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Classification of Geometric Design Information and Manipulation for Vague Geometric Modelling

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Abstract
Conventional CAD systems have made significant contributions towards the detailed modelling and analysis of geometric designs, but are generally incapable of supporting the early conceptualisation and synthesis stages of design. To overcome this weakness, these systems need to improve in several areas: (a) they should be able to support designers in establishing geometric models using vague geometric information; (b) suitable manipulations should be available to evolve vague geometric models towards the final definite design; and (c) while using the systems, the designers should not need to alter their course of design unnecessarily or unnaturally. This paper discusses these key requirements based on experience from developing a prototype system for early geometric configuration design. Geometric information, manipulations and the corresponding design process are examined and classified. Finally, brief description is given on the geometric configuration system being developed to explore these requirements.

Keywords
Early design support system, vague geometric modelling, computer aided geometric design, geometric configuration, CAD

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1 INTRODUCTION

Recent studies show that about 85% of the life cycle cost of a product is committed in the design process (National Research Council, 1991). Further, 70% of these costs are determined early in the course of development when only 3 - 4% of the effort of a project has been expended (Andreason and Olesen, 1990). Since they induce cost commitments which cannot be changed readily at later detail design stages, early design decisions at the concept phase have a large effect on the overall success of a product. Therefore the rapid capture and evaluation of design concepts which represent the first embodiment of these decisions and which can lead to a reduced design cycle and right first time designs is seen as a major goal in design practice.

For most products geometry is a very important consideration throughout the design process, and is a key aspect of the embodiment of new designs. At the early design stages, geometric information may manifest in various forms, such as shape, size, location and orientation. Since precision is not of great concern at these stages, there exists a considerable amount of geometric information that is only vaguely known as observable from written brief of design concepts, specification and, most obviously and typically, from various design sketches (Guan and MacCallum, 1995). Such early expressions of form or geometric design contain enough of a designer's concept to be carried downwards into the more detailed geometric definition and specification of the final product. In current practice, however, such form concepts are unable to be readily transferred into or directly developed in existing CAD systems. More precise and detailed specifications have to be developed before the geometric design can be copied into an existing CAD system to support a range of downstream activities. An important factor which has inhibited this continuous development of geometric design concepts using CAD systems has been the gap between the 'vague' expressions of form used by designers and the formal and precise representations of geometry in the systems.

The vague expressions of form used by designer are given the term 'vague geometry' in our work. The focus of our research is thus to seek appropriate computational schemes which are compatible with vague geometry. By being compatible with vague geometry, the schemes are able to represent and reason about both imprecise and precise geometric specification. This makes it possible for the designer to develop the geometric design concepts continuously, making commitments based only on what is known or intended.

One of the key areas of investigation during this research has been the recognition and formulation of the essential requirements for the corresponding computational schemes or systems. It is our belief that development of a CAD system that supports the early stages of geometric design process should be guided by the principles of minimum commitment modelling and incremental refinement (Guan and MacCallum, 1995), and take into consideration the following aspects:

- the types and characteristics of geometric information used during the design process, in particular, at the early stages where designers most frequently carry out 'back-of-the-envelope' design activities through sketching,
- the types of manipulation it must provide to support the corresponding design activities, and
- the way the manipulations can be used by the designers.

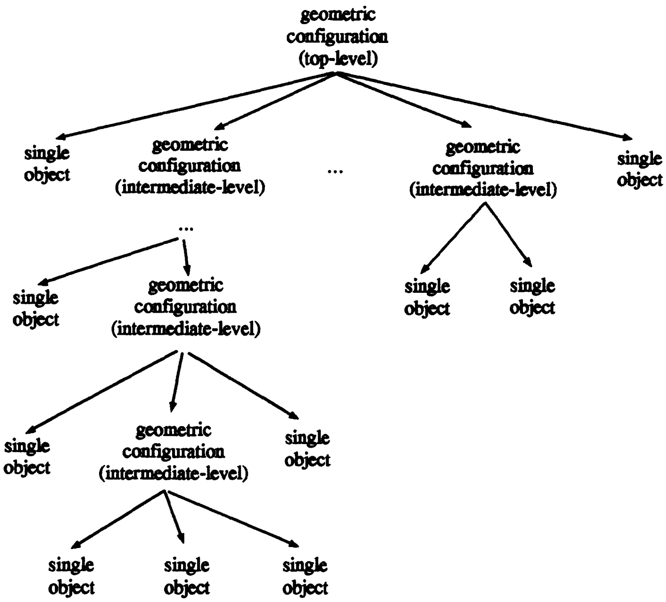


Figure 1 A geometric configuration may have multiple levels of details.

The key step taken to gain an in-depth understanding of the geometric information is the identification of different types of vagueness and different aspects of geometry to which the vagueness can be applied. The result of this, a taxonomy for classifying geometric design information, is presented in Section 2. The types of manipulation that the system needs to provide are related to the types of geometric design activities conducted. We have divided them into three types: synthesis, analysis and re-use. These are discussed in more detail in Section 3. The way such manipulations are used should suit the nature of geometric design, or design in general. In other words, it should not force the designers to change the course of design, or follow a pre-defined sequence, unnecessarily. Requirements on this aspect are also discussed in Section 3. Finally, in Section 4, we give a brief account of the prototype system through which these requirements are explored.

2 A TAXONOMY OF VAGUE GEOMETRIC INFORMATION

Geometric design is regarded as a process of defining the geometric configuration of a product. Each configuration may have multiple levels of details (Figure 1), namely, it may consist of one or more single, non-decomposable geometric objects (referred to as single objects) and/or one or more intermediate geometric configurations (i.e. configurations at a lower level of detail). A configuration is defined if and only if all of its constituent single objects and/or intermediate configurations are defined.

Geometric design information is the set of facts that are specified and used to describe or derive the geometric configuration of a product. It can be classified based on the type of geometric properties it describes. The geometric properties of a single object are classified into its *shape* and *size*, as well as its *orientation* and *location* in forming the corresponding upper-level geometric configuration. These properties are described by geometric parameters. A single object is defined if and only if all of its characterising geometric parameters are uniquely defined.

A piece of geometric information could also be classified in terms of how *vague* it describes the geometric configuration of the product being designed. Two types of *vagueness* have been identified:

- *incomplete* - which refers to the situation where elements of geometry are specified as existing either explicitly or implicitly, but values of these elements are not yet defined or known.
- *approximate* - which refers to the situation where some piece of information is imprecise or uncertain and presents a range of possible choices on the aspects of a geometric object. Note that approximation here concerns the definition of the nominal geometry of objects. Tolerances related to manufacturing are not part of the concern.

Table 1 defines the various combinations admitted by the two view points discussed above, i.e. the type of geometric properties described and the characteristic of the description, and illustrates them through examples. The classification of a piece of information that gives a relative definition of a geometric configuration depends on both the relation and the reference object. For example, 'the shape of object A is the same as that of B' defines the shape of A in relation to that of B. Since the relation - *the same as* - is precise, therefore whether information about the shape of A is incomplete or approximate depends only on whether the information on the shape of B is incomplete or approximate. On the other hand, 'the shape of object A is almost the same as that of B' defines the shape of A in terms of that of B through an approximate relation - *almost the same as.* Thus information on A is certainly approximate. But whether it is also incomplete depends on whether the information on the shape of B is incomplete. This example also demonstrates the possibility that a piece of information can possess a combination of the characteristics of vague and definite.

3 MANIPULATIONS FOR VAGUE GEOMETRIC MODELLING

A CAD system for supporting the entire process of developing geometric configurations of a product should provide utilities that enable or facilitate the use of the various types of geometric information classified above in ways suited to the nature of the configuration design process. Figure 2 presents a classification of the various types of manipulations or utilities envisaged so far for such a system.

- **Synthesis** - This type of manipulation can be used to make the geometric configuration models of a product. Such a model may be vague initially, but is completely and precisely defined at the end of the design process. Consequently, these manipulations must support the process of evolving the configuration model from vague to definite.

Table 1 Classification of geometric information - definitions and examples.

Type		Characteristic			
		complete	*incomplete*	*precise*	*approximate*
shape	defn.	Shapes with all elements given.	Shapes with missing elements.	Shapes uniquely defined.	Shapes not uniquely defined.
	exmp.	• Manifold shapes. • Shape of A is the same as that of B, and shape of B completely defined.	• Non-manifold shape. • Shape of A is the same as that of B, and shape of B has missing elements.	• Shape of A is a cuboid. • Shape of B is the same as that of C, and shape of C is a cuboid.	• Shape of A is roughly a cuboid. • Shape of B is the same as that of C, and shape of C is a roughly a cuboid. • Shape of D can be any of {cuboid, cylinder, sphere}.
size	defn.	Value of all size parameters known.	Not all the size parameters are given values.	Unique values given for size parameters.	Value of size parameters not uniquely defined.
	exmp.	• Three size parameters $\{width, depth, height\}$, all given values.	• $width$ not given value.	• $depth = 20$. • $height = depth/2.34$, $depth = 28$.	• $depth \approx 10$. • $depth = [20, 30]$. • $depth \approx height \times 2$. • $height = depth/2.34$, $depth \approx 28$.
orient.	defn.	Value of all orientation parameters known.	Not all orientation parameters are given values.	Unique values given for orientation parameters.	Values of orientation parameters not uniquely defined.
	exmp.	• Three orientation parameters $\{angle_x, angle_y, angle_z\}$, all given values.	• $angle_z$ not given value.	• $angle_x = 45°$.	• $angle_x \approx 45°$. • $angle_x = [45°, 50°]$. • A orthogonal to B. • Face 2 of A parallel with Face 1 of B.
location	defn.	Value of all location parameters known.	Not all location parameters are given values.	Unique values given for location parameters.	Values of location parameters not uniquely defined.
	exmp.	• Three location parameters $\{x_d, y_d, z_d\}$, all given values.	• y_d not given value.	• $x_d = 38$.	• $x_d \approx 35$. • $x_d = [34, 40]$. • A above B. • Parallel ribs should be placed at least two rib widths apart.

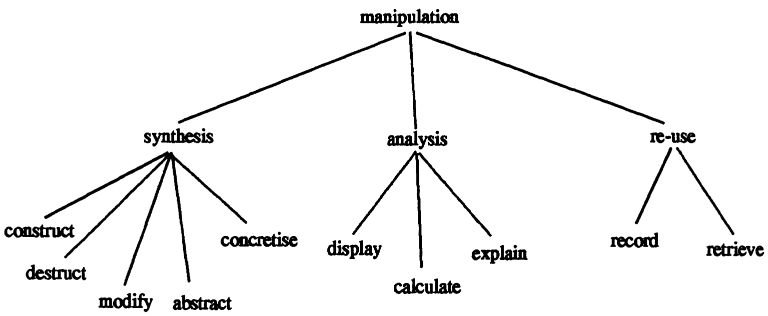
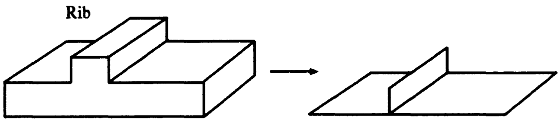
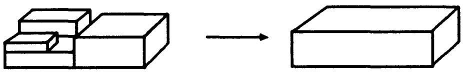


Figure 2 Classification of manipulations to be supported by vague geometric modelling systems.



(a). Skeletonising - an abstraction of an injection moulding part (Chern et al, 1990)

(b). Simplifying



(c). Packing

Figure 3 Generation of geometric abstractions for configuration synthesis.

Five types of synthesis manipulations are therefore identified: *construct* which can be used to establish a configuration initially, *destruct* which destroys a configuration model, *modify* which supports a user to add missing elements to, refine an existing element of, or remove an existing element from a configuration model, *abstract* which generates a suitable geometric abstraction of a configuration or a part of it to facilitate synthesis (or analysis) manipulations, and *concretise* which, as the counterpart of *abstract*, generates detailed models from a given abstraction.
The issue of using abstraction as a tool for simplifying or facilitating configuration synthesis is worth of elaborating upon. Figure 3 illustrates utilities that may be developed to form a chosen abstraction of a given geometric model, such as *skeletonising* (a) where medial axes or surfaces of objects are generated via *fire-propagation* or *medial axis transformation* (Blum, 1967, Chern et al, 1990, Dutta and Hoffmann, 1990, Patrikalakis and Gursoy, 1990), *simplifying* (b) where a complex shape is replaced by a simpler one such as its bounding box, and *packing* (c) which generates the geometric abstraction of a set of objects by forming or estimating their total or outlining geometry e.g. by constructing the bounding box enclosing all of the objects. On the other hand, synthesis of a geometric configuration may start from an abstract model which is then detailed and refined through certain concretisation utilities.

- **Analysis** - This type of manipulation can be used to analyse a model or part of it for the purpose of evaluation or synthesis. Three types are identified: *display* which enables and facilitates the user to inspect and compare developed configuration models, *calculate* and *explain* which provides the user with information related to the properties of an established model and to the corresponding process.

- **Re-use** - This type of manipulation facilitates the recording of generated designs and their re-use in new projects or downstream activities. Two types are identified currently: *record* which enables the user to store a developed configuration model into, e.g., a library, and *retrieve* which supports a designer in re-using existing configuration solutions in synthesising new configuration models. One issue of interest is the feasibility of using *generalisation* in maintaining the library of existing geometric configurations when new configuration models are recorded. *Generalisation* has been used in a numerical and object-based design system, NODES, to maintain libraries of design concepts (Duffy et al, 1996). The issues here are (a) whether it is useful to make use of generalisation similarly in aid of geometric configuration conservation, e.g. to form, from concrete and detailed facts about individual configuration design cases, general conclusions about the geometry of the type of designs, and (b) how feasible it is to develop the required computational mechanisms.

When using a system equipped with the above types of manipulation, a designer may approach a geometric configuration problem in the following ways:

- **Adapting a past solution** where the designer searches relevant geometric configuration libraries for similar configurations developed previously. Once an appropriate solution is found, the designer will then select and, if necessary, modify it to suit the new problem using the synthesis utilities available in the system.
- **Developing a new solution** where the designer makes use of the other resources, e.g. generic shape libraries and standard component libraries, and synthesis utilities available in the system to develop incrementally and iteratively a new configuration for the problem.
- **The combination** where the designer may first develop a new vague configuration concept from scratch and then for some of the constituent components use geometric models available from the geometric configuration libraries and the standard component libraries, or vice versa.

At the end of the design, the designer may decide to store the developed solution in a library. Figure 4 illustrates the above process.

The corresponding support system should facilitate the manipulations described earlier to be used during the above process in ways that reflect or accommodate, as much as possible, three characteristics identified for the process: *incremental*, *iterative* and *non-sequential* (Figure 4). Requirements for the manipulations imposed by each of these characteristics can be interpreted as follows:

- **Incremental** - Use of the manipulations does not demand complete or precise knowledge or information of a configuration, i.e. bits and pieces of vague or definite information can be used to initialise a configuration model and introduced into the initial model gradually when available as design progresses.
- **Iterative** - Use of the manipulation should support the modification of any part of a configuration model already defined until it is satisfactory.

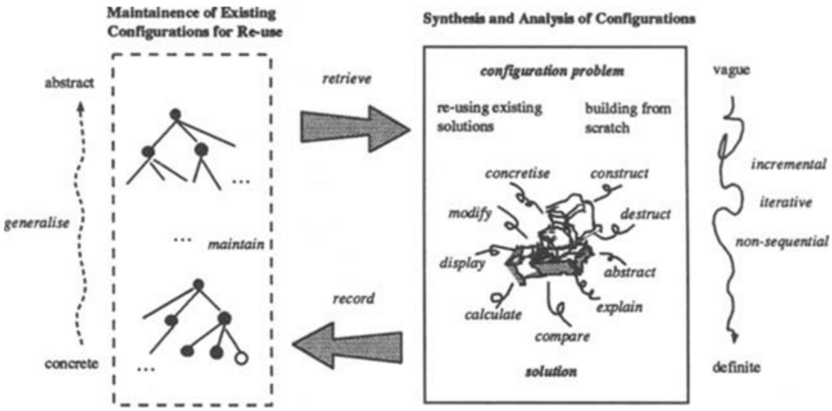


Figure 4 Geometric configuration design and re-use.

Table 2 Vague geometric information being studied in the GEMCON system.

		GEOMETRIC PROPERTIES			
		Shape	*Size*	*Orientation*	*Location*
VAGUE	*Incomplete*		✓	✓	✓
	Approximate		✓		✓

- **Non-sequential** - Use of the manipulations does not require the user to follow a specific, fixed or pre-defined sequence.

4 GEMCON SYSTEM

Our research into computational schemes for accommodating the requirements discussed in this paper has led to the development of a prototype system, GEMCON (an earlier version of the system was presented in (Guan and MacCallum, 1995)). The scope of investigation so far has been restricted to simple geometric configuration problems. The emphasis has been placed on enabling (a) the use of those types of vague geometric information marked in Table 2 by a $\surd$, (b) the utilities for supporting the synthesis of configurations as well as display utilities for visual inspection of developed configuration models, and (c) the incremental, iterative and non-sequential development of geometric configurations. Configuration synthesis manipulations being developed include construction, destruction and modification.

The system is implemented using Harlequin LispWorks (Common Lisp and CLOS) running on a Silicon Graphics or Sun Sparc platform. In the following, we briefly describe the representation and reasoning mechanisms developed and summarise the features of the system with respect to the requirements discussed earlier.

Representation and Reasoning The representation of geometric configurations in the system can be viewed as consisting of three parts: *geometric structure* which provides the required elements for representing a geometric configuration consisting of objects at different levels of details, *parameterised geometric model* which provides the parametric representation of the geometric properties including shape, size, orientation and location of an object, and *constraint models* which capture geometric design constraints carrying information that defines the geometric parameters of objects.

An entity called geom is used to encapsulate the geometric properties of an object. Each geom object is allowed to contain other geom objects as its components which may in turn contain other geom objects. This results in a tree-like geometric structure and provides support for representing a geometric configuration with multiple levels of details.

The shape of an object may be any primitive - cuboid, frustum, sphere, prism, cylinder - whose size is characterised by size parameters such as width, depth, etc. The value of a size parameter can be defined approximately or precisely and is represented by an interval which is in turn represented by a lower and an upper bound. The orientation of an object is characterised by the rotation of the object with respect to a global co-ordinate system, determined by the rotation angles, the co-ordinate axis about which a rotation is carried out and the order of rotations about the axes. The location of an object is characterised by a datum point chosen as the geometric centre of the object. It lies in a 3D cubic uncertain region which captures the approximation or uncertainty associated with the location and is represented by three intervals.

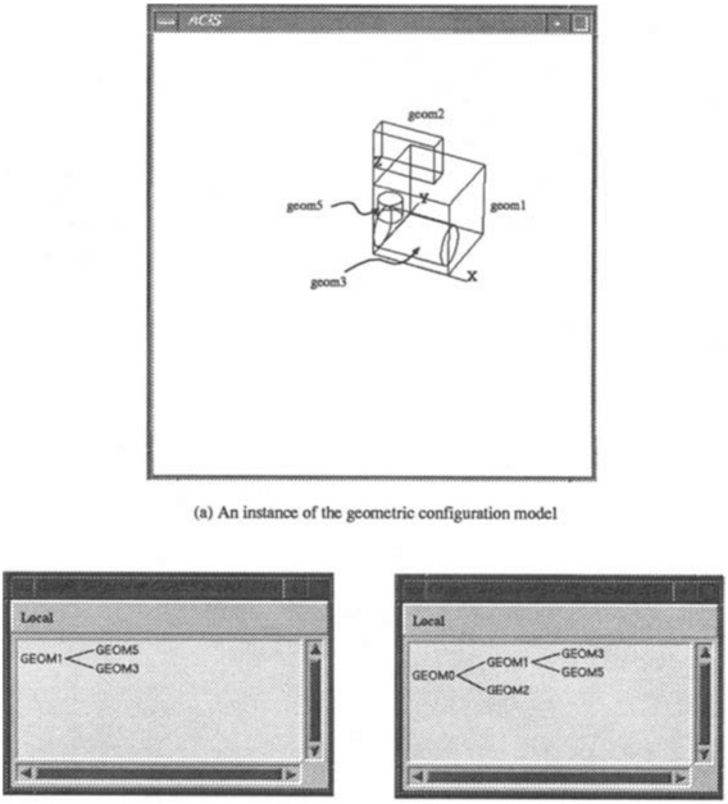
A size constraint model, an orientation constraint model and a location constraint model are associated with each geom object to hold all the constraints specified for all the geom objects contained by the object. These constraints define the values of the corresponding geometric parameters.

The constraint-based mechanism described in (Guan and MacCallum, 1995) has been extended to process size, orientation and location information about a multi-level geometric configuration. It includes four stages: *update of constraint models* which resolves constraints based on certain defined strategies, updates the corresponding constraint model and extracts relevant set of constraints, *satisfaction of constraint* which satisfies the set of constraints extracted in the update stage, *update of configuration model* which updates the relevant parts of a configuration model according to the results derived from the satisfaction stage, and *propagate changes* which re-evaluates other parts of the configuration model affected by the modified part to maintain the global consistency.

A more detailed account of the representation structure and reasoning mechanism may be found in (Guan et al, 1996).

Major Features of the System The system is able to model a multi-level geometric configuration defined incrementally. As an example, Figure 5 shows a two-level configuration developed using the system.

Incomplete geometric information is handled in the system using default values. If the shape or size of an object is not specified, then the corresponding default values known to the system will be used in establishing an initial geometric model which can be modified incrementally and iteratively by the user as information becomes available. These default values are modifiable by the user. The default value of a size parameter is



(a) An instance of the geometric configuration model

(b) Local component structure

(c) Global component structure

Figure 5 A two-level geometric configuration.

given a range or an interval of numbers, defined by a lower and an upper bound, instead of one single number. If the location of an object is not specified, then the object is assumed by the system to be movable in a configuration space associated to the upper-level geometric configuration that contains the object. This way of handling incomplete information reflects a minimum commitment approach to geometric modelling that has been adopted in our work.

A user can also describe the location of objects in a configuration using ***approximate information*** such as spatial relations and precise information such as co-ordinates of a point. The set of spatial relations currently supported are: `above`, `below`, `right`, `left`, `behind`, `front`, `above-orth-dist`, `below-orth-dist`, `right-orth-dist`, `left-orth-dist`, `behind-orth-dist`, and `front-orth-dist`, where 'above-orth-dist' denotes ***above with an orthogonal distance*** (the same notation applies to the others). In Figure 5, for example, `geom2` is above `geom1` with a given orthogonal distance, while `geom5` and `geom3` have an above relation. Again, following the minimum commitment principle, these spatial relations are not treated as defining precise point positions for the corresponding geometric objects, here `geom2` and `geom5`, but as defining regions of possible positions for the objects.

Orientation of an object can be specified through its rotation about the axes of a global co-ordinate system. For example, the orientation of *geom3* in Figure 5 is established by specifying a 90° rotation about the Y axis.

Approximate or precise size information may also be used in establishing the geometric model of an object. For instance, size information about a cuboid shaped object - `height` being approximately 15, `depth` between 20 and 25 and `width` exactly 30 - can be used in establishing the corresponding geometric model of the object through the following command:

```
(make-geom :shape 'cuboid
           :size '(((width = 30)) ((height ~= 15)) ((depth = 20 -> 25))))
```

The use of the system, therefore, does not demand complete or precise knowledge or information of an object. Rather, bits and pieces of vague or precise information can be used to initialise a configuration model, which can be built up incrementally. The system also supports geometric configuration to be carried out iteratively and in a non-sequential manner. It is iterative in the sense that the user can return to a previously defined geometric object carrying out modifications, non-sequential in that the user can define any geometric object at any stage. The modelling operations can be invoked in different sequences or orders on different objects. These features of the system are illustrated in (Guan et al, 1996) in detail through examples.

5 SUMMARY

In this paper, requirements of CAD systems for supporting the entire geometric design process have been examined in terms of the types and characteristics of geometric design information used during the design process, in particular, at the early stages, the types of manipulation that require to be provided to support the corresponding design activities, and the way the manipulations can be used by the designers. Geometric design information and manipulations have been classified. These classifications provide a foundation towards the development of vague geometric modelling systems following the principles of minimum commitment and incremental refinement. They may be used, e.g. to guide the definition of a representation language supported by the corresponding systems, as a framework for assessing the ability of existing systems to support early geometric design, and to identify areas of further research.

A pilot investigation into such a vague geometric modelling system has also been described briefly. The current implementation of the system has been focused on the construction, destruction and modification of geometric configuration models based on a subset of vague and precise information. Further research is therefore proposed to enable the use of the other types of vague geometric information, synthesis and analysis manipulation described in this paper. Support for the re-use of existing geometric configurations also remains as an issue for future investigation.

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7 REFERENCES

Andreason, M. M. and Olesen, J. (1990) The concept of dispositions. *Journal of Engineering Design*, **1**.

Blum, H. (1967) A transformation for extracting new descriptors of shape. *Models for the Perception of Speech and Visual Form*, Wathen-dunn, W. (ed.), MIT Press.

Chern, J-H, Gursoz, E. L., Prinz, F. B. and Hall, M. A. (1990) Geometric abstractions using medial axis transformation. *Proceedings of Manufacturing Internation'90*, 25-28 March, Atlanta, GA, USA, **1**, 51-56.

Duffy, A. H. B, Persidis A. and MacCallum, K. J. (1996) NODES - A numerical and object based modelling system for conceptual engineering design", to be published in *International Journal on Knowledge Based Systems*, Elsevier pbs, May 1996.

Dutta, D. and Hoffmann, C. M. (1990) A geometric investigation of the skeleton of CSG objects. *Advances in Design Automation 1990*, Ravani, B. (ed.), **1**, 67-75.

Guan, X. and MacCallum, K. J. (1995) Modelling of vague and precise geometric information for supporting the entire design process. *Knowledge Intensive CAD-1*, Tomiyama, T., Mäntylä & Finger, S., Eds., Preprints of the 1st IFIP WG5.2 Workshop, 301-319. IFIP.

Guan, X., MacCallum, K. J. and Duffy, A. H. B. (1996) A prototype system for supporting the incremental modelling of vague geometric configurations. Submitted to *AIEDAM Special Issue on Geometric Representation and Reasoning in Design.*

National Research Council (1991) *Improving Engineering Design: Designing for Competitive Advantage*, Committee on Engineering Design Theory and Methodology, Manufacturing Studies Board.

Patrikalakis, N. M. and Gursoy, H. N. (1990) Shape interrogation by medial axis transformation. *Advances in Design Automation 1990*, Ravani, B. (ed.), **1**, 77-88.

8 BIOGRAPHY

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Professor Ken MacCallum obtained his first degree in Naval Architecture from the University of Glasgow, proceeding to postgraduate study in Imperial College, University of London where he obtained a PhD for research into the application of computer graphics to free-form surface design. After three years with a software company, he joined the University of Strathclyde, establishing the CAD Centre in 1985 as a research and postgraduate centre. He is currently the Head of Design, Manufacture and Engineering Management in the Faculty of Engineering at the University of Strathclyde. Ken MacCallum's main area of research has been the application of Artificial Intelligence to Engineering Design. He has led projects concerned with intelligent design modelling, data exchange, computer based design coordination, and computer aided learning. He is editor of the International Journal on Artificial Intelligence in Engineering, is a member of IFIP WG5.2, and has been on the Technical Programme Committees of a large number of Conferences and Workshops concerned with computer aided design.

Alex Duffy completed a Shipwright designer/draughtsman apprenticeship and a further two years in the shipbuilding industry before going to the University of Strathclyde to obtain his degree in Naval Architecture in 1982 and a Ph.D in 1986 on knowledge based support for conceptual engineering design. He has recently spent one year at the Institute for Engineering Design, Technical University of Denmark, and is presently the director of the CAD Centre, University of Strathclyde, and senior lecturer in engineering design, Computer Aided Design and knowledge based techniques in engineering. His main research interests have been the application of knowledge based techniques in early stage design, product development, machine learning techniques and past design utilisation, and design coordination.