) from a usage perspective

(b) from a communication perspective

Figure 1: Overview of the AR-Bot solution.

The paper is organized as follows. Section 2 presents some related work. In Section 3 we provide a high-level description of the AR-Bot ecosystem with details on devices, architecture and robot operating mode. In Section 4 we describe the user interactions and the global workflow. Section 5 provides some details about the processing modules that are involved, e.g. the coordinate system management, the scene modeling, the robot and phone relocalization modules. Some elements of discussion are provided in Section 6, before conclusion in Section 7.

2 RELATED WORK

Many AR-based robotic systems have been proposed in recent years, with applications in various domains such as medical robotics, robot programming, motion planning, collaborative interfaces, or robot swarms (Makhataeva and Varol, 2020; Piumatti et al., 2017; Kuriya et al., 2015; Kundu et al., 2017; Guhl et al., 2017).

An early system called TouchMe allows the user to manipulate each part of a robot by directly touching it on a view of the world, as seen by a camera looking at the robot from a third-person view (Hashimoto et al., 2011). Each robot is equipped with a marker and user interactions are done through a PC.

In (Kasahara et al., 2013), the authors present ExTouch, a system to control devices through an AR-based mobile interface. When users touch a moving device shown in live video on the screen, they can change its position and orientation through multi-touch gestures or by physically moving the screen in relation to the controlled object. However the target position of the moving device can only be given with respect to the current position.

In (Frank et al., 2017), the authors propose a mobile mixed-reality interface approach to enhance HRI in shared spaces. A common frame of reference is created for the user and the robot to effectively communicate spatial information and perform object manipulation tasks. The robots are also affixed with visual markers to locate them in the environment.

A more elaborate solution called PinpointFly enables users to arbitrarily position and rotate a flying drone using an AR-based interface running on a smartphone, where the position and direction of the drone are visually enhanced with a virtual cast shadow (Chen et al., 2019). In this system as well, the target position is defined with respect to the original position. It also requires a calibration step with a chessboard and there is no management of the surrounding environment.

Recently, in (Manring et al., 2020), a Microsoft HoloLens headset has been used to create an AR environment to control a robot: the user places a virtual robot in 3D space, then uses the virtual robot to control the motion of the real robot. The real robot is manually positioned in the real environment.

This type of systems offers easy ways to interact with robots, but the initial position of the robot relatively to the phone needs to be explicitely determined, which requires manual initializations or visual markers to be set on the robot.

3 SYSTEM OVERVIEW

3.1 Devices

The system includes a robot, one or several phones, and a central server (see Figure 1b). It also comprises a wireless network part connecting the robot and the mobile phone(s) to the server, as well as other wired connection elements such as a desktop PC server doing the heavy processing.

The robot is equipped with a LiDAR which is used for the spatial registration with the real-world envi-

ronment. The robot navigation is achieved through the Robot Operating System (ROS) (ROS, 2013).

The phone is used for both modeling the scene in 3D and for controlling the robot. These two tasks can be achieved by different users with different phones. For 3D scene reconstruction we only need an RGB camera. In particular, we do not need any embedded or external depth sensor. For the robot controlling interface the phone needs to support ARKit or ARCore (ARKit, 2020; ARCore, 2019).

3.2 Server Architecture

In the AR-Bot ecosystem, the server consists of two elements. The first one, "Robot Controller", oversees the robot control. It relies on ROS, a framework mostly focused on managing robot(s) in a possibly widely distributed setup. The second element, "AR-Bot server", embeds processing modules and a network interface, a HTTP server, for communicating with the smartphones. To facilitate a distributed architecture, the communication between both server elements is based on the Message Queuing Telemetry Transport (MQTT) protocol, a publish-subscribe-based messaging protocol (MQTT, 2016). The diagram in Figure 2 depicts the high-level architecture.

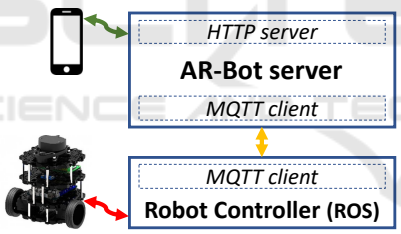


Figure 2: High-level overview of the architecture.

3.3 ROS

The ROS framework provides libraries and tools to help software developers create robot applications. It combines many roles that can be hosted on one single machine (a robot for instance), or inversely be spread onto multiple machines communicating through a network (ROS, 2013). The main node, the ROS Master, provides naming and registration services to the other nodes. Also based on a publisher/subscriber approach, some nodes provide services, some others generate data at various frequencies on so-called topics, and some others subscribe to such topics to process data when broadcasted, or make use of services from other nodes.

When a ROS node is started on a machine, this one must be properly setup regarding the ROS environment, and specifically regarding the ROS Master node defined by its network name or IP address. Some nodes may also require that machines participating to the same ROS setup share a very precise time base; this is typically the case when the robot publishes timestamped LiDAR data, but relies on another node to generate its neighborhood map for moving around. This last requirement was solved by defining a unique local Network Time Protocol (NTP) server in the system (NTP, 1992) that is used for the time synchronization of all the devices, including the robot.

4 EXPERIENCE DESCRIPTION

4.1 User Interface

The main user interactions are related to the mobile relocalization (to align the world reference with other used coordinate systems) and the robot target assignment.

When starting a new session, the phone is first connected to the server. Then it is localized in the physical world before the user can select a target location for the robot. For this purpose, an image is captured by the user and sent to the server for relocalization computation. The method is explained in Subsection 5.5. When the relocalization is completed, a virtual planar polygon corresponding to the ground area is displayed in semi-transparency on the top of the camera view. This visual feedback enables the user to qualitatively check the relocalization consistency. The computation of the ground area is explained in Subsection 5.3.

In order to summon the robot, the user simply taps on a desired location on the visualized ground plane (see the selection pointer as a red dot in Figure 3). This casts a virtual ray that is thrown with respect to the underlying scene model aligned with the location. If a collision with the ground area is detected, the hit point is set as the new robot target and it is rendered in AR on the user screen via a green dot.

Finally, the "move" command is sent to the server as a new HTTP request. The path followed by the robot is displayed in AR on the user screen, following the robot motion in real-time. The mobile application also informs the user about the command result via a textual pop up.

A top view of the scene is also rendered as a thumbnail in the corner of the screen, to help the user having an overview of the environment (see Figure 3).

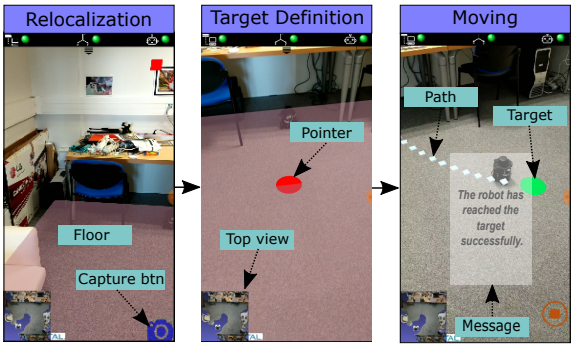


Figure 3: Graphical User Interface of the mobile application during three states. From left to right: relocalization initiated using a capture button and visualized using a virtual floor plane; target selection using a pointer (red circle); robot displacement with visualization of path (white dots), target (green circle) and end message.

4.2 Workflow

The overall workflow is presented in Figure 4 and consists of a set of pre-processing processes followed by a set of runtime processes.

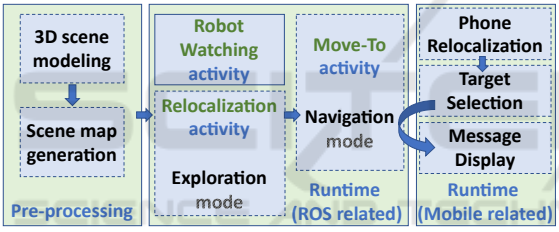


Figure 4: Overall workflow of the sytem including several steps, modes and activities, with runtime being detailed between ROS related tasks and mobile oriented tasks.

4.2.1 Pre-processing Processes

The scene in which the robot operates is first modeled. The modeling process is twofold, including 3D scene modeling and scene map generation, both required at runtime. The 3D scene modeling module is described in Subsection 5.2. The scene map is a 2D representation of the 3D scene model and it is used in the runtime period to support robot relocalization and navigation. The scene map computing module is described in Subsection 5.3. This module also determines the ”ground area”. This pre-processing step is only required once but must be performed again each time the scene layout changes.

4.2.2 Runtime Processes

The part of the workflow dedicated to the robot includes specific elements referred as modes and activities, which are presented in Figure 4. We have split the robot behavior into two modes named “exploration” and “navigation”, each of them including one or several activities corresponding to a given task to accomplish.

At runtime period, the first activity to be launched is the Robot Watching activity, in charge of detecting and periodically checking the presence of the robot in the system (connected, ready). This is also the last activity to be stopped.

Assuming a robot is detected, the first mode to be activated is exploration, which involves launching all the standard ROS nodes enabling the robot building a robot map of its surroundings. Starting with the Relocalization activity, the robot moves a few seconds straight forward then stops to build the robot map. This latter is registered with the scene map generated during pre-processing to estimate the robot pose in the reference model (see Subsection 5.4). If the relocalization request does not succeed, more time is given to the robot to further explore and capture the environment, then a new relocalization request is sent.

If the robot relocalization succeeds, then the exploration mode is stopped along with related ROS nodes, and the navigation mode is launched. It starts all the ROS nodes needed for navigation (path estimation, ...) with the particularity of using the scene map rather than the partial robot map. Obstacle detection and related path computation are however dynamically updated using live information update, as commonly used in ROS environment.

As for the mobile phone, it is first relocalized in the scene (see Subsection 5.5). When the user selects a target and requests the robot to move to this designated target, then the Move-To activity of the robot is engaged, using the target point as a standard ROS goal destination. The task is done by polling the various messages related to the navigation operation: the dynamic robot position is updated several times per second, and the final success or failure of the robot route is also polled, then forwarded to the system and the user in the relevant coordinate system. Textual explanations are provided to the user in all cases, using a pop up to display the message on the screen.

5 PROCESSING MODULES

The processing modules are hosted on the system server for performance considerations.

5.1 Coordinate System Management

The AR-Bot system maintains knowledge about the environment of the user and the robot as a recon-

structed 3D model, while also getting updated information about their respective position and orientation within this environment. However, the mobile application and the robot use different coordinate systems. The server is in charge of transforming the position data between different coordinate systems. More precisely, the 3D position of the designated target needs to be represented within the 2D map representation which is used by the robot for navigation; reciprocally, the periodically updated robot position, provided with respect to its 2D map, needs to be converted back into a 3D representation compatible with the AR-based user interface.

We distinguish the following coordinate systems (schematically represented in Figure 1a):

- Model Space (MS): the coordinate system of the reconstructed scene model,
- Robot Space (RS): the robot map coordinate system used for the robot navigation,
- World Space (WS): the coordinate system of the mobile device AR session. To track the mobile device in the physical space we rely on the world tracking concept of the AR Foundation framework available within Unity (ARFoundation, 2020), so that at every instant we get the pose of the mobile device with respect to the so-called "World Space" (WS), which varies for each session since it directly depends on the real world position that the session starts with.
- Camera Space (CS): the coordinate system attached to the camera of the mobile device.

5.2 3D Modeling

Various solutions can be used for the reconstruction of a 3D scene model, depending on available sensors (depth sensors, color cameras). We decided to develop our overall AR-Bot system without any use of depth sensors, so that most smartphones can be used. Importantly, the captured data must enable the subsequent relocalization of the phone and the robot.

For the 3D modeling of the scene, a set of images is captured and sent to a tuned photogrammetry pipeline based on OpenMVG (Moulon et al., 2016). This includes an important rescaling step which is interactively performed by the user, once per scene reconstruction. This step ensures that the reconstructed scene scale corresponds to the real world one. The number of images depends on the complexity of the environment (in dimension, texture, etc.). For instance, the room in Figure 5 has required about 50 images to be modeled.

A 3D point cloud is generated as an output further used to estimate the scene map and the ground area as explained in Subsection 5.3. Along with this 3D point cloud, the image poses and the key-points extracted during the reconstruction are also stored.

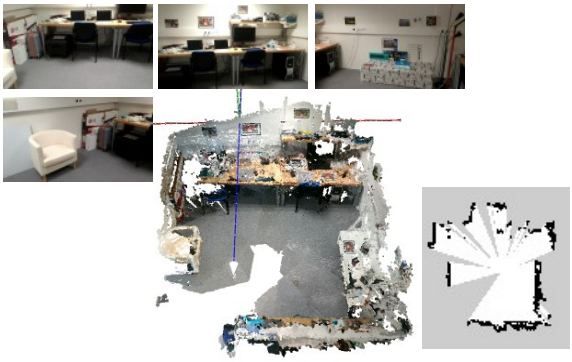


Figure 5: 3D modeling stage: from image sequence (only 4 are shown) to dense scene point cloud (centre), allowing the generation of a scene map at the robot height (right), which is compatible with ROS use; occupied pixels are black, free pixels are white, and unknown pixels are grey.

5.3 Scene Map and Ground Area

The control of the robot requires a 2D scene map, which is computed during the pre-processing step, as presented in Figure 4. Within this step we also determine the ground area, which is needed in the user interface to provide feedback on the relocalization and to select the target (see Subsection 4.1). The generation of both the scene map and ground area is based on the analysis of the reconstructed 3D point cloud.

Given the height of the robot LiDAR, a slice 3D point cloud is cropped in parallel to the ground plane at the robot height to generate a 2D scene map. To ensure having enough data, we also crop the partial data above and below the slice plane with a predefined margin. Then, by using the same meta-data as the robot map (e.g. map resolution, pose of map origin, pixel values to indicate occupancy probability), the cropped point cloud is projected onto the image plane, whose pixels are valuated to indicate whether they are occupied, free or unknown. An example of 2D scene map is shown in Figure 5. Note that at this stage, the scene map must be reformatted to match the ROS underlying map representation, hence enabling the use of ROS navigation.

In addition, planes are extracted from the 3D point cloud based on geometric criteria, then classified into horizontal and vertical planes, assuming that the gravity direction is the inverse direction of the Y-axis in the Model Space. The ground plane is determined as the furthest significant horizontal plane along the gravity direction. The wall planes are selected among the vertical planes that surround the scene point cloud.

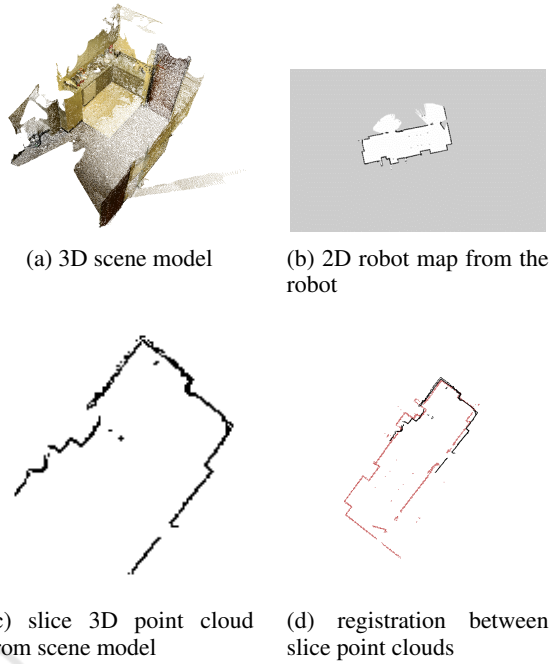
Finally, ground corners are extracted as the intersection points between the wall planes and the ground plane, which defines the ground area.

5.4 Robot Relocalization

The relocalization and navigation of a robot using ROS is a standard use case which is commonly solved with dedicated nodes. These nodes process data coming from the robot LiDAR and from wheel sensors (odometry). They enable the computation of a 2D robot map around the robot, and the estimation of its location. However, both relocalization and navigation are accomplished in the Robot Space, the coordinate system attached to the robot. In order to control the motion of a robot with the AR-Bot application, it is necessary to locate this robot in the Model Space, with respect to the scene model. The problem of robot relocalization is hence regarded as computing the transformation between the current robot map and the 3D scene model. Therefore, while the target destination is first specified in the Model Space, it must be converted into the robot map to enable the autonomous navigation of the robot. Besides, the scene map generated in Subsection 5.3 can also be transformed to replace the current robot map if necessary.

In our work, the computation of the transformation between the 2D robot map and the 3D model is accomplished by registering their corresponding slice point clouds. In Figure 6a, the 3D point cloud of a domestic scene is reconstructed using the pipeline proposed in Subsection 5.2, and the 2D robot map captured by the robot is shown in Figure 6b. These heterogeneous data should be converted into a consistent representation for the registration. For the scene point cloud in Figure 6a, a slice point cloud (Figure 6c) is cropped in parallel to the detected ground plane with the known height of the robot LiDAR. For the 2D robot map, the occupied pixels (black in Figure 6b) are converted to a slice point cloud (red in Figure 6d) using the map meta-data (resolution, origin, etc.). The conversion into slice point clouds constrains the relocalization/registration problem to 2D and reduces the number of parameters to be optimized.

In the registration process, a coarse-to-fine strategy is employed at different levels of data representation. For the two slice point clouds, the structural representations are first extracted, e.g. lines and key points. Then an initial alignment is implemented based on these structural representations to get a coarse result using the algorithm of 4-points congruent sets (Aiger et al., 2008). To refine the registration, an ICP-based method is applied to the two slice point clouds, initialized with the coarse alignment.



(a) 3D scene model

(b) 2D robot map from the robot

(c) slice 3D point cloud from scene model

(d) registration between slice point clouds

Figure 6: Robot relocalization in scene model. In (d), the slice point cloud of the scene model is in black, while the slice point cloud of the 2D robot map is in red.

The relocalization is considered as being successful when two conditions are met: 1) the ratio between the area sizes of the partial robot map and the scene map is above a given threshold value (set to 0.3), which guarantees that the partial robot map contains enough information for the registration; 2) the registration error, defined as the maximum point-to-point distance between the corresponding points of both slice point clouds, is below a given threshold value (set to 15 cm). In this case, we consider that the robot is successfully relocalized in the Model Space. An example of registration result is shown in Figure 6d. The transformation between the 3D scene model and the 2D robot map is retrieved using the transformation between these two slice point clouds. Thus, the navigation to the target destination can be accomplished by ROS nodes with obstacle avoidance using the captured robot map or the transformed scene map.

5.5 Phone Relocalization

On the mobile device side, we have developed a user-friendly AR application powered by Unity. For the relocalization of the mobile device in the environment, we rely on our client-server architecture: the client mobile device captures a single camera frame and sends it to the server for processing.

When the server receives a relocalization request, it launches the relocalization computation based on

OpenMVG to relocalize the image into the scene reconstructed during pre-processing. The output of this relocalization computation is the camera pose in the Model Space, at the time the request image was captured. As said earlier, we rely on AR Foundation to track the mobile device in the World Space all along the AR session. To bridge the gap between the World Space and the Model Space, we transit through the Camera Space at the time the image to be relocalized was captured, and thus simply multiply transform matrices to finally reach the Model Space. The camera pose in the World Space is provided by AR Foundation and stored when capturing the request image. The camera pose in the Model Space is computed on the server by the relocalization module.

6 EXPERIMENTATION AND DISCUSSION

For our experiments, we used a TurtleBot3 BURGER robot (TurtleBot3, 2020), for which the original low-range LiDAR was upgraded to a LiDAR RPLIDAR A2M8 (2D scan on 360°, range up to 12 meters). This robot is a 3-wheel low-size robot, fully controlled through a multi-interface and a controller card chained to a common Raspberry Pi 3 card. It runs a Raspbian Linux distribution as well as ROS packages needed for ROS environment to manage this specific robot model and equipment.

We used two different smartphones to validate the fact that the offline 3D reconstruction and the runtime phone relocalization can be performed with different phone models. The color pictures used as input of the 3D reconstruction pipeline were captured with the rear high-resolution camera of an Asus ZenFone AR (with no use of the depth sensing camera), while the end-user mobile device was the Google Pixel 2 XL, an Android smartphone supporting ARCore.

The robot controller and the AR-Bot server were both hosted on the same Linux PC.

We experimented the system in different rooms of the lab, with different geometric characteristics and different acquisition conditions. Figure 7 shows some examples captured in our main demo room.

In our informal testing involving targeting task, and in comparison to the traditional pointing on a static 2D floor map, we found that our AR approach significantly improves mobile robot navigation in terms of accuracy, efficiency and user experience satisfaction. If our AR system imposes the users to have the target in sight when selecting it, it is not perceived as a limitation since they get the satisfaction of visually perceiving live the virtual target overlapping the desired location. Also, because our centralized solution does not require any manual intervention to designate the initial location of the robot w.r.t. the phone, the users can start controlling it without even having to think about its current location.

The navigation task is considered successful when the robot reaches the target designated with the phone. The quality of the experience therefore mainly depends on two factors: the quality of the robot relocalization on one hand, and the quality of the phone relocalization on the other hand.

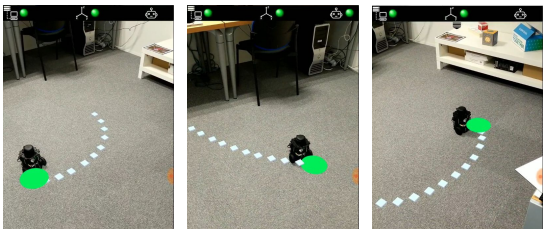


Figure 7: Examples of robot final position when reaching the target.

6.1 Robot Relocalization

The robot relocalization is mainly impacted by the limitations in the LiDAR sensor accuracy, which generally appear in case of very poor or ambiguous geometric details. For instance, if the robot is close to a long planar wall with no geometric features, or if the robot is located in a large room with no furniture or wall within the LiDAR range, then the relocalization cannot be achieved. In this case it is necessary that the robot acquires more data before performing the relocalization process. In our implementation, after being started, the robot autonomously moves for 30 seconds for scanning its environment before sending the relocalization request. In case of failure, a new request is sent 30 seconds later to enable the robot to further capture the environment. The impact on the experience is that the user might have to wait longer for the robot to start the task.

In some cases, although the initial relocalization of the robot is correct, we found out that the internal robot tracking system could sometimes fail. This typically happens when the odometry information is taken into account whereas it should not (for instance, wheels slipping on the floor when the robot is stuck under furniture such as a chair). Using additional information coming from LiDAR sensor could help a lot to detect and handle such cases.

6.2 Phone Relocalization

The computation time required for phone relocalization (including data transfers) is about 2 seconds. We implemented it as an asynchronous task so that the application does not freeze during this time. Since the relocalization approach is based on the output of the 3D reconstruction pipeline, no specific marker is required in the scene. Assuming a reasonably textured scene, the phone relocalization can be computed from any frame and any point of view, as long as the areas visible from this point of view have already been observed and reconstructed when modeling the environment.

The precision of the phone relocalization depends on many factors including the precision of the 3D reconstruction, the accuracy of the intrinsic parameters of the cameras, the image quality and the size of the overlapping regions in the request and target images.

As a first experiment to qualitatively evaluate the phone relocalization accuracy, we have displayed small virtual objects at pre-determined locations that correspond to locations of real physical objects (typically, a small virtual red cube on top of the origin of the reconstructed environment, or X, Y and Z RGB axes to illustrate the basis of the environment). Such a virtual red cube is visible in Figure 8 where a real poster was voluntarily stuck on the wall for this specific evaluation use (also used for the interactive rescaling step performed during pre-processing as mentioned in Subsection 5.2). Please note that this poster is NOT used for marker-based relocalization or marker-based tracking.

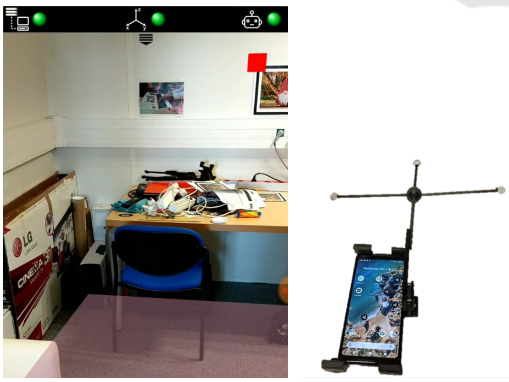


Figure 8: Phone relocalization evaluation. Left: Virtual red cube displayed on the top of the image to visually validate the relocalization accuracy. Right: Smartphone prototype with OptiTrack marker used during our experiments unfortunately suspended due to lockdown.

From what we observed in the first tests:

- the relocalization accuracy varies between 5 and 20 cm,
- the relocalization is successful in 9 cases out of 10,
- blurry request images should be carefully avoided, meaning that the user must pay particular attention to stabilize the device when sending the relocalization requests,
- some new relocalization computations may be required during a session to compensate for tracking drifts or failures (e.g. after few seconds in darkness if light has been switched off/switched on).

In this type of application dedicated to robot navigation within a room (for cleaning tasks for instance), an error of twenty centimeters on the target location remains acceptable.

The evaluation of both the robot and the phone relocalization quality clearly deserves a significant evaluation study, preferably based on some ground-truth references. We started an encouraging quantitative evaluation involving an OptiTrack kit (Figure 8) but it was unfortunately suspended as we could not access our facilities anymore due to COVID-19 containment.

7 CONCLUSION

We have presented a full solution to control an autonomous robot equipped with a LiDAR, using a simple and intuitive AR-based interface running on a mobile device. It relies on an ecosystem comprising the robot, the mobile device, a robot controller and a central server. The added value of the system is to have both phone and robot independently located within the same 3D space. As a result, contrarily to other comparable systems, they do not need to be explicitely spatially registered to each other nor in direct line of sight, and it is possible for instance to summon a robot which is not visible by the phone. Furthermore, their respective positions within the 3D scene can be accessed and displayed at any time. The key point of the solution is the use of dedicated registration algorithms and their integration into a global system. Experimentations have showed that the relocalization of both the robot and the phone is accurate enough to achieve the desired task. The proposed solution was designed to be easily extended and may be seen as a general architecture supporting intuitive AR interfaces for in home devices interactions. The next step is to assess the system with a quantitative accuracy evaluation and a proper user study.

A valuable improvement would be the automatic management of the image-based phone relocalization, without having the user to explicitly send a request image. Another point that would also deserve future investigations is the automatic detection of erroneous

positioning of the robot, in order to automatically launch the relocalization process whenever required. This would be useful when the user takes the robot to place it somewhere else without notifying the system ("kidnapping" problem), or when the robot gets temporarily stuck in a place (under a piece of furniture, on a carpet...). As a longer-term work, a full home network environment could be considered, with multiple robots (possibly of different types: vacuum cleaner, washer, domestic robot) and multiple users, each user having different roles and rights.

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