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On the Evolution of Geometrical Reconstruction as a Core Technology to Sketch-Based Modeling

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ABSTRACT

In this work, the background and evolution of three-dimensional reconstruction of line drawing over the last thirty years is discussed. A new general taxonomy is proposed to describe and discuss the historical evolution of geometrical reconstruction and its challenges. The evolution of geometrical reconstruction from recovering know-how stored in engineering drawings to sketch-based modeling for helping in the first steps of conceptual design purposes, and the current challenges of geometrical reconstruction are also discussed.

Categories and Subject Descriptors (according to ACM CCS): I.7.5 [Document and Text Processing]: Graphics recognition and interpretation. I.2.10 [Artificial Intelligence]: Perceptual reasoning

1. Introduction

Description of the geometry of three-dimensional objects on a two-dimensional surface has been an academic discipline for more than two thousand years. The inverse problem is concerned with how to "recover" the geometrical and topological structure of a three-dimensional object by interpreting two-dimensional representations. Of course, *implicit* recovery actions have always been carried out by humans in order to "read" drawings. Yet, *explicit* formalization of this problem only began to attract a certain amount of attention in the 1960s, when the development of computers made some kind of automatic approaches possible. This problem, called *geometrical reconstruction* (or *line drawing reconstruction*, or simply *reconstruction*), implies the determination of geometrical and topological relations of all atomic parts of an object depicted in a drawing. It must not be mistaken for *restitution* and *recognition* – two well-defined fields concerned with some kind of identification of objects and not with a detailed description of its geometry.

Most of the known approaches are now in experimental stages, and are able to interpret (without many errors) almost all kinds of polytopes. Interpretation of the most usual surface elements (like cylinders, spheres, etc.) is also considered by some of the approaches. In any case, as the complexity of objects increases, automatic processes usually give way to different semiautomatic approaches.

In this paper the result of an intensive bibliographical search on geometrical reconstruction is summarized. Besides validating the criteria already established by other authors, a new general classification criterion is proposed that will allow us to observe the historical evolution of geometrical reconstruction and the challenges involved.

One of the first attempts at geometrical reconstruction was to extract information from engineering plans, or blueprints. This was an important goal since already existing designs represent an important amount of "know-how", which is stored in engineering drawings. This means that automatic solid-model generation from standardized drawings could have been the "bridge" needed to recover the information that is built into the thousands of old designs filed away in drafting rooms. To do so, all information included in technical drawings had to be "read". But the task proved to be difficult because engineering drawings convey 3D information represented through *complex* views (main orthographic views, particular views, cuts, etc.) and annotations (dimensions, tolerances, etc.). In fact, current multiple-view based approaches are usually limited to considering only main orthographic views without annotations. They do not even accept standardized conventions like particular views and sections.

However, the main goal of the reconstruction community changed in the 1990s. Nowadays, most of the systems are oriented toward conceptual design, via sketch-based modeling, and use only a sketch generated by the user as input data. Until now they have avoided the most specialized conventions on general principles of representation and are limited to generating only proportional models, while they leave the exact dimensioning for a later phase.

During the discussion, we will argue that the goal of geometrical reconstruction is far from being accomplished since CAD systems have non-sequential (graphic) outputs, but accept only sequential (verbal) inputs. This is a direct consequence of the sequential nature of algorithmic languages used for programming tasks. In contrast, design processes, and in particular ideation processes, need non-sequential thought. Yet it is important to notice that we do not claim for the physical implementation to become non-sequential; it is just the conceptual model (and the interaction front end) that must be "graphical", in the sense of its being non-sequential. Consequently, a graphical language is required to improve the present communication between designers and CAD systems.

Among the challenges to be dealt with, we shall highlight the fact that projective geometry laws are unable to resolve the problem, because it is well known that biunivocal correspondence among 2D images and 3D models does not exist. Hence, visual perception contributions are required. However, visual perception is still not prone to algorithmic formulations because it has only rarely been studied. Moreover, all of the current approaches contain a more or less balanced mixture of geometric and perceptual principles, but the coupling is still not well solved.

2. Related work

First, a brief summary of the background of sketch-modeling is included to establish its link with geometrical reconstruction. After that, a reduced set of references is included in the next section. An extensive list of works on geometrical reconstruction is available at `http://www.tec.uji.es/d/regeo/`, although only the references necessary to emphasize the main points we find in its evolution are included in this paper.

As to references on geometrical reconstruction reviews, the book by Sugihara [Sug86] is the most comprehensive reference to the early history of line drawing interpretation. Nagenda and Gujar [NG98] published a comment on eleven papers published between 1973 and 1984 on this topic, including a categorization tree. Wang and Grinstein [WG93] updated the categorization and developed a taxonomy of 3D object reconstruction from line drawings in two-dimensional projection. The classification relied on different but dependent aspects. Distinctions were made based on the nature of the objects to be reconstructed, the internal representation of the generated model, the number of 2D views needed, the required premises, and the degree to which the user interacted.

2.1 Reconstruction and sketch-based modeling

The need for sketch-based geometric modelers in the environment of conceptual design can be traced back to the last decade [UWC90], [Cug91], [Dor95], [Ull02]. At present, two main approaches to 3D modeling by sketching exist: gesture and reconstruction-based methods.

Gestural modeling systems provide predefined gesture alphabets that encode some geometric modeling operations. Examples include SKETCH [ZHH96], SKETCH-N-MAKE [BZF*98], Quick-Sketch [EHBE97], GIDeS [PJBN00], ISID [BMFH02]. Some sketch-based modeling applications are oriented to freeform surface modeling [WY03], such as Teddy [IMT99], where the system automatically generates one surface using a polygonal mesh that matches the silhouette drawn by the user.

In *Reconstructional modeling*, geometric reconstruction techniques serve to build the object's geometry from a sketch. A preliminary stage may exist where batch [PV97] or interactive beautification is performed [JM92] [IMKT97]. Interactive beautification provides the user with immediate feedback because it operates as the user draws the sketch and it offers better integration with a calligraphic interface. Batch beautification allows some analysis to be implemented, for example symmetry detection, which is better carried out over the whole sketch [CCCP04]. Some examples of reconstructional systems that implement a batch beautification stage include "Digital Clay" [SG00]. This application provides sketch input, with batch beautification, which feeds a reconstruction browser that uses Huffman-Clowes algorithms [Huf71], [Clo71] to reconstruct the object geometry. The Stilton [TCP00] reconstruction process uses the optimization approach and genetic algorithms. An example of the interactive beautification approach is CIGRO [CNJC03], which provides a calligraphic interface that implements an interactive beautifier and feeds a reconstruction engine operating on an axonometric projection. The system supports rectangular polyhedral objects and provides dynamic viewpoints that make it easy to implement an incremental modeling strategy. GEGROSS [NCAJ04] extends CIGRO capabilities, transforming it into a hybrid system (using both gestural and reconstructional approaches).

To sum up, there are two main methods to capture designer intents: automatic (reconstruction-based) and interactive (gesture-based). Differences in the beautification process also exist. Design intents that have a "local" impact (i.e. they affect the geometry only in the neighborhood of some element) are mostly carried out concurrently with sketching (interactively). Beautification that affects design-intents that require global alterations of current geometry, however, are better done after sketching (in batch mode). Corners that do not meet are good examples of local beautifications, while symmetry requires a more global consideration [PMC03].

3. Geometrical reconstruction taxonomy

Our own classification, which is described in detail in [Piq03], is summarized in two tables, distinguishing between single view (*Table 1*) and multiple view (Table 2) approaches. Only a reduced set of references are included in the tables, since both of them are intended to emphasize the historical evolution, while clearly summarizing the main characteristics of each algorithm: the types of surfaces, the need for interaction, the internal representation of the 3D model, the main characteristics of the input 2D drawing, and whether or not the algorithms search for all the possible solutions or stop just after finding the first valid one. In *Table 1* the approaches are also classified in six different categories, from "labeling" to "regularities". Such a classification is not included in multiple views (Table 2) as the differences between the approaches are considered to be less relevant.

There is a historical distinction between single-view and multiple-view approaches, and this is still relevant since

Table 1: *Single-view reconstruction approaches*

			Approach						Surface		Inter-action		Represen-tation			Input			2D Hidden lines		Solu-tions	
Year	**Reference**	**Authors**	Labeling	Gradient space	Linear pro-gramming	Progressive	Primitive identi-fication	Regularities	Planar	Curve	Yes	No	B-rep	CSG	Labeling	Perfect line-drawing	Imperfect line-drawing	Sketch	Yes	No	One	Multiple
1963	[Rob63]	Roberts					*		*			*	*				*			*	*	
1968	[Guz68]	Guzman	*						*			*	*			*				*	*	
1971	[Huf71]	Huffman	*						*			*			*	*				*		
	[Clo71]	Clowes	*						*			*	*		*	*				*		
1973	[Mac73]	Mackworth		*					*			*	*			*				*	*	
1975	[Wal75]	Waltz	*										*									
1978	[Sug78]	Sugihara	*						*				*						*			
1980	[Kan80]	Kanade	*						*			*	*			*				*	*	
1982	[Sug82]	Sugihara			*				*		*		*				*			*	*	
1986	[Sug86]	Sugihara			*				*		*		*				*			*	*	
1987	[Mal87]	Malik	*						*	*		*			*	*				*		*
	[Wei87]	Wei		*					*			*	*				*			*	*	
1989	[WG89]	Wang & Grinstein					*		*			*		*		*				*	*	
1990	[LB90]	Lamb & Bandopahay				*			*		*		*					*		*	*	
1991	[Mar91]	Marill						*	*			*	*			*			*		*	
1992	[Wan92]	Wang					*		*	*		*		*			*			*	*	
	[LF92]	Leclerc & Fischler						*	*			*	*			*			*		*	
1993	[WG93]	Wang & Grinstein					*		*	*		*		*						*	*	
	[MRLV93]	Marti et al..	*						*			*			*		*		*			
1994	[BCN94]	Branco et al.				*			*		*			*				*		*	*	
	[SP94]	Shimshoni & Ponce			*				*		*		*				*			*	*	
1995	[GM95]	Grimstead & Martin			*				*			*	*					*		*		*
1996	[GM96]	Grimstead & Martin			*				*			*	*					*		*		*
	[LS96]	Lipson & Shpitalni						*	*			*	*					*	*		*	
	[Par96]	Parodi							*			*								*	*	
	[PW96]	Brown & Wang						*	*			*	*			*				*	*	
1999	[CGC99]	Company et al.						*	*			*	*				*		*		*	
2000	[VM00a-c]	Varley & Martin			*				*			*	*					*		*	*	
2001	[VM01]	Varley & Martin	*						*			*			*			*		*		
2002	[RT02]	Ros & Thomas			*				*			*	*				*			*	*	
2003	[VMS03]	Varley et al.	*		*				*			*	*			*				*	*	
2004	[CCCP04]	Company et al.						*	*			*	*					*	*		*	

the methodologies in both cases are clearly different. This distinction is also noticeably associated with the change of objective in the geometrical reconstruction Obviously, multiple-view reconstruction was of capital importance for recovering designs stored in engineering drawings. Hence, many of those approaches use perfect line drawings as input, and include hidden edges and curved surfaces.

Our classification distinguishes between algorithms that accept flat surfaces and those that accept curved surfaces. That is to say, we distinguish between reconstruction of polytopes and other forms. In general, the type of surfaces that a system is able to reconstruct is essential to verify the versatility of an application. But the reliability and efficiency to solve particular types of surfaces is also an important aspect.

First attempts at 2D line drawing interpretation were limited to *prototype objects*. The objective was the identification of shapes whose projections had been previously recorded. In other words, given an image of an object, the system identifies the object by first extracting a line drawing from the image and then searching for a prototype whose projection coincides with the line drawing. This approach was closer to recognition than to reconstruction.

A general solution was later obtained for the reconstruction of *polyhedral objects*. Nevertheless, it was sometimes necessary to draw a distinction between Eulerian and non-Eulerian polyhedral objects. In addition, the complexity of polyhedral objects was measured in terms of the number of nodes and node "degrees" (the number of edges ending in a node), and this posed a limit to some reconstruction processes. This problem is still being considered [VSM04].

Some other attempts were particularly concerned with reconstruction of *revolution objects* (like cylinders and cones) and *extruded objects* – two special cases of "sweep" geometry. Initially very important restrictions were necessary in the orientation of those objects. Finally, some improvements were introduced and the orientation of curved objects was softened or even disappeared.

Table 2: *Multiple-view reconstruction approaches*

			Surface		Inter-action		Representation			Input			2D Hidden lines	
Year	Reference	Authors	Planar	Curve	Yes	No	B-rep	CSG	Labeling	Perfect line-drawing	Imperfect line-drawing	Sketch	Yes	No
1973	[Ide73]	Idesawa	*			*	*			*			*	
1981	[WM81]	Wesley & Markowsky	*			*	*			*			*	
1982	[HQ82]	Haralick & Queeney	*			*	*							
1983	[Sak83]	Sakurai	*	*	*		*						*	
	[Ald83]	Aldefeld	*	*		*		*		*			*	
1984	[Pre84]	Preiss	*	*		*	*			*			*	
	[AR84]	Aldefeld & Richter	*	*	*			*		*			*	
1986	[GTS86]	Gu et al.	*	*		*	*			*			*	
1988	[CP88]	Chen & Perng	*	*	*			*						
1989	[GN89]	Gujar & Nagendra	*			*	*						*	
1992	[CPCW92]	Chen et al.	*	*		*	*							
1993	[MP93]	Meeran & Pratt	*	*		*		*		*			*	
1994	[YCT94]	Yan et al.	*			*	*			*			*	
1995	[AT95]	Ah-Soon & Tombre	*	*		*	*			*			*	
	[LDK95]	Lysak et al.	*	*		*	*					*		
1996	[YY96]	You & Yang	*	*			*				*		*	
1997	[MN97]	Masuda & Numao	*	*			*				*		*	
	[SLYK97]	Shum et al.	*	*	*			*		*			*	
1998	[Kuo97]	Kuo	*	*		*	*				*		*	
	[SS98]	Shin & Shin	*	*			*			*			*	
	[TIHW98]	Tanaka et al.	*	*		*	*				*		*	
1999	[SKK99]	Suh et al.	*				*			*			*	
	[SSM99]	Sastry et al.	*		*		*			*			*	

Nowadays, a wide range of objects can be reconstructed. This includes manifold and non-manifold objects containing flat and cylindrical faces. However, reconstruction processes tend to become more prone to error when the objects involve curved surfaces.

Reconstruction systems can also be classified in terms of the degree of participation they require from the user and we can distinguish between automatic and guided systems. The aim is to detect who makes the critical decisions. Yet, some guided systems require so much participation from the user that they could be classified as "intelligent" modeling systems, rather than reconstruction systems.

From Tables 1 and 2 it can be concluded that the 3D object representation most commonly used in reconstruction problems is BRep (boundary representation). Nevertheless, some attempts have been made to reconstruct CSG (Constructive Solid Geometry) models from 2D representations of *extruded objects*. Approaches whose main result was labeling 2D drawings are also indicated.

Input comprises perfect line drawings, line drawings containing some "minor" mistakes, and sketches. The distinction was made to highlight the evolution from perfect line drawings to sketches, which illustrates the change of goal from extracting information contained in engineering plans to sketch-based modeling. Other more "academic" distinctions concerning input were not considered since there is almost complete agreement on the best alternative.

For instance, it is generally assumed that only edges and contours are represented in the input. Consequently, we can say that only "standardized" principles of representation are used as input for reconstruction purposes. Sometimes it is said that only "pure" line drawings are considered. By "standardized" or "pure" we mean that texture, range, shadowing and other additional representation resources are not considered. It is important to note that these other resources are currently used in object recognition.

Another general agreement concerns a limitation usually added onto the point of view. In perspective projections, the direction of projection cannot be parallel to any face or parallel to any pair of collinear edges. This constraint is named "general point of view convention" and usually eliminates potential degeneration cases (in which, for instance, one face can project in one line, or two distinct edges can project on the same line).

The need to include hidden lines in the input drawing is judged to be another relevant criteria, since there is a clear separation among methods where the input includes all lines in the drawings (transparent models) and methods that reconstruct from an input that only contains the visible edges (opaque models). In the transparent models approach, all lines must be drawn in the input, but generally there is no need to distinguish between visible and hidden lines. In the opaque models approach, the system generally infers the rear part of the model after reconstructing the front part.

Finally, the distinction among "solutions" was considered relevant in single-view approaches because it is obvious that the problem has many solutions, except in the simplest cases. Hence the strategy to find the "best" solution is, in general, relevant. At first, the usual procedure was to find a set of solutions and let the user choose the most appropriate one, i.e. the *completeness* of the approach was the goal. Nowadays, the tendency is to include more or less heuristic criteria to choose the best option automatically, i.e. the *ease of use* is the goal. Hence, our classification of the approaches as "one solution" could have been refined by distinguishing between approaches that stop when the first solution is found and those that include criteria to continue with the search until some sort of "best" solution is found.

4. Discussion

As was said in the introduction, our aim is to describe both the evolution of geometrical reconstruction and its challenges. The evolution has been revisited in the previous section, where we distinguished between a number of different inputs, but it can be seen that all of them are quite simple compared to current engineering drawings. Moreover, in single view reconstruction, two different "schools" can be observed. One is centered on labeling and linear programming approaches, while the other one comes from primitive identification and is more or less regularities-based. Hence, we are going to discuss what we consider to be the main challenges in geometrical reconstruction, namely, the current situation and the tendencies in the relation between both reconstruction and engineering drawings, and reconstruction and perception.

4.1 Reconstruction and engineering drawings

Geometry definition and geometrical compatibility studies are very often the "core" of design processes of mechanical parts, assemblies, and even small systems. Designers make use of physical *prototypes* when faced with the most challenging problems, but these are expensive and slow. "Mind's eye" models can substitute physical prototypes when the designer has some expertise with the problem [Fer92]. If the problem is more complex, mind's eye models can still be useful for the overall design, but formal models are also needed to complete the design.

In the so-called "design-by-drawing" method, geometrical design is carried out through the formalized body of knowledge known as descriptive geometry, where the physical prototypes and mind's eye models are advantageously substituted by engineering drawings, in order to fix the geometry that satisfies all the design specifications. See [Boo63] for an excellent history of the matter.

When engineering drawings contain only incomplete information and the signs and figures used are to be interpreted only in an approximate sense, the representation is said to be a *sketch*, while it is said to be a *plan* or "blueprint" when complete, exact and exhaustive information is represented. This distinction is important because sketches are not contractual documents whereas plans are. In addition, sketches usually have a short life span but plans are filed and belong to the history of the industry. Furthermore, plans must be "self-contained" (i.e. they must require no complementary explanations) while sketches are usually complemented with verbal explanations and textual annotations.

In the design-by-drawing method, plans were used on a massive scale while sketches were left aside. They served to synthesize initial ideas, but received little attention. The same happened when Computer Aided Drawing systems appeared (the so-called CADD systems, in the terminology of the late 1980s and early 1990s). This was a fairly logical consequence of the fact that freehand drawings are done with simple instruments (paper and pencil) whereas line drawings are done using "geometrical" instruments (i.e. instruments that guarantee the correctness of geometrical constructions). The main difference is, of course, the geometrical information contained in the two kinds of drawings. In other words, it is "legal" to measure on a line drawing (if geometrical procedures are ensured) to extract dimensional information. However, only proportions and some other geometric characteristics (like symmetry, parallelism, and so on) can be roughly derived from a freehand drawing.

With the advent of CADD systems, and in the name of productivity, there was a rapidly growing interest in some sort of automatic recovery of old designs stored on paper plans. In this context, the need was partially covered by multiple-view reconstruction approaches. However, it was soon realized that, for computers to run processes to explore engineering drawings, they ought to be able to extract not only iconic (signs based on geometry) but also symbolic (signs based on social conventions) information from engineering drawings. Besides, the mismatches, errors and "complicity" present in all engineering drawings ought to be filtered by computers. In sum, it proved to be a difficult objective to reach and, more importantly, the need that generated the goal almost disappeared at the end of the 1980s because some CAD vendors and many independent software consultants began to offer complete translation services from paper plans to CAD files.

Moreover, in the late 1980s, CAD software produced a revolution in the design-by-drawing method when virtual 3D *prototypes* began to be generated and manipulated directly by 3D CAD systems. Nowadays, geometrical modeling has completely replaced descriptive geometry. Hence, the new paradigm includes sketches to synthesize initial ideas. Then, geometric models are constructed and are used for analytical purposes. Finally, detailed drawings are obtained automatically to record and transmit the precise data needed for the production process. In this scenario, a new tool is still required to help the designer in the phase of fixing ideas. Such a tool would be capable of "capturing" the ideas generated by the designer and automatically generating the model of the design. In other words, the solid model should be made "transparent" to the designer (that is, it must be an *internal* model for the CAD system).

Indeed, some sketch-based modelers provide, early in the design process (during the idea generation phase), models that can be constructed quickly so that the design ideas can be tested. In sketch-based modelers speed is more important than geometrical accuracy. Yet, to date, computer-based sketching capabilities continue to be limited and disconnected from CAD systems.

Moreover, design attempts must be converted into sketched geometry before they can be "read" by these experimental sketch-based modelers. In other words, the system creates a digital prototype, but the creation task is not "linked" to any previous conceptual synthesis task.

In our opinion, for this purpose, some *language* oriented toward creativity enhancement must be defined to improve communication between the designer and the CAD system.

The aim is not easy to accomplish because communication between designers and CAD systems is unbalanced in favor of programming needs. As things stand today, CAD systems force the designer to control a sequential flow, directed from specifications to detailed design.

The sequential nature of algorithmic languages is the reason why these languages are at the back end of today's computer tools (and Graphical User Interfaces are no exception to this rule). The need for programmers to define an implementation model of the process to be executed reinforces the sequential tendency. Because, for programmers, defining a "conceptual" model of a process ("what" the system can do) that comes as close as possible to the "implementation" model ("how" it does it) is always the simplest solution. As a result, the designer is continuously asked for *actions* (well-defined, sequential actions) to be done by the CAD system. And this is not a good strategy when the designer is trying to fix "visions", that is, ill-defined and non-sequential ideas.

Transparent commands (i.e. temporary interruption of an order to execute another "nested" order) can give the wrong impression that the user can do almost everything at almost every moment. And, in fact, CADD systems (*drawing* systems) are highly "interactive" because they impose few limitations on "wandering" users. But we must remember that the reason is that they are based on descriptive geometry and technical drawings, that is, disciplines based on non-sequential languages. Unfortunately, this is not the case of real 3D CAD systems (*design* systems). CAD systems can create virtual three-dimensional models that, in turn, can be shown in beautifully rendered (and, of course, graphic) images. But the construction of these models is strictly sequential. One single action follows every command and the system turns back to the "neutral" state waiting for the next explicit command.

To sum up, a lot of work has been done, since sketch-based libraries (like Cali [FJ01]) and sketch-based systems (like Smartpaper [SC04]) now exist, but our problem is that "non-verbal" thought cannot be expressed in a "verbal" language. Verbal is defined as being synonymous with sequential. That is, verbal languages are based on variations of a set of signs over time, regardless of whether the signs are sounds or graphical forms. On the other hand, non-verbal (or "graphic") languages are those in which transmission of information is based not only on the meaning of a predefined set of signs but also on the spatial relations between all signs; that is, the resemblance, order, proportion and neighborhood relations present in every written communication (and necessarily absent in oral communications). It must also be noted that in non-sequential communication, the time needed and order followed to write and read the message does not affect the information.

The utopian objective would be a design system capable of integrating all the information contained in a sketch interactively during the sketch creation and refinement phases; capable of formalizing the non-formalized ideas contained in the sketch; and capable of analyzing and evaluating the provisional model, as well as giving the designer feedback on the performance of the intended idea.

We can consider engineering drawings as a language used for communication and therefore related to standardized conventions. However, languages are not only useful for communication – they also play an inherent part in our thinking processes (it can be said that we use languages to "dialog" with ourselves) and, in this domain, psychology and perception rules play the most important role.

4.2 Reconstruction and perception

What is "true" in a drawing depends on what such a representation is intended for. In fact, engineering graphics differ depending on their purpose or "audience". The dependence is on the amount of information (required clarity, precision and level of detail) the receiver requires and/or can process. Three forms are usually distinguished:

- made for personal use, and not meant to be understood by anyone but the individual who produced it.
- intended to communicate with someone who understands technical drawings.
- used to further clarify design ideas and to communicate those ideas to non-technical individuals.

In the evolution of geometrical reconstruction the emphasis has moved from geometry to perception. At first, geometry was the center of attention. As justified above, this was partially due to the need to interpret what we have classified as drawings intended to communicate designs that were already finished. However, there was an ever-increasing tendency for the emphasis to shift to perception, in parallel to the growing interest in the use of drawings to further clarify design ideas and to communicate those ideas to non-technical individuals.

Indeed, perception has been less studied than geometry, but excellent references exist to cover the needs of an introductory study for the geometrical reconstruction community [Pal99] [Hoff00].

In our opinion, perception is a process involving the extraction of information from stimuli that have some value as signals. Stimuli that promote some sort of action are the ones that are considered to be signals, and they are actions because perception is an active, constructive process. In other words, as the process is constructive, it is performed through stages (sequential) and levels (hierarchical). Hence, it is a *behavior*. Furthermore, this behavior departs from an innate base and is empowered by learning.

Because perception is a behavior, it requires *intention* and *attention*, the former being needed because it is a sequential and selective behavior. We observe by way of successive eyeing, and only some specific aspects are considered while eyeing. In fact, this behavior explains why caricatures work – they simplify the images but keep and enlarge the pertinent aspects.

Because perception is empowered by learning, training is to be directed toward increasing attention. It is *deliberate* (we "pay attention") and *directed* toward an objective (we "look for something"). This is why camouflage works – when the aspect we are searching for is hidden, the entire object disappears.

In fact, the optimization approach (like [Ma91] et al. in the "regularities" column in *Table 1*) is iterative (or sequential); deliberate, because we search for regularities (i.e. we direct intention and attention toward the properties of the image that we believe to correspond to properties of the model); and, obviously, it is directed toward an objective (i.e. we optimize a figure of merit). It is also hierarchical, since regularities are weighted in the objective function. However, recent contributions to the linear programming approach (like [GM95], [VM00a] and [VMS03]) include sophisticated hierarchism algorithms that output good algorithmic solutions to "deliberation" on what is pertinent in the drawing in order to obtain the best characterization of the model.

In sum, the reconstruction approaches are increasingly taking into consideration the principles and laws of perception and, consequently, they are on the way to *artificial perception*.

5. Conclusions and future developments

The first "revolution" of graphical capabilities of computers in the design process was to assist drafting, and almost automate it. The second has been to introduce interactive creation and manipulation of 3D virtual models to reduce (and almost eliminate) the need for descriptive geometry. In this work, we have argued that the next "revolution" will be to make engineering drawings a universal language for the whole computer-aided design process, in order to reduce (and virtually eliminate) the need for data transfer between different phases in the process.

Geometrical reconstruction is going to play a fundamental role as a core technology in this process, since automatic solid-model generation from standardized drawings is the most efficient way of establishing fluid communication between designers and CAD systems. This is the challenge of 3D *reconstruction* of design models from engineering drawings, and perception must play a relevant role in this process.

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