



IEEE Standard 3D Map Data Representation for Robotics and Automation

IEEE Robotics and Automation Society

Developed by the
Standing Committee for Standards

IEEE Std 2751™-2025

STANDARDS

IEEE Standard for 3D Map Data Representation for Robotics and Automation

Developed by the

Standing Committee for Standards
of the
IEEE Robotics and Automation Society

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IEEE SA Standards Board

Abstract: Specifications for representing three-dimensional (3D) maps for robotics and automation are provided in this standard. A recommended format for exchanging map data among robots, computers, and other devices is defined in this standard. The representation format specified by this standard considers static maps and describes their elements and associated uncertainty independently of the geographic scale and sensor modalities used to build the maps. In particular, this standard (a) defines a hierarchy of terminologies related to 3D robot maps for robotics and automation; (b) specifies a data model for each element of the hierarchy; and (c) specifies a JSON format for map data exchange between different robots, computer systems, and devices. This standard provides formats for exchanging 3D map data between robots and devices (e.g., by transmitting them over a communication channel or by saving them on some storing devices). This standard is not intended to affect internal formats that robots and devices use to build, update, and use maps.

Keywords: automation, grid maps, IEEE 2751™, octrees, point clouds, polygonal meshes, robotics, three-dimensional maps.

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³ Available at: <https://ieeexplore.ieee.org/browse/standards/collection/ieee>.

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Introduction

This introduction is not part of IEEE Std 2751-2025, IEEE Standard for 3D Map Data Representation for Robotics and Automation.

This standard specifies three-dimensional (3D) map data models and formats intended for robot operations, including navigation and manipulation tasks. The standard does not prescribe the internal representations the robots should use but provides specifications for representing 3D maps with the aim of exchanging map data among robots, computers, and other devices.

To this end, this standard provides the following:

- a) A definition of a hierarchy of terminologies related to 3D robot maps
- b) A specification for a data model for each element of the hierarchy
- c) A specification for a JSON format for map data exchange between different robots, computer systems, and devices

Annex A provides a brief introduction to robot maps, including a few typical use cases of robot maps, and highlights the need for the 3D map data representation for robotics and automation (3D-MDR) standard.

Annex B presents some examples of the use of this standard.

Contents

1. Overview	10
1.1 Scope	10
1.2 Purpose	11
1.3 Background.....	11
1.4 Word usage.....	12
2. Normative references.....	12
3. Definitions, acronyms, and abbreviations	13
3.1 Coordinate systems and transformations	13
3.2 Maps	14
3.3 Map components.....	15
3.4 Map usage.....	15
3.5 Other definitions	16
3.6 Acronyms and abbreviations	16
4. Conventions.....	16
5. 3D map data models	17
5.1 Data models for local maps	23
6. 3D map data formats	30
6.1 GlobalMap.....	30
6.2 LocalMap.....	32
Annex A (informative) Background and industry practices	52
Annex B (informative) Examples of use	57
Annex C (informative) Bibliography.....	66

IEEE Standard for 3D Map Data Representation for Robotics and Automation

1. Overview

This standard specifies a common representation of three-dimensional (3D) maps intended for robot operations in indoor and outdoor environments. This standard is called 3D Map Data Representation for Robotics and Automation (3D-MDR).

1.1 Scope

This standard provides specifications for representing 3D maps. This standard defines a recommended format for exchanging map data among robots, computers, and other devices. The map representation format specified by this standard only considers static maps; in other words, moving elements are not explicitly represented in the maps. Additionally, no limit is placed on geographic scale or sensor modalities in applying this standard.

To this end, the standard:

- a) Defines a hierarchy of terminologies related to 3D robot maps for robotics and automation
- b) Specifies a data model for each element of the hierarchy
- c) Specifies a JSON format for map data exchange between different robots, computer systems, and devices

This standard expands upon IEEE Std 1873-2015, IEEE Standard for Robot Map Data Representation for Navigation which covers two-dimensional (2D) robot maps. The maps that can be represented with the IEEE Std 1873-2015 can also be represented with this standard. However, the JSON format defined by this standard is different (i.e., not a superset) of the XML format employed by the IEEE Std 1873-2015.⁶

This standard provides formats for exchanging 3D map data between robots and devices (e.g., by transmitting them over a communication channel or by saving them on some storing devices). This standard is not intended to affect internal formats that robots and devices use to build, update, and use maps. These maps represented in these internal formats could be translated to and from the format prescribed by this standard. As a consequence, the formats provided by this standard are agnostic about how maps have been built (e.g., using LIDARs or cameras or multiple sensors).

⁶ Information on references can be found in Clause 2.

1.2 Purpose

The purpose of this standard is to define a common representation for robot 3D map data, including metric and topological maps. It is intended to facilitate interoperability among different robots, extending operational range and application areas of the robots. While facilitating technological advancement for spatial mapping carried out by robots and/or other relevant devices, this standard does not cover the activities of building, maintaining, updating, and revising robot maps.

1.3 Background

This standard is one of several other standards related to 3D representations of environments already published or under development from other standard developing organizations (SDOs), including the International Organization for Standardization (ISO) and the Open Geospatial Consortium (OGC) which developed the City OpenGIS Geography Markup Language (GML)⁷ and the 3D Tiles⁸. The scope of this standard compared against the scope of other similar standards is defined in Table 1. The standards with the same scope as this standard are either not explicitly developed for robotics (like Universal Scene Description, or USD)⁹ or are developed for simulation (like the Simulation Description Format, or SDF¹⁰, and the eXtensible 3D format, or X3D¹¹), in both cases without fully accounting for uncertainty affecting the elements of maps.

Table 1—Application scope of IEEE Std 2751 along with those of other related standards

Types	Room scale	Vista scale	Environment scale
Examples	Home, office, shop	Factory, terminal, farm, campus	Town, district, city
Applications	Robot vacuum cleaner, robot companion, entertainment robot	Agricultural robot, logistics robot, surveillance/security robot	Autonomous car, unmanned aerial vehicle, military robot
Target standard		ISO map service (2D representation)	ISO GML, OGC CityGML, GDF [B4]
	OGC IndoorGML		
		OGC 3D Tiles	
	IEEE Std 1873-2015 Standard for Robot Map Data Representation for Navigation [2D representation]		
	IEEE 3D Map Data Representation for Robotics and Automation (3D-MDR), USD, SDF, X3D		

⁷ Available at: <https://www.ogc.org/standard/gml/>

⁸ Available at: <https://www.ogc.org/standard/3dtiles/>

⁹ Available at: <https://openusd.org/>

¹⁰ Available at: <http://sdformat.org>

¹¹ Available at: <https://www.web3d.org> (and ISO/IEC 19775 [B4] and related standards)

1.4 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{12,13}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 754™-2019, IEEE Standard for Floating-Point Arithmetic.^{14,15}

IEEE Std 1873™-2015, IEEE Standard for Robot Map Data Representation for Navigation.

ISO 8373:2021, Robotics—Vocabulary.¹⁶

ISO 8601-1:2019, Date and time—Representations for information interchange—Part 1: Basic rules.

ISO 9787:2013, Robots and robotic devices—Coordinate systems and motion nomenclatures.

ISO 19111:2019, Geographic information—Spatial referencing by coordinates.

ISO/IEC 9899:2018, Information technology—Programming languages—C.¹⁷

ISO/IEC 10646:2012, Information technology—Universal Coded Character Set (UCS).

ISO/IEC 11578:1996, Information technology—Open Systems Interconnection—Remote Procedure Call (RPC).

ITU X.680-X.693, Information Technology—Abstract Syntax Notation One (ASN.1) & ASN.1 encoding rules.¹⁸

WGS84, World Geodetic System 1984 (also known as EPSG:4326).

¹² The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

¹³ The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

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¹⁸ ITU standards are available from the International Telecommunication Union (<https://www.itu.int/>).

3. Definitions, acronyms, and abbreviations

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹⁹

The references reported in the notes are provided to link the defined concepts to similar concepts used in other standards. In this sense, the references are reported for further information only and do not represent the sources of definitions nor contain requirements needed to understand and implement this standard.

The terms are categorized according to functionalities and are listed in the respective categories in an incremental order of use.

3.1 Coordinate systems and transformations

absolute pose: A geo-referenced pose that identifies a unique position and a unique orientation in the physical world. *Syn:* **spatial reference.** A coordinate system whose position and orientation are defined with respect to Earth is also called a coordinate reference system and is composed of a coordinate system and a datum, which provides the geo-localization. OGC GeoPose defines methods for the interoperable exchange of absolute poses with coordinate reference systems anchored to the Earth's surface.

NOTE—See ISO 19111:2019 and OGC GeoPose 1.0 [B9].^{20,21}

Cartesian coordinate system: A coordinate system that gives the position of points relative to n mutually perpendicular axes.

NOTE—See ISO 19111:2019 and ISO 9787:2013. Since this standard focuses on 3D maps, $n = 3$ and the axes are called x , y , and z with x pointing forward, y pointing left, and z pointing up.

coordinate systems: A set of mathematical rules for specifying how n coordinates are to be assigned to points in a n -dimensional space. *Syn:* **reference frame.**

NOTE—See ISO 9787:2013 and ISO 19111:2019.

coordinate transformation: A process of changing the coordinates of a pose from one coordinate system to another, through applying rotation and translation in this order. A transformation is a way of representing one coordinate system (or one of its points) with respect to another one. Since this standard focuses on 3D maps, coordinate transformation is limited to 3D translations and rotations.

NOTE—See ISO 8373:2021 and ISO 19111:2019.

global coordinate system: A coordinate system that is defined over the entire space for robot operation. The origin is defined by users according to their requirements. *Syn:* **allocentric coordinate system; world coordinate system.**

NOTE—See ISO 9787:2013.

local coordinate system: A coordinate system that is defined over a region of the entire space for robot operation. The origin of a local coordinate system is defined by users according to their requirements. *Syn:* **egocentric coordinate system.**

¹⁹*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

²⁰ The numbers in brackets correspond to those of the bibliography in Annex C.

²¹ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

rotation: In 3D, a vector R of 4 scalar numbers that represents the quaternion associated with the rotation. See Clause 5 for details and use.

NOTE—See 4.3 Rotations in ISO 9787:2013 for further details.

spherical coordinate system: A 3D coordinate system in which position is specified by one distance coordinate and two angular coordinates.

NOTE—See ISO 19111:2019.

translation: In 3D, a vector T , whose scalar components are displacements along the x -, y - and z -axes of a given Cartesian coordinate system, respectively, and are measured in meters.

NOTE—See 4.2 Translations in ISO 9787:2013 for further details.

uncertainty: Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

NOTE— See ISO/IEC Guide 98-1:2024 [B8].

3.2 Maps

NOTE—For all definitions in this clause see IEEE Std 1873-2015. The following definitions refer to 3D maps representing 3D spaces.

continuous metric map: A map that maintains a list of geometric features (such as points, lines, polygons, planes, ...), the coordinates of which use a continuous range of values. *Syn:* **geometric map; vector map.**

discrete metric map: A map that decomposes the representation of the environment into (usually cubic) cells that constitute atomic pieces of information about the environment. *Syn:* **voxel map; grid map.**

global map: A set (collection) of local maps, possibly with information about their relative poses and their poses with respect to a global coordinate system. A global map is a directed graph consisting of vertices and arcs. Vertices represent local maps, and arcs represent transformations (rotations followed by translations) to move the coordinate system of the ending vertex to the coordinate system of the starting vertex. A special null transformation is used when there is no metric information about the relative displacement of two vertices. “Global” does not mean worldwide, but just indicates a collection of local maps (also called atlas). Local maps in a global map can refer to the same region of space and represent different layers of representation.

local map: A metric map that represents a region of the entire space for robot operation.

map: A map (or robot map) represents the robot’s knowledge about its workspace and surrounding environment as well as objects contained therein.

metric map: A collection of map elements (for example, voxels, points, and polygons) with the following property: given any two elements, a and b , in the map and a definition of metric distance, the distance between a and b can always be calculated. It should be noted that the preceding “any” is what makes metric maps different from topological maps, where metric distance can in general be calculated only for some elements.

occupancy grid map: A map that is a discrete metric map where the content of each voxel indicates occupancy state of that voxel by an obstacle. Usually the content is related to the probability of occupancy.

topological map: A graph-based representation of an environment, comprising vertices and arcs, and their connectivity relations. Vertices (nodes) of a topological map represent characteristic features (for example, sensor readings, unique signature of the corresponding region, metric maps, and so on) of the environment. Arcs (edges) of a topological map represent direct (one-hop) connections (direct reachability) between neighboring vertices. An arc (edge) is an ordered pair of vertices (nodes), (t, h) , with the meaning that the arc is oriented from vertex t (the tail) to vertex h (the head)

3.3 Map components

feature: A representation of an environment pattern that differs from its immediate neighbors. For example, in an image-based representation of an environment, a feature is a portion of an image (representing some environment pattern) that exhibits distinctive characteristics in terms of intensity, color, or texture. Note that “feature” is used in Geographic Information Systems (GISs) with a different meaning to denote the label of an object.

landmark: A feature that is used for localization of a mobile robot. It is a feature whose pose in a coordinate system can possibly be measured (localized) by the robot’s sensors with respect to a given map.

NOTE—See ISO 8373:2021.

line segment: A straight line between two points.

node: A structure that is an element of a tree, that can contain value, condition, or any other data structure.

octree: A type of tree where each node has either exactly eight descendants or no descendants.

point: Location in space with an associated vector of characteristics.

polygon: Plane figure composed of consecutive line segments that form a closed chain.

tree: An abstract data type representing a hierarchical tree structure with a root and subtrees of children with a single parent node, represented as a set of linked nodes.

voxel: A cubical fragment of 3D space with an associated vector of characteristics.

3.4 Map usage

localization: The process of reconstructing the pose of a robot or identifying the pose of a robot within a given map.

NOTE—See ISO 8373:2021.

mapping: The process of constructing a map of an environment, representing landmarks, obstacles, free space, connectivity between locations, or any of their combinations.

NOTE—See ISO 8373:2021.

navigation: The process of deciding and controlling the direction of travel, derived from localization and a given map.

NOTE—See ISO 8373:2021.

pose: A combination of position and orientation in space. In a three-dimensional (3D) map, the pose of a mobile robot is represented by 3D position (x , y , z) and 3D orientation (θ , ω , ψ) with respect to a given coordinate system. See Clause 5 for details.

NOTE—See ISO 8373:2021 and OGC GeoPose 1.0 [B9].

3.5 Other definitions

universally unique identifier (UUID): A universally unique identifier (UUID) is 128 bit long and helps guarantee uniqueness across space and time.

NOTE—See ISO/IEC 11578:1996.

3.6 Acronyms and abbreviations

2D	two-dimensional
3D	three-dimensional
BIMs	Business Information Modeling
GIS	Geographic Information System
GML	Geography Markup Language
MDR	Map Data Representation
OGC	Open Geospatial Consortium
UML	Unified Modeling Language
UUID	Universally Unique Identifier
XML	eXtensible Markup Language
X3D	eXtensible 3D

4. Conventions

In this standard, the following conventions are used to indicate an obligation status, which is represented in the “M/O” column of the corresponding tables.

Obligation	Definition	Meaning
M	Mandatory	This attribution shall be supplied.
O	Optional	This attribute may be supplied.

Also, the Maximum Occurrence (MO) column indicates the maximum number of occurrences of the corresponding attribute values that are allowed, with N indicating no upper limit.

5. 3D map data models

This clause illustrates the standard data model for representing an environment as a 3D map used by robots. Some useful concepts are introduced first, and then specific data formats are given.

This standard uses a *global map*, which is a directed graph consisting of vertices and arcs, to represent collections of 3D *local maps*. Vertices represent local maps, and arcs represent transformations (rotations followed by translations) to move the coordinate system of the ending vertex to the coordinate system of the starting vertex, where a transformation $RT = \langle dx, dy, dz, X, Y, Z, W \rangle$ represents a counterclockwise rotation $R = \langle X, Y, Z, W \rangle$ around the origin, followed by a translation $T = \langle dx, dy, dz \rangle$ along the x, y and z axes of the local coordinate system of the ending vertex.

More precisely, a global map shall be represented by a directed graph $G = (N, A)$, where N and A are the vertices and the arcs, respectively. Each $n_i \in N$ is a local map represented as a metric map of different types (see 5.1). Graph G may have a special vertex n_G whose coordinate system is the global coordinate system F_G to which all the coordinate systems of the maps can be transformed. Each $a_{i,j} \in A$ connecting n_i and n_j is associated to a transformation $a_{i,j} = \langle dx, dy, dz, X, Y, Z, W \rangle$. Assuming that quaternions are unit, namely $\sqrt{X^2 + Y^2 + Z^2 + W^2} = 1$, the transformation $a_{i,j}$ moves a point $\langle x_j, y_j, z_j \rangle$ in the coordinate system F_j of map n_j to the corresponding point $\langle x_i, y_i, z_i \rangle$ in the coordinate system F_i of local map n_i is expressed by:

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} W^2 + X^2 - Y^2 - Z^2 & 2(X \times Y - W \times Z) & 2(W \times Y + X \times Z) \\ 2(X \times Y + W \times Z) & W^2 - X^2 + Y^2 - Z^2 & 2(Y \times Z - W \times X) \\ 2(X \times Z - W \times Y) & 2(W \times X + Y \times Z) & W^2 - X^2 - Y^2 + Z^2 \end{bmatrix} \begin{bmatrix} x_j \\ y_j \\ z_j \end{bmatrix} + \begin{bmatrix} dx \\ dy \\ dz \end{bmatrix}$$

The values X, Y, Z, W have the following geometrical meaning:

$$W = \cos \frac{d\theta}{2} \times \cos \frac{d\omega}{2} \times \cos \frac{d\psi}{2} - \sin \frac{d\theta}{2} \times \sin \frac{d\omega}{2} \times \sin \frac{d\psi}{2},$$

$$X = \sin \frac{d\theta}{2} \times \cos \frac{d\omega}{2} \times \cos \frac{d\psi}{2} + \cos \frac{d\theta}{2} \times \sin \frac{d\omega}{2} \times \sin \frac{d\psi}{2},$$

$$Y = -\sin \frac{d\theta}{2} \times \cos \frac{d\omega}{2} \times \sin \frac{d\psi}{2} + \cos \frac{d\theta}{2} \times \sin \frac{d\omega}{2} \times \cos \frac{d\psi}{2}, \text{ and}$$

$$Z = \sin \frac{d\theta}{2} \times \sin \frac{d\omega}{2} \times \cos \frac{d\psi}{2} + \cos \frac{d\theta}{2} \times \cos \frac{d\omega}{2} \times \sin \frac{d\psi}{2}$$

where

$d\theta$ is the rotation angle (measured counterclockwise) between the forward-pointed x-axis of F_i and the forward-pointed x-axis of F_j

$d\omega$ is the rotation angle (measured counterclockwise) between the left-pointed y-axis of F_i and the left-pointed y-axis of F_j

$d\psi$ is the rotation angle (measured counterclockwise) between the up-pointed z-axis of F_i and the up-pointed z-axis of F_j

$\langle d\theta, d\omega, d\psi \rangle$ are called Euler angles.

The standard uses 3D Cartesian coordinate systems with three perpendicular axes (x, y, and z) oriented using the right-hand rule (x pointing forward, y pointing left, and z pointing up).

Note that the preceding representation allows for the overlay of the regions represented by local maps in graph G . For example, if two vertices are connected to n_G by arcs representing the same transformation, the two corresponding local maps are overlaid, namely they represent the same portion of the environment.

Moreover, a special null transformation (which is different from the transformation $\langle 0,0,0,0,0,1 \rangle$) is used when there is no metric information about the relative displacement of two vertices (i.e., in the case of pure topological maps).

Uncertainty over the transformations can be added to the arcs. It is naturally specified as a 7×7 covariance matrix, with the 49 elements (of which 28 are independent) indicated by a pair of indices (row, column), as described later in Table 6. Note that it is up to the user to translate the 6×6 covariance matrices returned by systems considering Euler angles to the 7×7 covariance matrix of the standard (based on the use of quaternions).

The “from” and “to” coordinate systems of a transformation (and of the related uncertainty) are implicitly defined by the vertices of the graph of the global map that are connected by the arc representing the transformation.

Given an ordered pair of vertices n_i and n_j , at most a single arc shall be defined from n_i to n_j . Some applications could benefit from defining several arcs between the same two vertices (for example, one arc representing the measured transformation and then other one the optimized transformation). Extending the standard to define more arcs with different labels (representing the different meanings of the transformations) between two vertices could be done in future versions.

The hierarchy of the local map structure is depicted in Figure 1. In the Unified Modeling Language (UML) (see ISO/IEC 19505:2012 [B5]) diagrams of this clause, attributes that are not explicitly annotated as optional or as multiple are mandatory and with a single occurrence, respectively. To define a common map class, a concept of a local map is introduced. Specific types of maps, like dense grids, sparse grids, octrees, point clouds, and polygon meshes shall be inherited from the local map.²² Table 2 to Table 6 illustrate defining elements of classes related to the local map.

²² As defined in Clause 3, geometric and grid map are different terminologies used for continuous and discrete metric map, respectively. In this document, the two sets of terminologies are used interchangeably; the former set (geometric and grid map) is preferred for relatively more technical descriptions of map data representation while the latter set is used for more introductory illustration as in Introduction.

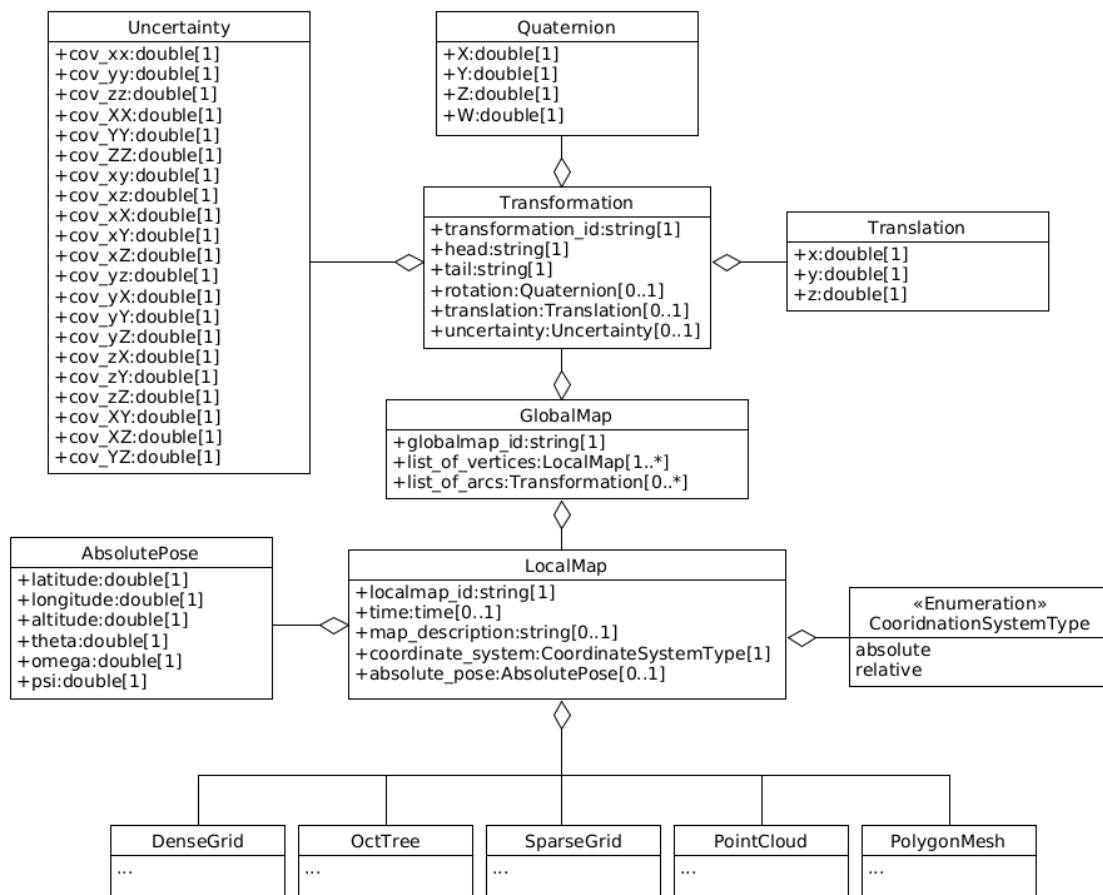


Figure 1—UML diagram of global and local map

Table 2—Description of GlobalMap

Attribute name	Description	M/O	MO	Data type	Reference
globalmap_id	Identifier of the global map.	M	1	string, UUID	ISO/IEC 9899:2018 ISO/IEC 10646:2012 ISO/IEC 11578:1996
list_of_vertices	List of vertices representing local maps.	M	N	List of elements of type LocalMap	A LocalMap is described in Table 3
list_of_arcs	List of arcs representing a rigid transformation between coordinate systems of two local maps.	M	N	List of elements of type Transformation	Transformation is described in Table 4

Table 3—Description of LocalMap

Attribute name	Description	M/O	MO	Data type	Reference
localmap_id	Identifier of the local map.	M	1	string, UUID	ISO/IEC 9899:2018 ISO/IEC 10646:2012 ISO/IEC 11578:1996
time	Time (including date) at which the local map has been built or last updated.	O	1	time	ISO 8601-1:2019
map_description	Information on acquisition of the map (robots, sensors, the owner, ...).	O	1	string	ISO/IEC 9899:2018 ISO/IEC 10646:2012
coordinate_system	Specifies if the coordinate system of the local map has an absolute (geo-referenced) pose or not.	M	1	CoordinateSystemType	CoordinateSystemType is described in Table 5
absolute_pose	Reference to a geo-referenced location expressed as a vector <latitude, longitude, altitude, theta, omega, psi>.	O	1	AbsolutePose	WGS84

Table 4—Description of Transformation

Attribute name	Description	M/O	MO	Data type	Reference
transformation_id	Identifier of the rigid transformation.	M	1	string, UUID	ISO/IEC 9899:2018 ISO/IEC 10646:2012 ISO/IEC 11578:1996
head	Identifier of the local map which is the head of the arc.	M	1	string, UUID	ISO/IEC 9899:2018 ISO/IEC 10646:2012 ISO/IEC 11578:1996
tail	Identifier of the local map which is the tail of the arc.	M	1	string, UUID	ISO/IEC 9899:2018 ISO/IEC 10646:2012 ISO/IEC 11578:1996
rotation	Rotation between the coordinate systems of the head and tail local maps, represented as a quaternion with 4 components (X, Y, Z, W), in this order.	O	1	quaternion, namely an array of 4 elements of type double	ISO 9787:2013 IEEE Std 754-2019
translation	Translation between the origins of the coordinate systems of the head and tail local maps, represented as an array of 3 components (x, y, z), in this order.	O	1	translation, namely an array of 3 elements of type double	ISO 9787:2013 IEEE Std 754-2019
uncertainty	Uncertainty of the transformation.	O	1	Uncertainty	Uncertainty is described in Table 6