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**Title: [FS\_ARSpatial] Spatial Computing Functions**

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# Introduction

The Study on Spatial Computing for AR Services (FS\_ARSpatial) was approved during the SA#104 meeting. The set of AR functions which process sensor data to generate information about the world 3D space surrounding the AR user are often collectively referred to as spatial computing. Spatial computing includes functions such as tracking (to estimate the movement of the AR device at a high frequency), relocalization (to estimate the pose of the AR device), mapping (to reconstruct the surrounding space), and semantic perception (to process the captured information into semantical concepts).

The resulting output of spatial computing is a set of spatial mapping information that is organized in a data structure called the XR Spatial Description for storing and exchanging the information.

This document provides a description of the main spatial computing functions and identifies the relevant set of spatial mapping information.

# Definitions

**Spatial Computing:** AR functions which process sensor data to generate information about the world 3D space surrounding the AR user.

**Spatial mapping:** The process of mapping real-world surfaces into the virtual world.

**XR Spatial Description:** a data structure describing the spatial mapping of the real world using anchors, trackables, camera parameters and visual features.

# References

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# Spatial Computing Functions

### 4.1 General

XR spatial computing encompasses a set of functions which process sensor data to generate information about the world 3D space surrounding the AR user. These include functions such as relocalization (establishing the position of users and objects within that space), anchoring, 3D Model construction, segmentation and labeling (semantic perception) and light extraction, are achieved through a combination of advanced sensors, cameras, and algorithms that enable devices to understand and interact with the three-dimensional space around them.

This requires accurately localizing the AR device worn by the end-user in relation to a spatial coordinate system of the real-world space. Vision-based localization systems reconstruct a sparse spatial mapping of the real-world space in parallel (e.g., SLAM). Beyond the localization within a world coordinate system, which is usually based on a sparse spatial map, dense spatial mapping of objects is also essential in order to place 3D objects on real surfaces and provides the ability to occlude objects behind surfaces, do physics-based interactions based on surface properties, provide navigation functions, or provide a visualization of the surface.

For the purpose of understanding and perceiving the scene semantically, machine-learning and/or artificial intelligence may be used to provide context for the observed scene.

The output of spatial computing is spatial mapping information that is organized in a data structure called the *XR Spatial Description* for storing and exchanging the information. Some spatial computing functions may also take an XR spatial description and may result in updates to the XR spatial description. Spatial computing functions typically include data exchange and require a network architecture.

An AR device may provide sensor data to the spatial computing function to create or update the spatial mapping information. The device may also access the spatial computing function to retrieve different spatial mapping information depending on the needs of the XR application.

The main functions provided by a spatial computing service are given in Figure 1 and explained in the following subclauses.

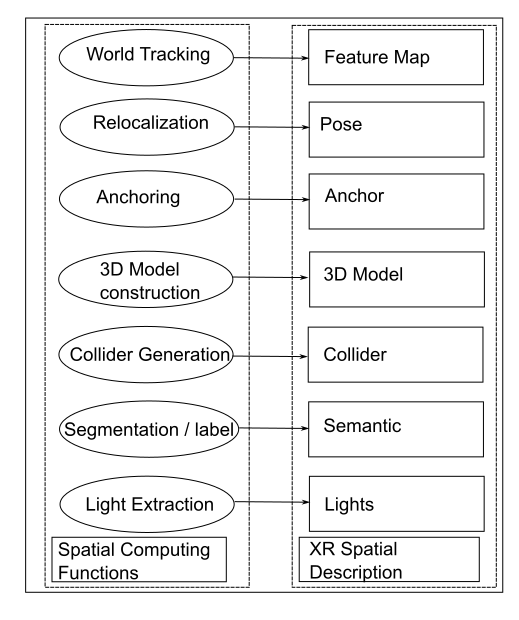


Figure 1 - Spatial computing functions

### 4.2 World Tracking

Simultaneous Localization and Mapping (SLAM) is a technology that allows an AR device to create a map of its environment while simultaneously determining its own location within that map. The goal of SLAM is to obtain a global, consistent estimate of the camera path. The map of the environment is usually kept for helping localization. SLAM achieves its objectives using two parts: (1) a tracking mechanism, which solves the localization problem by comparing the new input data with the currently existing map, and (2) a mapping mechanism, which supports the tracking by providing, maintaining and expanding the map itself based on the information obtained from the input data obtained by the tracking part. Loop detection is the process of identifying when a device has returned to a previously visited location. When a loop is detected, this information is used to reduce the drift in both the map and pose. Loop closure is the process of correcting the device’s pose and map based on the detected loop. This involves adjusting the device’s trajectory and the map to ensure consistency and eliminate drift. Beside localization, loop detection and loop closure are two main challenges in SLAM.

The visual-based approaches can be divided into three main categories: visual-only SLAM, visual-inertial SLAM, and RGB-D SLAM [xx].

Visual-only SLAM refers to the techniques based only on 2D images provided by a monocular or stereo camera. This type of SLAM uses images captured from one or more cameras to detect features in the environment, track their movements across frames, and estimate the motion of the camera and the structure of the environment. The primary challenge in visual-only SLAM is dealing with scenarios where visual information is poor, such as in low-light conditions or in textureless environments. It is also susceptible to accumulating drift over time since it only relies on visual data. Robustness of the algorithms can be increased by adding information from an inertial measurement unit (IMU). Visual-inertial SLAM techniques combine data from cameras and inertial sensors (accelerometers and gyroscopes) to estimate the pose of the device. RGB-D SLAM techniques employ a depth sensor and leverage depth data alongside visual data, which simplifies the mapping process but can be limited by the operational environment of the depth sensors (more suitable to indoor environments).

Another algorithm used for world tracking is the visual inertial odometry which combines information from the device’s motion sensing hardware and computer vision analysis of the scene visible to the device’s camera. The process recognizes notable features in the scene image, tracks differences in the positions of those features across video frames and compares that information with motion sensing data. The result is a high-precision model of the device’s position and motion.

The main difference between visual SLAM and visual odometry lies in considering, or not, the global consistency of the estimated trajectory and map. While visual odometry performs only local optimizations, visual-SLAM algorithms also employ loop closure detection [xx].

By aligning the pose of the virtual camera that renders the 3D content with the pose of the device's camera, virtual content can be rendered from the correct perspective. The rendered virtual image can be overlaid on top of the image obtained from the device's camera, making it appear as if the virtual content is part of the real world.

As the AR device moves through the world, SLAM is used to understand where the device is relative to the world around it. The process detects visually distinct features in the captured camera image called *feature points (=feature map)* and uses these points to compute a change in location. The visual information is combined with inertial measurements from the device's IMU to estimate the pose (i.e., position and orientation) of the camera relative to the world over time.

ARCore supports world tracking using visual-inertial SLAM [4], while ARKit uses Visual Inertial Odometry [5].

For world tracking, the following input data may be used:

- Sensor data:

* Images captured by AR Device
* IMU data
* pose of AR Device
* Depth maps

### 4.3 Relocalization

Relocalization is a function that is used to estimate the pose of the AR device at initialization, when tracking is lost, or regularly to correct the drift of the tracking (TR 26.998 [3] clause 4.2.3). Cameras capture the real world, while sensors (accelerometers, gyroscopes, and depth sensors) contribute additional data for mapping and positioning. Computer vision algorithms process this data to determine the location and orientation of the device relative to its environment.

SLAM, Visual Localization, e.g., Visual SLAM (vSLAM), or Visual Positioning System (VPS) are all algorithms that can be used for mapping unknown environments while also maintaining the localization of the device/user within that environment, as explained in TR 26.928 [2] clause 4.1.4.

For relocalization, the following input data can be used:

- Sensor data:

- images (for SLAM)

- local pose of AR Device

### 4.4 Anchoring

Spatial Anchors are a concept in Augmented Reality that enable the persistence and stability of virtual content in the real world. Virtual objects or information are anchored to specific locations in physical space.

A spatial anchor acts as a marker or reference point in the real world that AR devices can recognize and track. These anchors serve as fixed reference points that AR devices can detect and use to position virtual content accurately relative to the real-world coordinates.

Spatial anchors are created using spatial mapping techniques, which involve capturing and analyzing the physical features of the surrounding environment. This can be done through depth-sensing cameras, LiDAR scanners, or other sensors to understand the geometry and spatial characteristics of the space.

Once the spatial mapping is performed, spatial anchors are placed at desired locations within the mapped environment. Anchor can be persistent for the entire duration of the session.

The three main AR SDK (Meta, Google and Apple) offer anchoring solution:

- ARCore, Cloud Anchor [6]

- ARKit, World Map [7]

- Meta Quest, Spatial Anchor [8]

For anchoring, the following input data can be used:

- Anchor pose for creation

- Sensor data:

- images

- pose of AR device

- LiDAR data

### 4.5 3D Model Construction

Spatial computing enables the creation of accurate 3D models of surrounding space. It accurately captures real-world scenes and objects using 3D scanning techniques or photogrammetry. These 3D models can be displayed in immersive 3D environments in real-time to provide users with a sense of interactivity and presence.

The 3D model of a real-world environment may also be constructed collectively by aggregating meshes captured by an AR device.

HoloLens (Microsoft) and AR SDKs from Apple and Meta can all build a 3D model of the surrounding environment in real time.

To build the 3D model, the following input data can be used:

* Sensor data:
* Images captured by AR Device
* pose of AR Device
* Depth map (image or texture)
* Mesh captured by AR Device

#### 4.5.1 Example: HoloLens (Microsoft)

HoloLens [9] has built-in cameras that continuously scan the environment, allowing it to construct virtual world geometry for real-world objects. Figure 2 demonstrates examples of 3D models constructed by HoloLens.

A person wearing virtual reality goggles

Description automatically generatedA green grid of lines

Description automatically generated

Figure 2 - HoloLens 3D Model construction and spatial mapping (from Unity)

### 4.6 Segmentation and labeling

3D Semantic Segmentation is a task that involves dividing a 3D point cloud or 3D mesh into semantically meaningful parts or regions. The goal of 3D semantic segmentation is to identify and label different objects and parts within a 3D scene. This is similar to semantic image segmentation where sections of an image are separated into clusters of pixels relating to corresponding objects, with respective classifications.

The three main AR SDKs (Meta, Google and Apple) support segmentation and labeling solutions. However, the domain in which these functions are performed (i.e., 2D vs. 3D) may differ from one SDK to another.

#### 4.6.1 Example: Space Setup (Meta)

Space Setup [10] automatically identifies and marks furniture in an indoor room. Segmented objects in Space Setup may assigned one of the following labels: floor (not displayed), ceiling (not displayed), wall (not displayed), door, table, sofa, storage, screen, or bed. Objects are represented with bounding boxes around each identified object and the segmentation can be adjusted manually.

A screenshot of a computer

Description automatically generated

Figure 3 - Space Setup

#### 4.6.2 Example: RoomPlan API (Apple)

RoomPlan [11] is a Swift API that utilizes the camera and LiDAR Scanner on iPhone and iPad devices to create a 3D floor plan of a room, including key characteristics such as dimensions and types of furniture. The 3D object-detection pipeline recognizes 16 object categories directly in 3D.

Segmented objects in the RoomPlan API may be assigned one of the following labels: storage, sofa, table, chair, bed, refrigerator, oven, stove, dishwasher, washer/dryer, fireplace, sink, bathtub, toilet, stairs, or TV. Objects are represented with bounding boxes.

A screen shot of a room

Description automatically generated

Figure 4 - RoomPlan API

#### 4.6.3 Example: Scene Semantics API (Google)

The Scene Semantics API [12] provides real-time outdoor semantic information, which complements existing geometric information in ARCore. Given an image of an outdoor scene, the API returns a label for each pixel across a set of useful semantic classes. ARCore provides a classification with 12 labels, as shown in Figure 5.

A screenshot of a video game

Description automatically generated

Figure 5 - Scene Semantics API in ARCore

For segmentation and labeling, the following input data may be used:

- A set of reference labels (objects that will be segmented and labeled)

### 4.7 Collider Generation

Colliders are used to handle collision between objects. A collider is a component that defines the shape of an object for the purposes of physical collisions [13]. Colliders are invisible, and do not need to be the same shape as the object mesh.

The consistent handling of collisions between virtual and real objects requires real objects colliders. Hence, one of the functions provided by spatial computing platforms is the creation of colliders used by physics simulation engines. These colliders are generated based on the input 3D model of the surrounding environment.

Collision shape of the object may be defined using either primitive shapes or mesh-based shapes.

Primitive shapes, such as a box, sphere, capsule, cylinder, or cone, are best in terms of memory and performance but do not necessarily reflect the actual shape of the object. They are calculated based on the object’s bounding box [14].

Mesh-based shapes (e.g., convex hull or mesh) are calculated based on the geometry of the object and are therefore a better representation of the object.

A computer screen shot of a machine object

Description automatically generated

Figure 6 - Combination of primitive colliders [15]

A green banana on a gray surface

Description automatically generated

Figure 7 - Mesh collider [16]

Input data can be:

- The 3D Model

### 4.8 Light Extraction

The consistent rendering of virtual and real objects, including occlusion and lighting/shadowing aspects, requires a 3D model and the detection/extraction of light parameters. The 3D model (from a certain point of view) can be used by the rendering engine for compositing.

Lighting estimation is a technique used by augmented reality platforms to match the lighting of the virtual objects in the scene to the lighting of the real world surrounding the viewer. Real light data provide different parameters that represent different characteristics of a light source. Those parameters can be used to instantiate a virtual light (i.e., a virtual representation of a real light) with the same properties, to achieve consistency between real and virtual scene. This virtual light is set with the same pose as the real one.

In ARCore, the Lighting Estimation API provides detailed information about the lighting in a scene [17].



Figure 8 – Rendering without light extraction (left) vs. with light extraction (right). Real object shadow highlighted in red and virtual object shadows in green.

Figure 8 shows an example of an inconsistency between the shadows without light extraction (left) and a more consistent rendering with light extraction.

Some algorithms, based on cast shadow [18], use the 3D model of the real scene to estimate light source.

For light estimation, the following input data can be used:

- Sensor data:

- Images captured by AR Device

- Poses of AR Device

# Proposal

It is proposed to document the spatial computing functions described in this document, along with the definitions in section 2 and references in section 3, in the technical report for the study on spatial computing for AR services (TR 26.819).