3D representation of objects in new generation intelligent computer systems

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***Abstract*—This article is dedicated to the issues of constructing and using a three-dimensional representation in various tasks of applied intelligent systems, as well as corresponding systems of spatial positioning and orientation. The description of the representation itself, as well as the principles of its construction, is implemented within the knowledge base of the OSTIS system, which allows for deep integration of various tasks and methods, and also subsequently leads to an increased degree of convergence of various research domains.**

***Keywords*—3D representation, 3D reconstruction, knowledge base**

I. Introduction

For the interaction of an intelligent computer system with objects of the external environment in applied tasks, it is necessary to create an internal representation of these objects. One of the types of such an internal representation can be a description of objects in the form of a three-dimensional model. At the same time, the formation of such an internal representation belongs to the class of tasks for analyzing sensory information and requires determining the exact location of the object, on the basis of which application systems can implement various interaction scenarios. In accordance with this, systems of spatial orientation and three-dimensional reconstruction, capable of forming and processing such representations, are of particular importance.

Application areas that require solving these problems include [1]:

- Intelligent robotic systems. Examples of tasks: environment analysis, motion trajectories building, object three-dimensional coordinates estimation.
- Intelligent production control systems. Examples of tasks: object deformation and structural changes analysis, non-contact dimension measurement for objects of arbitrary scale and configuration, production process control.
- Intelligent systems of complex medical monitoring and service. Examples of tasks: examination result analysis, tracking disease development dynamics, treatment planning.
- Scientific research.
- Other applied areas (architecture, cartography, etc.).

The subject area of the three-dimensional object representation concerns both the description of the object itself and the methods for obtaining this description. Based on these representations, the following classes of problems can be solved:

- building a three-dimensional representation of an object, group of objects or environment,
- determining the size of an object, including calculation of deviations from a given template or parameters, for example, in medical diagnostic systems,
- carrying out additional constructions that further refine the created generated three-dimensional representation,
- building a movement trajectory,
- etc.

Despite the fact that some of the above tasks require additional steps, they are all based on obtaining a three-dimensional object representation.

Thus, the declarative formulation of the problem of three-dimensional reconstruction is to obtain an internal representation of an object belonging to the class of three-dimensional representations.

II. Analysis of existing approaches to 3D reconstruction

At the moment, there exists a large number of methods that operate with different concepts: photogrammetric restoration from photo / video recording, radio frequency methods in different ranges, magnetic and inertial methods, neural network analysis, etc. For example, artificial neural networks that solve the problem of three-dimensional reconstruction can take individual images, image sets, panoramic and stereoscopic images, a combination of images and data from various types of sensors, sets of key points, a voxel cloud as input. For each method, a set of characteristics of the external environment (room, lighting, presence of movement) and input representation (size, type of surface) can be defined, within which this method is correct and demonstrates the best results for one of the target criteria. The resulting internal representation may also differ: some of the methods allow to restore the internal structure, others - only the surface (external shape) of the object.

In addition, in the tasks of analyzing sensory information, it is generally possible to install several different types of sensors, but they must, firstly, be suitable for studying this type of object, and, secondly, the information obtained must complement each other (increase the level of detail, resolution, accuracy, etc.) - that is, the system must be able to adapt to a specific task and external conditions.

All these factors impose serious restrictions on the possibility of using various methods of three-dimensional reconstruction in solving a specific applied problem, which must be taken into account when designing a system.

The problems of the existing solutions include:

- Lack of consistency of concept systems and descriptions of methods in various sources. There are different descriptions and terminologies for the same methods and their modifications, and difficulties and misunderstandings constantly arise because of this.
- Lack of binding and insufficient attention to the issues of convergence of the subject area of three-dimensional reconstruction with the subject area of the formation of three-dimensional scenes and environments of user interaction with the three-dimensional environment, for example, in systems of three-dimensional modeling, virtual and augmented reality.
- High complexity of developing applied systems using 3D reconstruction methods, and the need to involve experienced and highly qualified developers in solving relevant problems.
- Lack of integrated design technology. Despite the abundance of algorithms and methods, the analysis of their applicability to various types of applied problems is extremely superficial. As a result, in most cases the best method is chosen by enumeration or empirically.
- Lack of means for integrating individual components, stages of various methods, various types of data in the description of the object and the resulting internal representations. In addition to the variability of individual actions, usually each method works with its own class of internal representation (a surface specified polygonally, a voxel cloud with a regular grid, a set of individual coordinates in three-dimensional space, etc.).

Thus, the systematization of knowledge in this subject area, as well as the creation of technology for development and automation of the design process of intelligent systems in this area are relevant and currently unresolved tasks.

III. Suggested Approach

The description of the representation itself, as well as the principles of its construction in this paper, are implemented in the form of a knowledge base of the OSTIS system [2]. As part of the formation of a knowledge base and a platform for the development of intelligent systems in this subject area, the following stages have been identified:

- highlighting the semantic representation of three-dimensional scenes;
- systematization of the subject area, existing approaches and establishing links with related areas;
- development of a set of agents that determine the appropriate methods and tools for specific application tasks;
- development of a set of agents that carry out aggregation of different methods in order to clarify or check the parameters of the three-dimensional representation (position) of an object.

The sequence of the main stages of the 3D reconstruction process and their connection with the OSTIS knowledge base is shown in Figure 1. Within the knowledge base, it is proposed to highlight the following blocks:

- description of the characteristics of the observed objects;
- description of types and principles of setting three-dimensional representations;
- a description of the physical principles of operation and specifications of the equipment with which information about the object under study can be collected;
- a set of different methods of reconstruction and localization with limitations and solvers of specific problems;
- methods for evaluating the results of the obtained 3D representations;
- description of the semantic representation of three-dimensional scenes and objects.

Further, we will consider in more detail the main indicated subject areas and onthologies.

IV. Semantic representation of objects and scene

An important component of intelligent systems that use an internal three-dimensional representation is the description of the semantics of this representation. Information about individual points, surfaces, polygons or other primitives does not allow to form a complex idea of the semantic content of this representation, just as individual letters do not allow to evaluate the semantic component of text messages.

The semantic description of an object implies the association of a set of points corresponding to some object in three-dimensional space with some object of the existing knowledge base. Relations in such associations

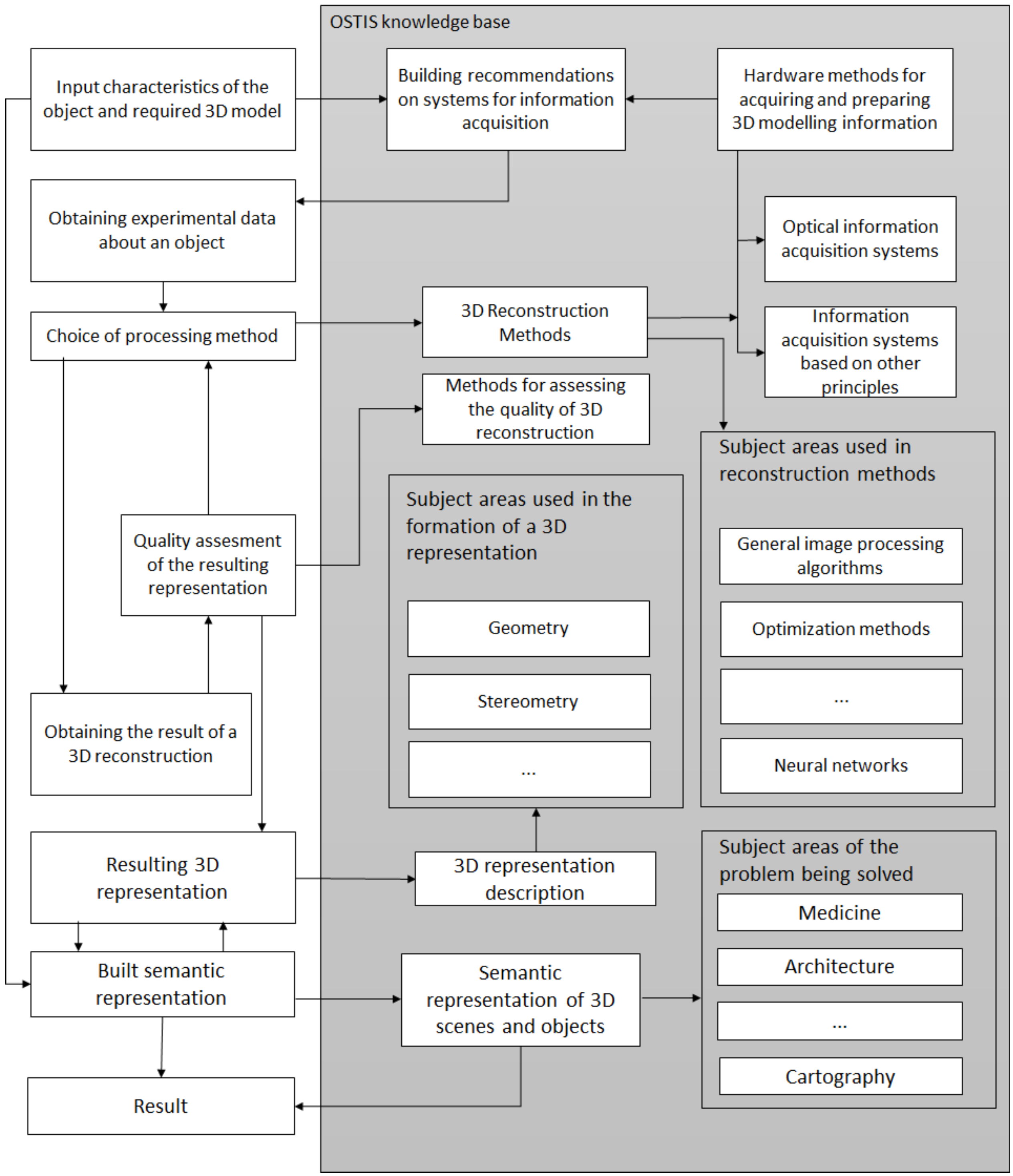

Figure 1. Description of the main stages of the 3D reconstruction process and their relationship with the knowledge base

can be represented as “object A is a three-dimensional image of some entity B”, where object A is defined by an internal three-dimensional representation, and entity B is defined by some description in the knowledge base.

Some properties of entity B associated with object A can be naturally inferred from the 3D representation of that object — in particular, information about shape, surface properties, coloration and texturing may already be present in the 3D description. Thus, with the help of additional processing, the three-dimensional representation of object A can be a source of factual information about the related entity B.

Similarly to the semantic description of a separate object, a semantic description of composite objects can be introduced. It should be kept in mind that the semantic content of individual components does not allow to fully determine the semantics of the entire composite object as a whole, therefore, a similar relation must also be set for the entire population. For example, the object "bicycle" can be decomposed into compound objects "chain", "frame", "wheel", etc., however, the set of semantic descriptions of three-dimensional representations of the components separately does not allow one to form or take into account the semantics of the entire compound object as a whole.

The semantic description of a part of an object should contain both information about the base object and additional context regarding the semantic content of the part under consideration. For example, in the videoendoscopic analysis of a section of the esophagus, information about which part of the esophagus in the body this section belongs to also becomes important.

The scene is a complex composition of several simple or composite objects in some common space, supplemented by data of their relative position. As in the case of composite objects, the semantic description of scenes should include not only descriptions of individual components, but also the semantic content of the emergent properties of all these components in the aggregate.

Thus, the following types of main entities have been identified within the framework of the semantic representation of three-dimensional scenes and objects:

object
:= [a set of points in space connected to each other and having one semantic representation]

compound object
:= [object that allows decomposition into separate individual objects]

object part
:= [a set of points in space belonging to some object, which can be distinguished by geometric or semantic representation]

scene
:= [set of several objects and data about their relative position in space]

For the scene, the semantic characteristics of the visual perception of the scene from the position of some observer placed in it or a machine vision system are important. In this context, the scene can be represented as a two-dimensional projection (or a pair of two-dimensional projections in the case of stereoscopic vision), while the semantics of the descriptions of the original three-dimensional objects and the corresponding parts of the resulting projections may also differ - for example, some objects may be out of view, or be perceived differently by the observer due to the presence of some optical, perspective, or psycho-physiological effects (eg, difference in lighting, optical distortion, various illusions of color or depth perception, eg, Ames room, etc.).

It is important for the semantic description of the scene to include both the definition of belonging of the individual objects of the scene to some entities of the existing knowledge base (e.g. as suggested in [3] and [4]), and a description of the possible relationships between these objects, arising due to their presence in the scene, or due to their pairwise mutual arrangement from the position of some observer. This information can naturally be used as reference properties of objects in the scene. For example, if there are two identical objects of type A and one object of type B in the scene, some logical statement or natural language query can utilize the fact of their relative position, for example, to identify one of them - "the object of type A, which is located to the left of the object of type B ".

- Information about the presence on the scene or the projection of the scene
  - The object is missing from the scene
  - The object is present but not visible in the projection
  - The object is present and partially visible on the projection
  - The object is present and is fully visible on the projection
- Information about the relative position on the stage
  - By height
    - Above another object
    - On the same level as another object
    - Below another object
- Information about the relative position on the scene projection
  - By depth
    - Behind another object
    - In front of another object
  - By height
    - Above another object

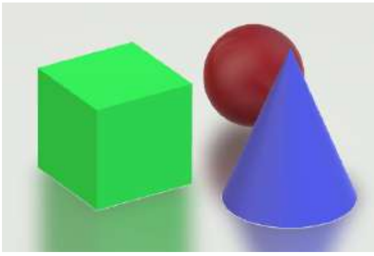

Figure 2. An example of a simple 3D scene rendered as a 2D projection from a specific camera position

    * On the same level as another object
    * Below another object
  - Location along the horizon line
    * To the left of another object
    * To the right of another object
- Information about the relative size of objects on the projection
  - Bigger than another object
  - Same size as another object
  - Less than another object
- Information about the visual similarity of objects
  - Similar or not another object in shape
  - Similar or not another object in colour
  - Similar or not another object in size

An example of a simple three-dimensional scene, as well as its semantic description in terms of the mutual arrangement of objects, is shown in Figures 2 and 3.

V. 3D REPRESENTATION

Systems for positioning, recognition and visualization of objects in the real world are based not only on the qualitative component of the description, but also on the relative spatial position of objects or their individual parts. In accordance with the perception of the surrounding world by a person, a three-dimensional representation is the most informative, although not mandatory. The resulting two-dimensional images used in many tasks are projections of three-dimensional space. Therefore, in this paper, a three-dimensional representation of objects, including a class of descriptions containing information about the relative position of objects or their parts in three coordinates, is chosen as the maximum class of the study objects.

3D representation
⇒ *split**:
{• *surface representation*
⇒ *includes**:
{• *polygon meshes*
• *NURBS surfaces*
• *separation surfaces*
• *surfaces based on T-splines*
}
• *voxel representation*
⇒ *includes**:
{• *point cloud*
⊃ *depth map*
• *structural mesh*
}
• *special representations*
⇒ *includes**:
{• *video 360*
}
}

VI. 3D RECONSTRUCTION

A three-dimensional reconstruction allows obtaining a three-dimensional representation based on other data. Three-dimensional reconstruction is the task of determining the true form of objects in three-dimensional space based on information about these objects obtained as a result of measurements, observations or experiments.

Each of the methods of three-dimensional reconstruction can be characterized, in addition to the physical principle of operation, also by the resolution, the type of input data, the size and internal structure of the reconstructed objects, etc. The full description is a non-hierarchical ontological model [5]. For further interaction of agents with a given structure, all these descriptions are mapped onto some characteristics. Characteristics can apply both to a separate method and to a group of methods, for example, the resolution can be common to the entire subclass of electromagnetic wave methods. These characteristics should be dynamically obtained by agents from the knowledge representation itself, which allows supplementing and modifying the overall structure. For convenience of presentation, these characteristics can be identified in the specification of the method, on the basis of which the scope and possibility of its application can be described. It makes it possible to use methods for solving specific applied problems. Within the framework of the specification (and, accordingly, the structure of the representation of methods in the knowledge base), the following can be specified:

- type of possible input parameters,
- the output representation type, in this case the corresponding 3D representation;
- working hours;
- resolution of the method;
- distance from the object to the camera;
- type of reconstructed object;
- scene composition (separate object, group of objects, surrounding space);
- surface type (gloss, transparency, color);
- the presence of an internal structure;
- object size.

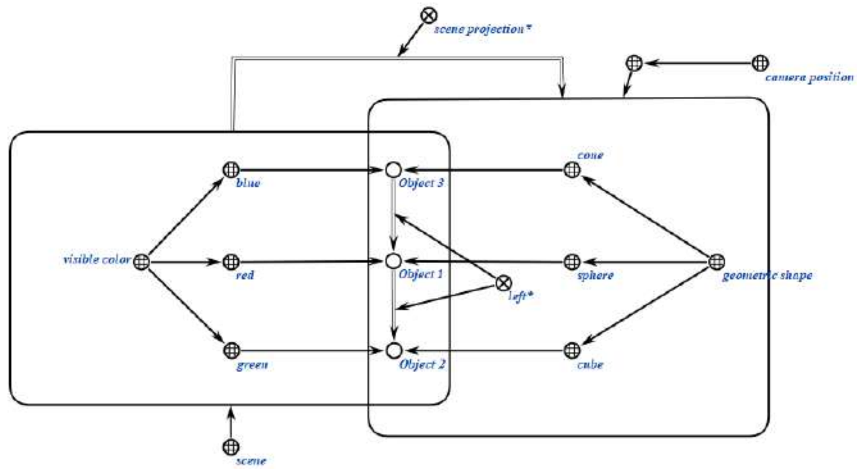

Figure 3. Semantic description of some relations of mutual arrangement of objects in the scene from the position of the observer

The described specification can be interpreted as an intermediate relation for each method. With such a description for the intermediate steps, this approach also allows to combine methods. For example, radio frequency methods do not make it possible to build a depth map, but allow to get the position of the camera in the global coordinate system at a specific point in time. [6].

3D reconstruction methods
⇒ *includes**:
{• *methods of photogrammetric reconstruction*
⇒ *divided by the relative position of the object and the camera into**:
{• *mobile systems*
• *macrophotogrammetry*
• *satellite photogrammetry*
• *aerophotogrammetry*
• *terrestrial photogrammetry*
• *near photogrammetry*
}
⇒ *divided according to the type of input information into**:
{• *single image*
• *stereo images*
• *multiframe*
}
• *methods of tomographic reconstruction*
⇒ *includes**:
{• *reconstruction based on Fourier projections*
• *back projection algorithm*
• *iterative reconstruction algorithm*
⇒ *includes**:
{• *ART*
• *SART*
• *SAMV*
}
• *conical beam reconstruction*
• *reconstruction based on deep learning methods*
}
• *structured highlighting methods*
⇒ *includes**:
{• *methods based on light sections*
• *methods based on band projections*
• *methods based on phase shift*
}
• *methods for estimating the reflected signal*
⇒ *includes**:
{• *distance measurement by optical modulation methods*
• *pulse modulation*
}
• *focus evaluation methods*
⇒ *includes**:
{• *evaluation methods from focus*
• *defocus evaluation methods*
}
• *methods based on the Fourier projection theorem*
• *neural network models*
}

Many 3D reconstruction systems are based on solving the problem of local positioning. It should be noted that, in general, the problem of local positioning is wider in scope; however, it is usually considered relative to the observer, and not to the object.

Characteristics of positioning systems:

- positioning accuracy,
- positioning authenticity,
- polling frequency,
- reliability,
- size.

An ontological description of positioning methods can be obtained on the basis of a subdivision, both according to the physical principle of obtaining initial data, and according to the calculation method.

VII. Ontology of domain actions

At a higher level, any 3D reconstruction method can be represented as procedural knowledge, such as a series of steps that transform the 3D reconstruction input into a final 3D representation.

A common feature of many methods of three-dimensional reconstruction is the use of an intermediate (or final) representation of the objects of the surrounding world in three coordinates. In other words, the 3D reconstruction method can be represented as a sequence of actions to form a set of elements characterized by coordinates in a common 3D space, which, if necessary, can be further built up to surfaces, combined with 2D representations, etc. to form the desired output representation:

$$r : Im(R^3) \to O \quad (1)$$

where I is the input data, R^3 is the common three-dimensional Cartesian space, $m(R^3)$ is the description of the element in the coordinate system of the common three-dimensional space, O is the output three-dimensional representation. Most often, individual points of three-dimensional space act as elements of an intermediate representation - in this case, such a representation is called a point cloud.

Curve segments, analytically defined surfaces, polygons and other types of objects can also act as elements.

The sources of data on three-dimensional coordinates for the intermediate representation can be:

- Direct absolute values of three-dimensional coordinates of points, i.e. in this case the input I is a set of points R^3. This is typical for all methods that allow building a scene depth map, because representation in the form of a depth map with known coordinates of the position of the observer and the focal length of the map allows to determine three-dimensional coordinates of any point on it.
- Data from which, with the help of some additional processing, the values of the three-dimensional coordinates of individual points can be obtained. Such representations tend to be much more common and easier to obtain.

It should be noted that different data sources can be used together when forming an intermediate representation, if each of the sources has some binding to a common coordinate system.

A. Actions for generating an intermediate 3D representation

Many remote sensing methods rely on the availability of a priori information about the three-dimensional coordinates of the object under study, from which a point cloud can be built for an intermediate three-dimensional representation. These include methods that allow you to estimate the distance from the measuring device to the object. However, the use of these methods requires more sophisticated equipment, which can be difficult to apply in some scenarios.

In this regard, it's possible to isolate a separate category of research methods - group of methods for forming an intermediate representation as a point cloud, based on more traditional types of information. These include methods for generating from a single image, a stereopair, a set of images, or a video sequence, which can also use information about the optical system of the camera that was used to obtain the image.

Thus, the following types of input data can be considered:

- A static image or set of static images;
- Video sequence (a set of static images with a timestamp);
- Stereopair (2 static images with optical system parameters) or a set of stereopairs;
- Stereo video sequence (a set of stereopairs with a timestamp).
- Information about the optical system of the camera.

In this case, a sparse point cloud of three-dimensional space acts as an output representation, with each of the points of this space bound to one or more points of the original input images.

The formation of a sparse point cloud includes the following steps, for each of which the specified parameters that can be determined:

- Preprocessing
- Keypoint detection
  - detector algorithm
- Keypoint matching
  - descriptor algorithm or optical flow algorithm
  - thinning
- Evaluation of camera positions
  - projection model
  - bundle evaluation algorithm
- Postprocessing

Detection and matching of key points allows to determine the points belonging to the same object of the studied three-dimensional space, if there are a sufficient number of images. At the stage of estimating the position of the camera, a mathematical projection model is used that specifies the relationship between the two-dimensional coordinates of a point in the image and the corresponding three-dimensional coordinates in the modeling space; at the same stage, empirical depth estimation can be carried out, for example, using neural network methods. Each keypoint match, described mathematically using the projection model, is further used in the pose estimation algorithm in order to restore the camera positions in three-dimensional space for each of the analyzed images, and also to determine the distances from the cameras to the points, based on some criterion for minimizing the back-projection error.

For example, the classical Structure from Motion three-dimensional reconstruction method from several input images within the presented pipeline can be described by the following characteristics:

- Preprocessing – conversion to grayscale;
- Detector algorithm - SIFT, SURF, FAST;
- Descriptor algorithm - SIFT, SURF, ORB;
- Thinning - RANSAC;
- Projection model – central projection;
- Pose estimation algorithm - global bundle adjustment method with Levenberg-Marquardt optimization.

As another example, consider the ORB-SLAM method of simultaneous localization and mapping [7], using a video sequence as an input representation:

- Preprocessing - frame thinning;
- Detector algorithm - FAST;
- Descriptor algorithm – ORB + Lucas-Kanade optical flow method;
- Thinning – RANSAC, motion invariant thinning;
- Projection model – central projection;
- Pose estimation algorithm - incremental bundle adjustment with a fixed camera position and a fixed position of key points between frames, mapping method;
- Post-processing - trajectory refinement and loop detection.

An ontological description of the presented sequence of actions, as well as an example of a specific algorithm implemented according to this sequence of actions, are presented in the figures.

Since each of the proposed stages is described as a functional mapping, it is assumed that stages are added, removed or modified during processing if the correspondence between the types of input and output representations is observed in the context of the problem being solved.

B. Actions for generating the final 3D representation

As already mentioned, in some problems a sparse point cloud in three-dimensional space can be a sufficient representation, and can be considered the result of a three-dimensional reconstruction algorithm. Also quite popular is the representation in the form of a dense colored point cloud.

However, in many problems such a representation is not enough, so it is possible to distinguish a class of actions when generating a more complex three-dimensional representation, depending on the type of output representation required. The input representation for this stage is a sparse point cloud, as well as additional information about the relationship of specific points in the cloud with the original representations.

The description of the methods for generating the final three-dimensional representation can be represented as a combination of the following stages, with the corresponding parameters:

- Point cloud density increase
  - algorithm for density increase
  - link to source data
- Surface Shaping
  - surface type
  - surface generation algorithm
- Refine surfaces
  - surface refinement algorithm
  - link to source data
- Surface texturing
  - texture method
  - link to source data
  - conflict resolution

At the point cloud density increase stage, information about the relationship between the 3D coordinates of the sparse cloud points and the source data is used to transfer additional points directly from the source representation to the 3D model. Next, by analyzing the obtained dense point cloud and the initial data, a rough estimate of the final three-dimensional surface is formed in the form of some three-dimensional primitive, usually by forming a polygonal mesh by combining the nearest points into triangles. At the stage of refinement of surfaces, smoothing, thinning and merging of primitives obtained at the previous stage can occur, based on some information from the source data. Finally, at the texturing stage, the original representation is transferred to the constructed 3D model to ensure its realism; also at this stage, conflicts are resolved to select the correct texturing strategy in the presence of several conflicting sources of information about the texture.

For example, the surface reconstruction algorithm proposed in the framework of the currently most popular implementation of bundle adjustment method can be described as the following set of parameters:

- cloud density increase algorithm - transfer of neighborhing keypoints
- surface type - polygonal with rectangular polygons

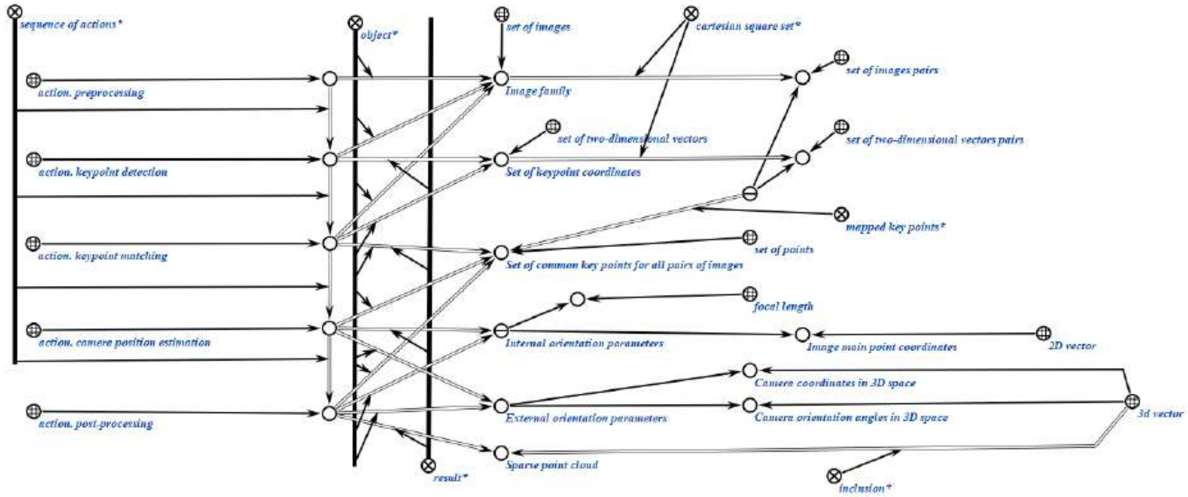

Figure 4. Ontological description of the sequence of actions for constructing an intermediate three-dimensional representation in the form of a sparse point cloud

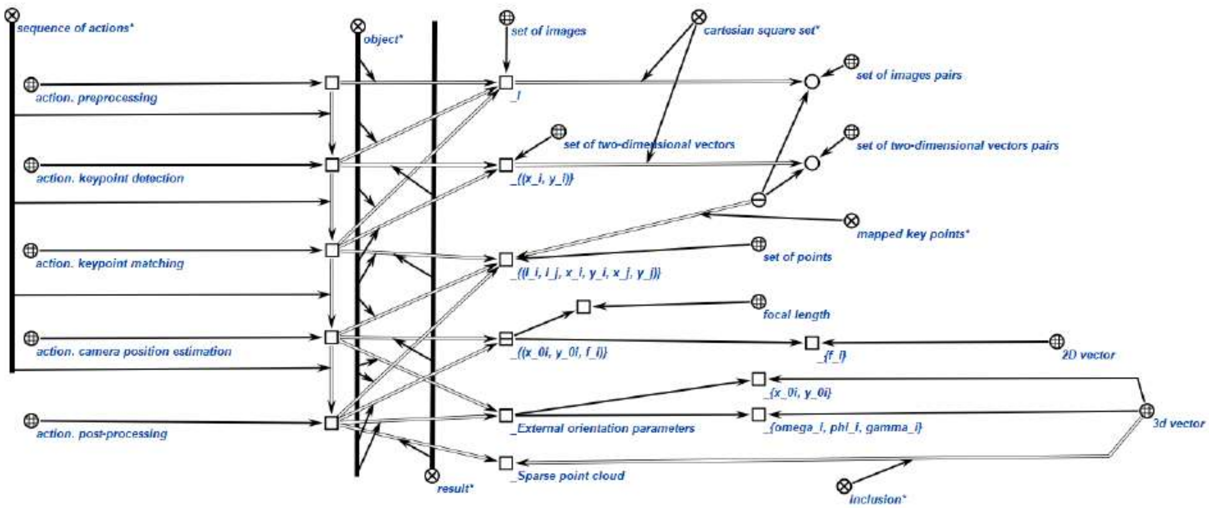

Figure 5. An example of an algorithm for constructing a sparse point cloud based on the presented description

- surface generation algorithm – estimation of camera translations using Delaunay triangulation, estimation of planar camera translations, interpolation between camera positions, manual adjustment
- surface refinement algorithm - missing
- texturing method - direct transfer from source images
- method of resolving texture conflicts - alpha-blending proportional to the distance to the point.

C. Actions for the selecting stages and generation of the algorithm

A detailed description of the structure of the methods is not sufficient for the direct implementation of a three-dimensional reconstruction according to some algorithm. Since there exists a large number of implementations for each of the stages of the final pipeline, the problem also arises of the optimal choice from the set of implementations of each of the stages for the most effective solution of the task.

An agent-based approach to information processing can be used both to select the stages of the 3D reconstruction algorithm and to directly implement it [8]. Agents communicate by accessing a common representation in the knowledge base, which generates a number of questions that specify further actions.

As the main questions on the basis of which the generation of the algorithm can be carried out, the following can be distinguished:

- What input will be used for the reconstruction?
  - Is it possible to determine the distance to a point in three-dimensional space from the input data, or directly its three-dimensional coordinates?

- Will images be used as data?
    - Are the optical parameters of the camera known?
    - Are the positions or orientations of the camera in space known for each image?
    - Is the set of images a continuous video sequence at a known frame rate?
  - If there are several sources of input data, is there information about binding the data they describe to a common coordinate system?
- What type of 3D model should be generated from this data?
  - Is reconstruction of 3D surfaces required?
    - Can the source data be used to form surface textures?

Based on the proposed approach, both the selection of a method that meets the requirements of the problem and the selection of individual stages of the algorithm can be carried out, for example, by choosing the most optimal keypoint detector and descriptor algorithm [9]. In addition, it is possible to combine 3D representations obtained by different methods [10].

VIII. Conclusion

The article considers an ontological description of the subject area of three-dimensional reconstruction of objects and actions for their processing in knowledge bases based on OSTIS technology. The description is presented in the form of the domain area of the scenes themselves, the methods for obtaining them, and the corresponding actions for processing them.

The advantages of using OSTIS technology for the considered tasks are:

- Introduction of a common system of concepts and descriptions of methods in a unified and consistent form.
- Possibility of convergence of the subject area of 3D reconstruction with the subject area of 3D scene and environment building and adjacent areas.
- Simplification of the development of applied systems using 3D reconstruction methods.
- Ability to build a complex design technology using intelligent agents that consume the proposed description.
- Ability to create integration tools for individual components, stages of various methods and resulting internal representations.

Using the proposed approach, it becomes possible to create intelligent systems that can receive and operate a three-dimensional representation for further processing in applied problems.

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3D-представление объектов в интеллектуальных компьютерных системах нового поколения

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Данная статья посвящена рассмотрению вопросов построения и использования трехмерного представления в различных задачах прикладных интеллектуальных систем, а также соответствующих систем позиционирования и ориентации в пространстве. Описание самого представления, а также принципов его построения осуществляется на основе базы знаний OSTIS-системы, что позволяет проводить глубокую интеграцию различных задач и методов, а также в последствии приводит к повышению степени конвергенции различных направлений.

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