Managing semantics knowledge for 3D architectural reconstruction of building objects

***Abstract*—This work aims at progressing the understandability and interoperability of semantics building knowledge expression among stakeholders to promote automatic reasoning and reusability of architectural reconstruction. After retrospection on cognitive origins of spatial semantics representations, semantics management of 3D objects is proposed from cognitive conceptualization toward semantics knowledge management. Firstly by applying a previous semantics formalization investigation, we propose a classification of related knowledge as definition, partial knowledge and ambiguous knowledge to facilitate the understanding and design. The formalization of the classification is demonstrated with transformations among closed world assumption (CWA) and open world assumption (OWA). Secondly an empirical implementation is conducted on a simplified building prototype complying with the IFC standard. The generation of empirical knowledge rules are revealed and semantics scopes are addressed both in the bottom up manner along the line of geometry → topology→ semantics, and a vice versa top down manner. Concrete implementation is on the platform of protégé with Semantic Web Rule Language (SWRL) rules. This work is promising for meeting an optimization requirement which integrates what users want, what theorists believe possible and what practitioners think practical.**

Keywords- semantics; knowledge management; formal; epistemology; cognition

I. INTRODUCTION TO MINING 3D POINT CLOUDS

Some of the earliest work on 3D point clouds [18], [19] have investigated the construction of geometrical shapes for a long time. Reconstruction of 3D objects from 3D point clouds has been investigated as a topic of computer graphics researches in [2], [3], [8], [22], which progress from large earth terrain towards precise building parts, etc. With the popularization of 3D laser scanning equipment and technologies, more and more focus is shifted on related very promising researches and applications. Most works [6], [7], [10], [20], [21] on 3D point clouds gained from laser scanning focus mainly on the 2D or 3D visualization and geometrical segmentation aspects. Later semantic[2], [3], [30] has been introduced to the process for improvement on automation, accuracy, efficiency and goal-directed applications from the knowledge engineering and artificial intelligence areas [2], [9], [27], [28]. We agree with the assumptions that there are different understandings on semantics segments in terms of meaning [12] or interpretation [25]. While in practices, semantics classifications succeeds for that they are simple for the users to understand and participate with their knowledge [11], and ontology could capture intrinsic structure of 3D shapes to achieve shape characterization with high probability in both general background and a specific domain [11].

In this work, we focus on the understandability [2] and interoperability among stakeholders and also knowledge bases while integrating the geometrical and semantics knowledge for implementation. Archi3D provides unprecedented rich semantic support for 3D reconstruction from point clouds which supports both refining natural language concepts like Wall to a set of points in point clouds and decidability on expressions like "a wall can not be inside a window", etc.

The rest of this draft is organized as follows. In Section II semantics management of spatial representations are reviewed from cognitive origin and conceptual level. Section III reveals the classification of related knowledge in natural and formal expressions. Section IV presents the case study on top down SWRL rules generation and bottom up reasoning. Section V compares the proposed approach with other technical procedures. Finally, Section VI summarized the expected contributions and concludes this work in progress with future works.

II. ON SEMANTICS MANAGEMENT FOR OBJECTS MANAGEMENT

A. *The cognitive origin of spatial representations with semantics*

Psychologically conceptualization could be a necessary step towards knowledge expression and manipulation hence after. The investigation of the conceptualization of special knowledge as cognitive issues can date back to as early as 1940s [34]. To our knowledge the earliest work which relates semantics knowledge for automatic managing spatial objects starts from the doctoral project of Benjamin Kuipers [35] at MIT during the 1970s.

B. *Conceptual level management*

Some object management approaches are based on conceptual levels which aim at fully managing the relationships and dependencies [32] among 3D concepts represented with NL terms' semantics at conceptual level. It is denoted as: conceptual ←→ conceptual. As the semantics terms are brought from NL independently, they are expressive and well accepted as every NL terms. But they suffer as that NL terms usually do not take overlap, consistency, and interoperability as explicit issues. Organization of these terms such as "aggregation", "owned by", "shard with" [33], for civil objects management will experience something that is similar to the management of semantics of UML hierarchy.

III. THE CLASSIFICATION OF KNOWLEDGE APPLICATION APPROACHES

A. *Natural expression*

Enlightened by the previous works, we propose to classify the related semantics knowledge for reconstruction purposes as definition vs. Partial knowledge vs. ambiguous knowledge. They are explained as follows:

(a) Definitions which are based on geometrical axioms or other enforcement are employed as basic knowledge for objects identification.

(b) Although concrete applications/problems may update with the introduction of new context, such as the application of 3D scanners, the fundamental thoughts underlying successful solutions get more stable. We appreciate this kind of solutions expressed by Benjamin Kuipers in [27], [35] with "partial knowledge"/"human commonsense knowledge"[27]: partial knowledge which is acquired from experience can be used effectively in spite of being incomplete and sometimes incorrect.

(c) Another view which we extend from [2] as a fundamental thought is that: it is necessary to work from a set of ambiguous or uncertain [44] inputs towards deciding what the beginning could be/have.

The (a) is the most often used knowledge form. The (b) and (c) have various successful applications in the AI areas directly or indirectly. To our knowledge no existing project explicitly integrates all the three kinds of knowledge. In Archi3D, we have explicitly employed all the three kinds of knowledge coherently to provide the most semantics interoperability. We create empirical SWRL rules to express the complete, the partial and maybe ambiguous knowledge of commonsense knowledge and implement the reasoning for the purpose of management of civil architectural objects at semantics level for reconstruction. We expect it to be helpful to achieve the most decidability beside advancement of battling available limited information or computational resources.

B. *Formal revelation on the knowledge classification*

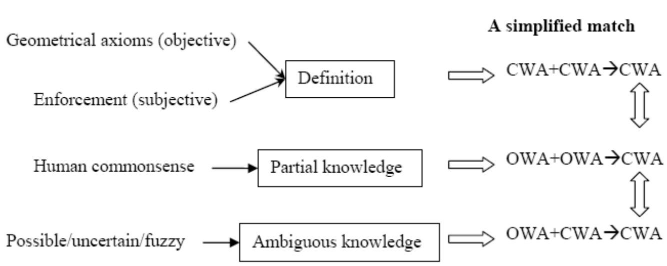

Figure 1. The semantics knowledge classification

An initial formalization of the above classification can be gained by applying the transformation modes of CWA vs. OWA [36] as is shown in Figure 1. If definitions are considered as complete knowledge or CWA, the situation of (a) matches to the semantics transformation from CWAs to CWA. It is denoted as: CWA+CWA→ CWA. If partial knowledge is considered as incomplete knowledge or CWA, the situation of (b) matches to the semantics transformation from OWA to CWA. It is denoted as: OWA+OWA→ CWA. If ambiguous knowledge is considered as combination of CWA and CWA, the situation of (c) matches to the semantics transformation from CWA to CWA. It is denoted as: OWA + CWA → CWA. Situation of (b) and (c) also involve the transformation from implicit [2] knowledge to explicit knowledge: implicit→explicit [36]. At the right side of the transformation, CWA is used for the expression of the conclusion which will be executed by machine and be accepted/validated by human. The modes can also be applied to revelation on complex knowledge integration composing multiple rules or multiple independent views.

Semantics vs. geometry: Although all meanings or reflections or thoughts or understandings in the mind which relates to but differs from the existence of real world can be classified as semantics, we explicitly adopt that the possible meaningful expressions which can be of interest for related topics are matched to two categories: geometry and semantics by following most of the existing practices [2], [5], [32], etc.

IV. CASE STUDY

The concrete case study of the semantics knowledge management of 3D reconstruction processes [3] is conducted with creating ontology on the platform of protégé with Web Ontology Language (OWL) [46], Semantic Web Rule Language (SWRL) [47] rules and its built-ins, and the reasoning is performed with SWRL Jess tab and Jena.

A. *Empirical definition of concepts*

In this section, the concepts used in this technical report are introduced. In addition, the concepts of the building element will be described with the introduced syntax. The syntax for definition here is similar to semantics of description logic (DL) [48] which is defined by interpreting concepts as sets of individuals/objects and roles as sets of pairs of individuals/objects. The definitions here are based on axioms of ZFC set theory [50] and DL related expressions [49] by default.

1) Classes

Things for Achi3D project are initially proposed as BuildingElement which maps to building elements and GeometricElement which maps to geometries.

Semantics given by means of interpretation I = $(\triangle^{I},\cdot^{I})$ [49]:

Thing is a ZFC set.

$Thing^{I} \subseteq \triangle^{I}$

The DL semantics of them is as follows.

BuildingElement = { Building, Wall, Door, Window, Ground, Platform, Site }

GeometricElement = {PlanEquation, Point}

A glance of the classes of Archi3D can be gained with figure 2.

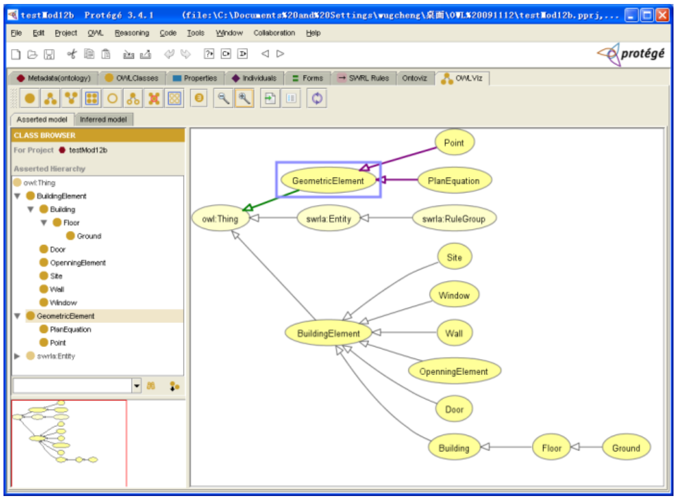

Figure 2. Classes of Archi3D

2) Properties

Properties for Achi3D project are classified as object properties which map among Things and datatype properties which map things to data types.

The DL semantics of them is as follows.

ObjectProperty = {hasGeometryElement, hasSemanticsDescription, hasSpatialRelationship, hasPoints, isSamePointTo, isDifferentPointFrom, …}

DatatypeProperty = {px, py, pz, ratioXYArea, …}

A glance of the properties of Archi3D can be gained with figure 3.

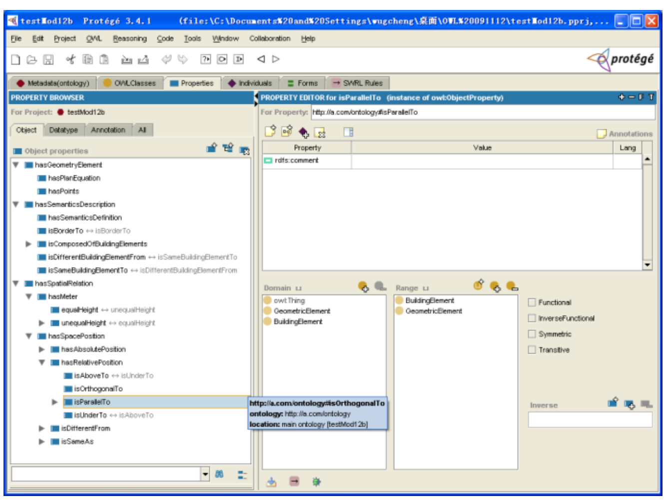

Figure 3. Properties of Archi3D .

3) Composed semantics expression

With a set of DL constructors, complex concepts and roles can be built with Classes and Properties. A classification of the composed semantics expression (CSE) is as follows:

$$CSE^{I} \subseteq \triangle^{I} \times \triangle^{I} \times \ldots \times \triangle^{I}$$

B. Empirical definitions of SWRL rules

The intended meaning of SWRL Rules which take the form of an implication "→" between an antecedent and a consequent can be read as: if conditions specified in the antecedent hold, then conditions specified in the consequent hold.

1) The top down implementation scheme

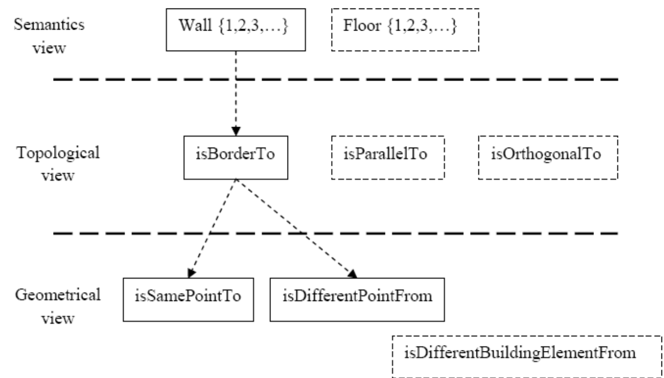

Figure 4. Example of the structure of the knowledge rules

At semantics view, top down implementation of the knowledge involves the mining the semantics relying relationship from semantics view towards topological view and geometrical view. Figure 4 illustrates the structure of the knowledge rules which span across three views of semantics, topological and geometrical. In figure 4, the identification of a Wall may require the rule of "isBorderTo" which might be implemented as:

hasPoints(?x, ?px1) ∧ hasPoints(?x, ?px2) ∧ isDifferentPointFrom(?px1, ?px2) ∧ hasPoints(?y, ?py1) ∧ hasPoints(?y, ?py2) ∧ isSamePointTo(?px1, ?py1) ∧ isSamePointTo(?px2, ?py2) → isBorderTo(?x, ?y)

The relying relationship shows that its implementation requires the implementation of "isDifferentPointFrom" and "isSamePointTo" which might be realized as follows:

px(?p1, ?px1) ∧ px(?p2, ?px2) ∧ swrlb:notEqual(?px1, ?px2) → isDifferentPointFrom(?p1, ?p2)

py(?p1, ?py1) ∧ py(?p2, ?py2) ∧ swrlb:notEqual(?py1, ?py2) → isDifferentPointFrom(?p1, ?p2)

pz(?p1, ?pz1) ∧ pz(?p2, ?pz2) ∧ swrlb:notEqual(?pz1, ?pz2) → isDifferentPointFrom(?p1, ?p2)

px(?p1, ?px1) ∧ py(?p1, ?py1) ∧ pz(?p1, ?pz1) ∧ px(?p2, ?px2) ∧ py(?p2, ?py2) ∧ pz(?p2, ?pz2) ∧ swrlb:equal(?px1, ?px2) ∧ swrlb:equal(?py1, ?py2) ∧ swrlb:equal(?pz1, ?pz2) → isSamePointTo(?p1, ?p2)

Corresponding implementation of the deduction of Wall can be realized with following rule:

isBorderTo(?x, ?y) ∧Floor(?y) ∧ isBorderTo(?x, ?z) ∧ Floor(?z) ∧ isDifferentPlanFrom(?z, ?y) → Wall(?x)

A glance of the knowledge implementation and reasoning results with SWRL and SWRL Jess can be gained with figure 5.

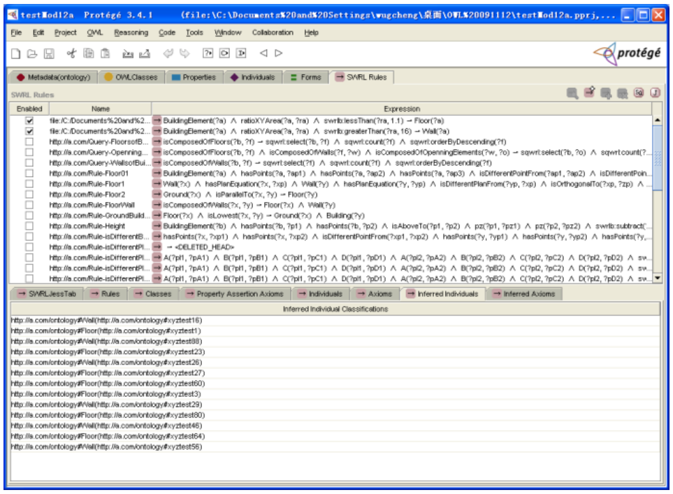

Figure 5. Knowledge implementation and reasonning result with SWRL

2) Bottom up bridging

The bottom up generation of walls and floors are intuitively shown as follows. It is proposed to use geometrical knowledge to identify parts of semantics objects of Walls and Floors from random generated building parts. Figure 6 shows 120 random generated building plans expressed with Virtual Reality Modeling Language (VRML). Example of the individual building plans is shown in Figure 7. By applying the knowledge rules transforming from the geometrical view to semantics view which are marked in figure 5, Floors and Walls can be identified as the output of Figure 5 and is intuitively shown in Figure 8 where there are 2 parts of Floors and 5 parts of Walls.

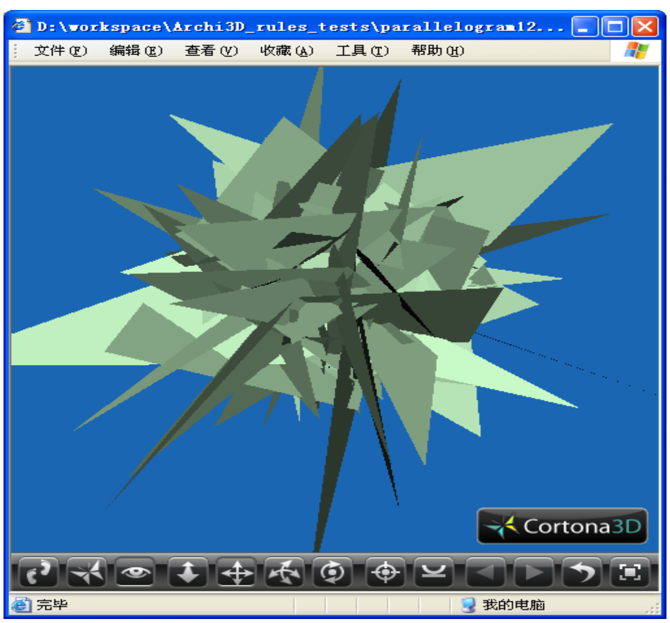

Figure 6. The 120 randomly generated builing plans

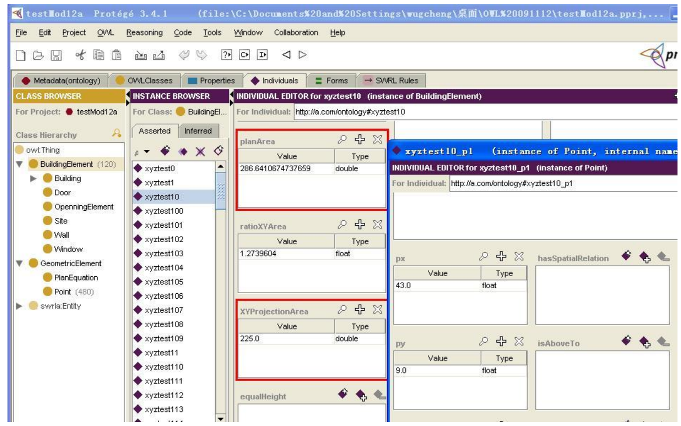

Figure 7. Individual building plans

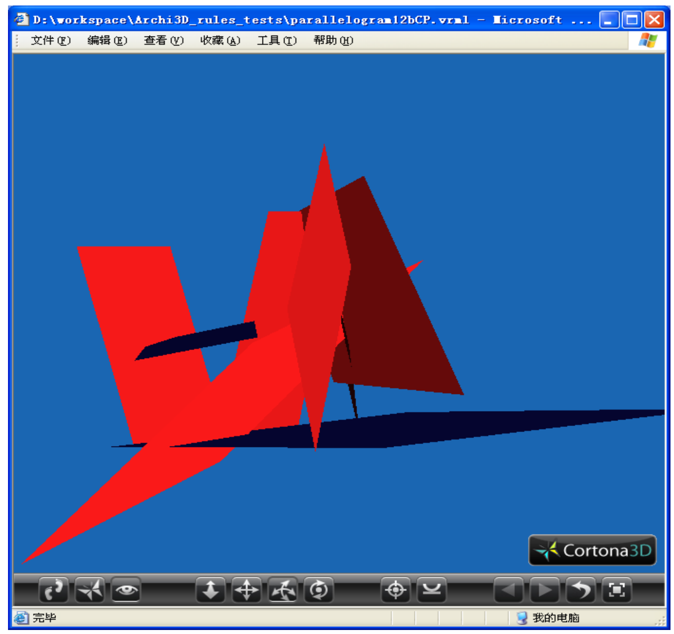

Figure 8. Initially identified parts of walls and floors in a bottom up manner

V. COMPARISON ON TECHNICAL PROCEDURES

Most works which deal with the point cloud gained with 3D laser scanning focus on achieving the visualization related issues ranging from various surface interpolation of creating mesh representation to post-processing operations of smoothing and texturing, etc. A systemic review on the surface reconstruction and visualization problems and solutions from either measured point cloud of photogrammetry or unorganized point clouds toward 3D polygons and shapes are reviewed in [17].

Some semantics processing projects do not relate their works to the processing of 3D point clouds. To our knowledge no work matches to the scheme of Archi3D exactly. The closest work to Archi3D which explicitly adopts semantics for scene interpretation and object detection of building semantics maps is described in [2]. Firstly a method called 6D SLAM [2] which compose a Iterative Closest Points (ICP) algorithm and heuristics to register the data of the point cloud from multiple scanners in a consistent manner. Then plane extraction on the point set proceeds with RANSAC (Random Sample Consensus) algorithm [39] with ICP optimization. Labeling is performed with background knowledge which is represented in a constraint network [2], [5]. The constraint network contains mainly relative and transitive binary relationships which are mainly geometrical between two objects. Prolog is used to implement the constraint network solver with unification and backtracking. During this stage, basic building elements are labeled out. After this stage, the 3D range and reflectance data is transformed into 2D images by off-screen rendering for detecting and localizing objects with a contour based approach [38] and cascade classifiers [37], e.g., Support Vector Machines (SVM), with the help of sensors.

Archi3D bases the plan extraction on a least squares estimation algorithm [42]. Compared to the work [2], Archi3D does not limit the attainable knowledge to the scope of geometrical. Instead, it makes full use of the semantically expressiveness of NL terms and description logic (DL) [41] to integrate all kinds of knowledge and properly deploys/organizes them for civil reconstruction purposes. Based on an OWL ontology and SWRL rules, the processing of Archi3Dcontains not only bottom up [2] processing from point cloud to planes and objects subsequently, but also the top down [2], [41] supports from objects to planes with the aid of a pre-drawn parameter-less coarse model (CM) [3]. The CM contains not only labeled features but also part of the objects definition information. The top down direction adopted by Archi3D coincidences with the future direction claimed by [2] as mostly unexplored "main direction of the work ahead". The semantics reasoning supports both classes' level and instances' level as what is proposed in [2].

Work [2] has also argued and demonstrated the relative advantage of semantics feature based labeling in contrast to direct labeling from point cloud such as in [40].

VI. SUMMARY AND FUTURE WORKS

We would like summary our ideology on related knowledge content as follows: in ordinary life, most of us get to know and contact with the world include buildings with natural semantics more than with geometries for the daily life and related thought. For example, human use a door for going in and out, and a window for looking out or bringing in the light much more often than that taking them as geometrical objects like systemic lines, plans of Euclid axioms, etc. This kind of knowledge could be either related or derived from the geometry or be independent or isolated as originating from different views. They could be statistically stable enough to be taken as semantics guidelines for directly or indirectly bringing geometrical computation, for example, functionally doors in a building is connective and windows/platforms grounds) can be related from doors; and statistically there are more walls in a building than platforms/grounds, etc. Similar knowledge is unachievable from pure geometrical computations although it is useful for relieving the dependency on thresholds [2] or parameters. The geometrical expression of the corresponding semantics knowledge is saved here for brief. By systemically working on knowledge of definitions, partial and ambiguous, Archi3D aims to contribute in many aspects including the follows:

- Archi3D[3] builds its basic semantics interoperability on the only open global standards Industry Foundation Classes (IFC) [29] to provide a semantics model for the reconstruction process which shares the same goal[2] of achieving automatic reconstruction from semantics knowledge in the form of constraint network [1], [2], [4], [5], [23] and common features[4], [15] etc. Archi3D pioneers in achieving semantics interoperability of architectural objects at the web platform [31].

- Unlike the work [1] which uses declarative Prolog for constraint knowledge representation and [16] which creates functions for feature modeling, Archi3D uses more expressive DL[2] based OWL and SWRL for the knowledge representation. The process involves the creation of an intuitive ontology with SWRL and OWL which enable the interoperability of more stakeholders. And the improved interoperability of stakeholders means that stakeholders can contribute their requirement, knowledge and experience at an earlier stage, and keep the system development more guided by interactive communication, etc.

For example, with OWL and SWRL, intuitive knowledge from civil specialist and other users can be integrated regardless of their origins of geometry, domain knowledge [15] or statistical knowledge, etc. Some extra non functional benefits can be gained as by products, e.g., the knowledge integrated will be fault tolerance, adaptive, extensible, etc.

Most existing semantics related approaches make use of either geometrical knowledge like orientations [1], [2], [4], or statistical hypothesizes [4], [26] and thresholds, OWL and SWRL implementation of Archi3D allows a seamless integration of the geometrical knowledge and the natural language semantics knowledge to realize an integrated management of civil architectural objects consistency which provides the interface and foundation for other applications to build on top.

- Unlike existing approaches of 3D construction from point clouds which restrict to use semantics for object annotations in a bottom up manner[2], Archi3D benefit fully knowledge with both bottom up and top down[2] manners through the integration of a coarse model [3] and an ontology. Concerning the bottom up manner, Archi3D realizes the computation of spatial relationships from the geometrical objects with the SWRL builtins at the protégé platform which is not supported with DL previously [43].

The coarse model and the ontology can provide semantics inference for civil objects which covering both the type/class level and the object/instance level.

- Through implementing spatial/geometrical and semantics information in a coherent manner [13], [14], Archi3D supports not only inquiry on the hierarchy of geometrical and semantics respectively at different levels, but also cross hierarchies and levels inquiries such as "is a point inside a window", etc.
- The strategic innovation of Archi3D: according to the

survey of [17], the ontology based architectural civil objects reconstruction process with the aid of a coarse model of Archi3D belongs to none of the known classification. Only recently work [2] and [16] have pointed out the importance of the premising direction of employing semantics for reconstruction. But the broad scopes and mechanisms of related semantics and applications are not systemically presented.

In the future, we would like to apply the proposed approach with large scale data set. Also we need to overcome the difficulties such as the influences of execution sequences of the rules, etc**.**

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