# An ontology-based approach to Acquisition and Reconstruction

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## Abstract

This paper aims at presenting the development phase of a novel ontology for modeling the knowledge underlying the pipeline of acquisition and reconstruction processes for shapes. We explain the urge to develop an ontology in this domain in a typical e-science scenario taking into account the approach and the technologies suggested by the current Semantic Web initiatives. We present the domain of our ontology, its possible applications and a list of informal desiderata, which eventually lead to the constitution of precise competency questions. Furthermore, a list of fundamental concepts for the acquisition and reconstruction pipeline are carried out. Finally, we present sketches of the ontology and the future work that should be done according to the users' needs.

**Keywords:** shape reasoning, knowledge management, e-science, semantic web, acquisition, reconstruction, ontology, web services.

## 1. Introduction

One of the main tasks of Computer Graphics and Vision is to process real or virtual objects in the digital context. Among the different types of resources processed, we may group under the word *shape* all the multi-dimensional data characterized by a visual appearance, such as pictures, sketches, images or 3D models of solid objects.
Nowadays, digital shapes are widely shared by the scientific community using internet technologies. In the near future, due to rapid evolution of competitive infrastructures, the Web will be the best place not only to share digital shapes but also to process and manipulate them. In the last years, great effort has been put in the development of semantic–based middleware technologies for sharing and processing knowledge over the Web. The goal of the *Semantic Web* initiative is to create a universal medium for exchanging data [1]. Facilities to put machine-understandable data on the Web are quickly becoming a high priority: the Web can reach its full potential only if becomes a place where data can be shared and processed by automated tools as well as by people (Figure 1).

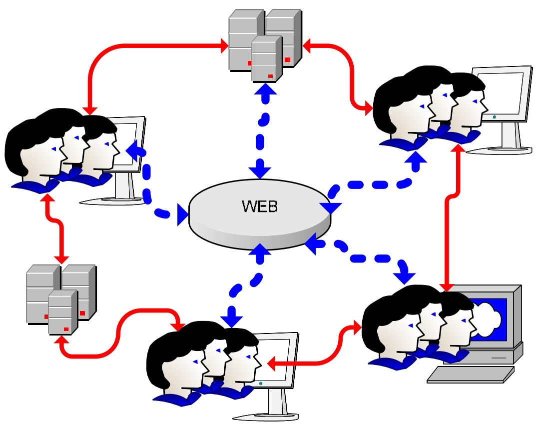


**Figure 1 – The research community interoperates massively using internet capabilities**

For the Web to scale, tomorrow's programs must be able to share and process data even when these programs have been designed totally independently [2] (for details on Semantic Web see [3][4]).
The development of the full spectrum of functionalities offered by the Semantic Web will provide a new level of interaction among scientific communities, changing the way research is carried out [5]. It will provide the basic communication tools by allowing the scientific community to work in a kind of 'smart' virtual laboratory where data, processes and workflows can be shared and can interoperate. The success of the Semantic Web as a support for e-science depends at a great

extent on the ability of the scientific community to build shared and agreed formalizations of the knowledge underlying the resources used.
In this context, the paper addresses the problem of defining and validating an ontology of one typical pipeline of operations of Computer Graphics and Vision: the *shape acquisition and reconstruction* pipeline, which is characterized by a sequence of operations that start from a generic shape, acquire it in the digital world, model it and, possibly, modify it with respect to specific needs.
Among the resources (not only shapes) used in this specific pipeline, the data that are shared via the web are typically the end product of a scanning process (e.g. a point cloud) or of the reconstruction process (e.g. a triangle mesh). All knowledge pertaining to the undergoing processes, for example the scanning history or the specific reconstruction method used, are lost as they are neither documented nor stored together with the shape data.
This fact implies that the typical use of digital shapes over the web is simply limited to browsing them, while more interesting issues could be addressed by researchers. Without a shared conceptualization, there is indeed a huge fragmentation and dispersion of energy: in order to reach the same result, similar and possibly incompatible processes may be implemented and the same resource may be duplicated several times.
Thus the usability of these processes and resources is not so simply guaranteed, especially if the research is done within a distributed community.
For interoperating and efficiently re-using existing know-how and resources it is important to annotate them thoroughly in order to retrieve them easily. Beside shapes, it is also necessary to annotate every sequence of operations to document clearly and persistently the whole reconstruction workflow. Ontology provides the conceptualization to achieve this aim, a precise set of meaningful metadata and an explicit formalization of the terms .
The task of building an ontology of the acquisition and reconstruction pipeline is not easy and requires a long and iterative process of refinement and validation.
As far as we know, there are no other efforts to conceptualize the entire acquisition and reconstruction pipeline even if there are some approaches to conceptualize the CAD design activity, as for example [6][7][8].

This paper describes the first results obtained in building an ontology for the acquisition and reconstruction pipeline. It focuses on the competency questions [9] that have been collected from the experts in the scientific community and on the initial structuring of the concepts and entities related to the specific field. The work has been done within the AIM@SHAPE network of excellence [10] which includes 14 excellent research institutions in foundational and applied fields of Shape Modeling.

## 2. Why an ontology?

As already mentioned, the domain considered in this paper is the *shape acquisition and reconstruction pipeline*. The intent is to model the knowledge encapsulated in the pipeline according to the scientific researchers' view and needs.
Presently a large amount of work is done through joint efforts among people possibly working in different institutions. Sometimes the specific expertise is slightly different, but the domain is substantially the same.
Even though the researchers in this field share the same domain of expertise, the creation of an ontology is necessary for building a common knowledge formalization.
Researchers working in this field, indeed, often use the same terms for describing different concepts. The word *reconstruction*, for example, is used to indicate the process of defining a single point cloud out of different range images as well as the process of defining a geometric approximation of the shape.

An ontology is an explicit formal specification of the terms in a domain and of the relations among them [11]. It defines a common vocabulary for researchers who need to share information including machine-interpretable definitions and it is formalized through classes, attributes and relations among them.
General motivations to develop an ontology are to share a common understanding of the structure of information, to make domain assumeptions explicit and to analyze and reuse domain knowledge [12].

Therefore, the design of an ontology plays a strategic role to build a shared formal conceptualization of the entire pipeline.

## 3. Designing the ontology

In order to design the ontology for the shape acquisition and reconstruction pipeline, we were inspired by the OntoKnowledge methodology [12], characterized by the specification of the requirements and an iteration of a refinement phase, an evaluation phase and a maintenance phase.

The adoption of this methodology paves the way for a possible extensibility of the ontology.

The following steps have been adopted to sketch the ontology in the first stage:

1. ontology domain specification,
2. applications identification,
3. desiderata collection,
4. key concept identification,
5. competency question elicitation,,
6. initial design of the ontology.

In the following, we will present the details for each step listed above.

### *3.1 Ontology domain specification*

The domain of our ontology is the development, usage and sharing of hardware tools, software tools and shape data by researchers and experts in the field of acquisition and reconstruction of shapes.

We decided to schematize the acquisition and reconstruction pipeline through the following macro-steps:

1. **Shape Acquisition** (and Registration): it is the phase in which sensors capture measurements. Often, because of the sensor's limited field of view or of the complexity of the object/scene to be scanned, multiple scans are required. Each view gives a set of measurements on a given coordinates system.
   In case of multiple scans, the acquired data have to be aligned, transforming all the measurements into a common coordinate system. This operation has to be done with the minimal possible error.
2. **Shaping**: it is the phase in which all acquired data are merged to construct a single shape.
3. **Shape Processing**: it is the phase in which further computations on the shape may be done as for example smoothing, simplification, texture mapping, remeshing, enhancement, and so on.

Figure 2 gives a general schema of the entire pipeline showing examples of data for each step.

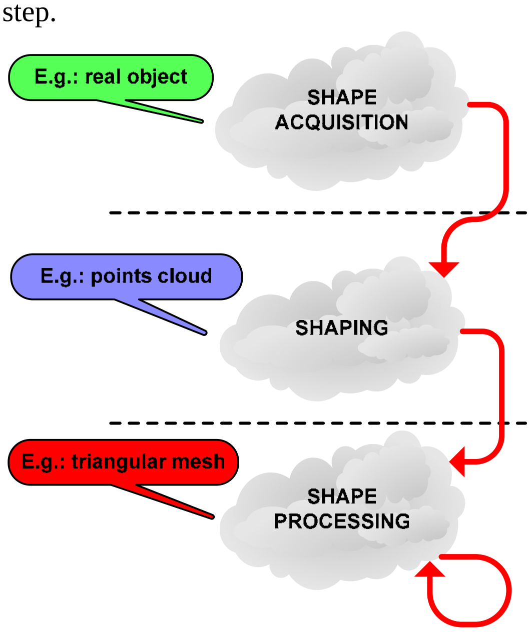


**Figure 2 : A general scheme for the acquisition and reconstruction pipeline**

Thus, the ontology we are targeting will model the knowledge of the shape entities but also concepts related to operative aspects such as shapes creation and manipulation.

### *3.2 Applications identification*

On the basis of the identified domain, a set of possible applications can be targeted. In particular, it is possible to mention:

- **Benchmarking**: comparing aspects of performance (functions or processes), identifying gaps, monitoring progress and reviewing the benefits.
- **Testing**: testing the functionality and correctness of a process (algorithm, method, approach) by running it. Testing is usually performed for defect detection or reliability estimation.
- **Data validation**: determining if data are accurate, complete, or meet specified criteria.
- **Multi-sensors Data Fusion**: studying means and tools for the integration of data from multiple sensors.
- **Acquisition Planning**: selecting and interconnecting the most suitable acquisition devices to the purpose of obtaining a satisfactory 3D acquisition.

- **Data enhancement**, modifying the shapes to improve or preserve particular attributes (e.g. automatic recovery).

The ontology we are defining should be able to support researchers in finding solutions to problems and questions related to the above applications.

### *3.3 Desiderata collection*

Guided by the list of possible applications, we invited experts, within the AIM@SHAPE network, to imagine possible interesting questions related to their research activities which could be asked to a knowledge-based system. In the following we list some of the desiderata we collected:

- Is it possible to scan this object considering these environmental conditions? How? At what price?
- What characteristics of the dataset are problematic/relevant for a specific algorithm?
- Is this algorithm efficient?
- Given an algorithm with precise input constraints (e.g. format, characteristics, water tightness) and given a generic dataset, is there a process able to apply the algorithm to the dataset satisfying the constraints?
- Given this model, where do its information come from?
- Given this dataset, is it possible to get information on the distribution of its data?
- What processes are able to integrate data coming from multiple sensors?
- What open research fields are related to this process?
- Is it possible to have global information on this composite process? (e.g. price, performance, global error)
- Are there processes/algorithms able to recovery/preserve this characteristic on this model (e.g. sharp features)?
- Given these initial conditions, which scanning devices can be used?
- Given this geometric model, are the information on its accuracy sufficient to simplify it up to a given level and without losing relevant information?
- Is it possible to convert this representation into this other?
- Is this method/process applicable?
- Does the model have any proprietary right?
- Is the model representing a real world object or a synthesized object?
- Is the model manifold and/or orientable?

Some of the questions may look naïve, vague or too ambitious but they are useful to determine fundamental key entities and their refinement can lead us to a definition of more precise competency questions.

### *3.4 Key concepts identification*

Based on the informal desiderata described in the previous section and on the community's expertise, some key entities and concepts related to each specific macro-step have been identified (i.e. Acquisition, Shaping and Post-processing) together with other entities and concepts that can be considered transversal to the three steps.

Since a lot of desiderata hinge on the processes themselves (feasibility, global accuracy, etc.) we decided to build our ontology as an "operative ontology": it will model not only the concepts like sensors, input, and output but also the knowledge on actions related to the pipeline. In this sense, for example, we point out key entities such as *algorithm* or *process*.

Some key entities relevant for each macro-step are listed in bold in the following paragraphs. The goal of these steps is just to collect possible *tokens* of the ontology, without pre-selecting which of them will become classes, attributes or relations in the ontology.

#### 3.4.1 Shape acquisition and registration

In the phase of acquisition and registration, we deal with digital shapes, real objects and the scanning devices for acquiring data. In particular, the **real object characteristics** are significant: the **scanning device** should be chosen with respect to the **size** (small/big), the **roughness**, the **reflectance**, the **material**, the **fragility** or the **concavity/convexity** or presence of **self-occlusions** in the object.

Also the **environment conditions** can help in choosing a suitable acquisition device: different decisions can be taken whether the object is **indoor**, **outdoor** or **underwater**.

The acquisition device itself can have different characteristics and properties: it can have **sensors** or **cameras**, it can be a **passive** or **active** device and it can be based on **structured lights** (see [13] for a detailed taxonomy).

In order to correctly choose an acquisition device some other characteristics can be taken into account like the **price** of the infrastructure, the **time of acquisition** and the necessary

**accuracy**. In the case of multiple scans, the **registration** of different data is necessary: the registration can be **manual** or **automatic** and the global and local **error** of the process can be estimated.

### 3.4.2 Shaping

In general, the shaping step can be **image-based**, when the final shape is obtained inferring on information given by a single **image** or multiple images, **surface-based** when a **surface** is extracted and **volume-based** when volumetric entities are used to build the related model.

For the sake of conciseness, we concentrate only on some key methodologies related to the surface-based shaping step. In particular, the final surface can be obtained via **zippering** operations or **marching intersections** (gluing different **range images** in a unique **mesh**) or via **sculpturing** methods (**alpha-shapes** …) or **volumetric** ones (**marching cube**…). In this step, also **implicit surfaces** can be generated. A method of shaping can be **local** or **global**, it can manage **out-of-core** operations and can run **online** or **offline**.

For a shaping method also the **size** of the model can be important as well as information about the **structure** of the input data (**organized**/**unorganized** dataset). For the output, some characteristics can be relevant such as **water-tightness**, **manifoldness** and so on.

### 3.4.3 Shape processing

The post-processing step may include different shape manipulation processes. In some cases, the model can be **enhanced** geometrically (**filling holes**, **recovering sharp features** or applying **subdivision**), while in other it can be **optimized** via **smoothing** or **simplification** operations.

If necessary, a model can be forced to be **manifold** via a **repairing** method. Finally a post-processing method can aim at enhancing the **appearance** of the final model (**color**, **texture**).

### 3.4.4 Transversal key entities

As we said before, there are some transversal entities that may appear in more than one phase. **Points** (points with normals), **point clouds**, **splats**, **image**, **range image** or **meshes** and in general **shape data**, can be used in any of the phases of the pipeline.

The concept of **process**, as a sequence of operations, is intrinsically used to describe the entire pipeline and each sub-step. A process has in general an **initial state**, a sequence of steps and a **final state**.

Each step can be a specific **algorithm** with its **input**, **output**, **parameters** and **implementation details**.

**Accuracy**, **complexity** and **performance** are concepts common to processes and algorithms, such as **limitations** (in topology, in online or offline execution and so on).

## *3.5 Competency questions elicitation*

One of the ways to determine the scope of the ontology is to sketch a list of questions (known as *competency questions*) that a knowledge-base, based on the ontology, should be able to answer [14].

To determine a set of questions we decided to refine (if necessary) some of the informal desiderata with respect to the key entities named in the previous section.

These competency questions are just a sketch and do not need to be exhaustive:

- Is there an algorithm for which this shape data can be the input?
- What processes use this algorithm?
- What is the history related to this shape data?
- Which are the processes that accept as input shape data coming from different scanning devices?
- What is the global price of this process?
- Does this shape data have any proprietary right?
- Is this shape data related to a real world object or to a synthesized model?

These questions will serve as a guide in the design phase and as an evaluation test at the end: Does the ontology contain enough information to answer these types of questions? Do the answers require a particular level of detail or representation of a particular area? [12].

## *3.6 Initial ontology*

According to the macro step presented in paragraph 3.1 and aiming at conceptualize flows of data and algorithms different shape data have been considered separately. For each Shape data it has been pointed out if it could be input (output) of the three main macro-steps. The drawing up of a table helped us in this task (see Table 1).

This and other tables and sketches were of support in developing our first ontology, which is presented in this section.

| Shape Data | Input | Output | Digital Real | Measured | Structured |
|---|---|---|---|---|---|
| Range image | AS | A | D | Y | Y |
| Image | ASP | A | D | Y | Y |
| Points Cloud | S | A | D | Y | N |
| Real Object | A | - | R | N | N |
| Mesh | P | SP | D | N | Y |
| Multiple scans | AS | A | D | Y | N |
| Synthesized Model | AP | SP | D | N | Y/N |
| Points | S | A | D | Y | N |
| Contour | SP | A | D | Y | Y |
| Line (linear) | SP | A | D | Y | Y |
| Implicit surface | P | SP | D | N | Y |
| Deformable Models | P | SP | D | N | Y |
| Volume based | P | SP | D | N | N |
| Distance Functior | P | SP | D | N | N |
| Legenda: A=Acquisition, S=Shaping, P=Post-processing, Y=Yes, N=No, D=Digital, R=Real | | | | | |

**Table 1 – Schematic characterization of some shape data**

The main idea behind the presented design is that all the knowledge can be modeled using three interconnected aspects:

- the Processes,
- the Acquisition System,
- the Shape data.

The first aspect is related to processes and algorithms and it aims at modeling the operations on Shape data and the processes included in the acquisition and reconstruction pipeline. The second aspect is devoted to the description of the possible acquisition devices and related methodologies and characteristics.
Anyway, Shape data is the fundamental concept around which our ontology will be built: it may be created by the use of acquisition systems and it is the entity manipulated by processes (and algorithms).
The focus of this paper is devoted mainly to deepen the knowledge related to Shape data: the conceptualization of processes may be inherited from existing workflow languages (e.g. WSFL [15] or XPDL [16]), while the complete conceptualization of the acquisition system is still under development.

In particular, for the acquisition system we have identified that it should be constituted by one acquisition device (or more), its functionalities (the specification of the way in which the acquisition devices operate) and a set of attributes related to environmental conditions, such as indoor, outdoor, underwater and so on.

### 3.6.1 Shape data

As we said before, Shape data is a general concept which includes all the data we decided to handle, including real objects.
**Shape data** is considered to be an *abstract class*: it cannot be directly instantiated. It collects the attributes that are shared by all kind of shapes as, for example, being structured or not, being digital or real, its format and dimension.
Moreover, any shape data in this domain can be annotated with a history which keeps track of the list of operations that lead to it. We defined this history as a class characterized by a list of evolving shape data, linked to the current shape via a relation.

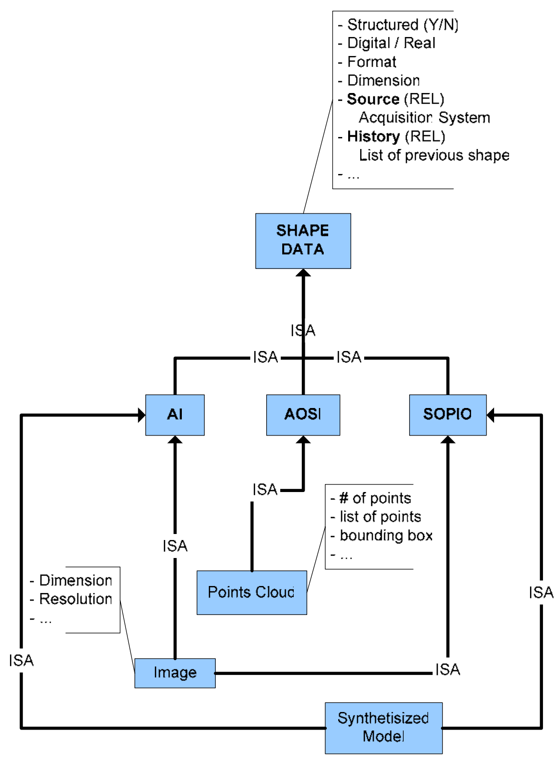


**Figure 3 : A zoom on the formalization of Shape data**

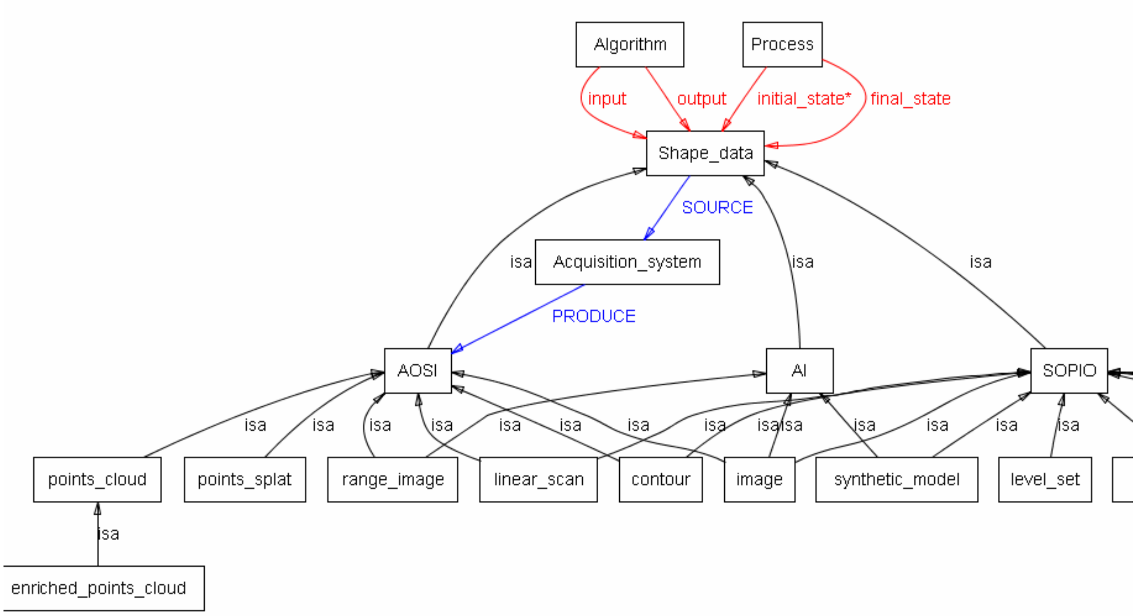


**Figure 4 : An Ontoviz visualization of part of the ontology we implemented in Protégé.**

Another relation that has been identified is the relation between the current shape data and the acquisition system (if there exists one) which has 'produced' it; we model this acquisition system as expressed in the previous section.

As explained above, the acquisition and reconstruction pipeline is divided in the three macro-steps of Acquisition (and registration), Shaping and Post-processing.

Some shape data can be input of the acquisition (e.g. real object), some other can be output of the acquisition and input of the shaping (e.g. range image). Finally some shape data can be output of the shaping step and input of the post-processing (e.g. triangular mesh).

Moreover, what is input of post-processing is also output of the same step, because different post-processing methods can be applied to shape data.

Thus, we defined three abstract subclasses of shape data (see Figure 3):

1. acquisition input (`AI`)
2. acquisition output, shaping input (`AOSI`)
3. shaping output, post-processing input and output (`SOPIO`)

Note that some shape classes can be specializations of more than one of the above classes. `Image`, for example, can be subclass of both `AOSI` and `SOIPO`.

Presently we are defining the metadata associated to each shape data. For example an image will have as attributes the dimension and the resolution, while a point cloud will have the number of points, other information related to points, and the relative bounding box (if possible).

## 4. Conclusions and future works

This paper presents an ontology-based approach to conceptualize the domain of shapes acquisition and reconstruction.

The effort was aimed at the creation of a connection between a well-know methodology for developing formal conceptualizations and the Computer Graphics and Vision research community.

The main contributions of the paper are: the identification of the key entities characterizing the domain, the desiderata obtained from experts in the field and the design of an initial ontology.

A first prototype of ontology using Protégé [17] has been implemented in order to test it and gather immediate feedback on it (see Figure 4 for an Ontoviz Visualization of part of the ontology).

This work is strictly related to the goals of the AIM@SHAPE Digital Shape Workbench: a shared repository containing tools and shapes.

In this context, the correct conceptualization of Shape data and the related processes could make explicit semantic information useful for the implementation of an innovative e-science support to the scientific community.

Obviously the work undertaken so far represents an initial step: the methodology we applied expects several steps of iterative refinement.

In particular, it is necessary to complete the conceptualization of shape data subclasses and to integrate a workflow language for the processes aspect.

Anyway, this work represents the basis for a knowledge-based system in the field of shapes acquisition and reconstruction.

## 5. Acknowledgements

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