Title:
Explicit 3D Functional Dimensioning to Support Design Intent Representation and Robust Model Alteration

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Introduction:
Development of computer-aided design systems for mechanical engineering (MCAD systems) has mostly been oriented towards the feature-based modeling paradigm. This trend is reflected in the modeling functionality and data structures provided by the majority of current commercially available MCAD systems. The concept of form features, coupled with parametric functionality and feature history trees, has been the foundation for enhancing CAD systems. Based on that foundation, efforts in both academia and industry took decades to drive developments from pure geometric modeling systems, which were based on the instantiation of geometric primitives and Boolean operations, to integrated and more efficient design support systems. Within this context, features were meant to be the concept capable of capturing the design intent, while parametric functionality was supposed to provide a means for making model alteration and reuse easier.

However, without knowledge relating to the original design intent and the initial use of features, feature history trees tend to become complex and ambiguous to the point of being incomprehensible. This drawback is aggravated by today's practice of requiring CAD models to be exchanged frequently between different systems, because in many cases information on feature trees is partially or entirely lost during data conversion, thus rendering those CAD models unfit for editing and reuse. In current commercial and industrial design practice this unfortunate situation is reflected in the common approach of constructing a new model from scratch instead of modifying an existing model.

In order to address the problem of feature-based model alteration, two main approaches have emerged in the past years: on the one hand, there is the methodological approach, based on the definition of best practices, guide lines, rubrics and, more in general, modeling strategies, able to lead to "well designed" feature-based models; on the other hand, there is an extension of the modeling system functionality, aimed at providing a faster and easier local modification of the model shape, independent of its feature-based representation. The extension of the second approach has led to the introduction of a new modeling approach, referred to as both *explicit modeling* and *direct modeling*. This modeling approach is based on the definition of 2D regions the user can interactively manipulate, to add volume to or remove volume from the model shape. Geometric constraints between model entities, as well as shape dimensions, are directly linked to the 3D model and they determine (drive) the way the model can be altered. Here explicit modeling technology is different from the feature-based approach, because the model shape is considered as a whole at each stage of the modeling process without referring to the sequence of previously executed operations. As the order of modeling operations used to create a model does not have any direct impact on the way a model can be changed, modeling sequence history independence provides one element central to a new outlook on how to represent and capture design intent.

When we consider both design intent representation and the way a CAD model can be altered, in terms of both dimensions and shape, some new opportunities unfold for the explicit modeling approach and we can perceive possible benefits compared with feature-based modeling. However, further investigation is required in order to gain insight and obtain a better understanding of the interacting elements involved. We also need to examine the impact of this new modeling approach on issues of representation and preservation of the design intent within CAD model creation, exchange, and remodeling using current versions of commercially available MCAD systems.

Motivation and Objectives:

If we compare the way a feature-based system and an explicit modeling system deal with the problem of robust model alteration, we may say the following. A feature-based system allows for the capture of design intent by using modeling features. However, if the feature-based model is not "well designed", the model alteration can become tricky because the features tree (i.e. the model history) no longer reflects the design intent. On the other hand, an explicit modeling system makes it easier to alter the model shape, but it does not seem able to support the explicit representation of the design intent that should drive a robust model alteration. Most research has been done, and still is being done, on achieving a better understanding of the strategic knowledge required to support a robust feature-based model definition and alteration. However, not much work (if any at all) has been carried out in the field of assessing how far explicit modeling systems are actually able to capture and preserve the design intent and support robust model alteration.

The objective of our work is to identify a methodological approach to explicit modeling that, by taking advantage of the new functionality provided by the explicit modeling systems, will be able to support design intent definition and robust model alteration. The proposed approach is based on the following assumptions. Firstly, we focus our attention on the embodiment phase of design (which is actually the phase that most requires the use of MCAD systems). Secondly, by design intent we mean the way elementary function can be achieved by the definition of specific shapes and dimensions. Thirdly, in the physical world dimensions are always related to tolerances. Fourthly, there is an explicit relationship between elementary functions and the way dimensions are specified on a component.

Design intent representation and preservation are well-known issues in the MCAD domain. Creation of 3D models that are capable of capturing and preserving the design intent is important from several viewpoints as discussed in [1, 2, 9]. Moreover, it is rapidly gaining importance in current commercial and industrial design practice as CAD model exchange and re-design are increasing considerably due to globalization-driven outsourcing and distributed design teams. More than ever before it has become necessary to communicate the functional meaning of a component and to be able to make model adjustments without modifying or even destroying geometric entities related to functional requirements.

On the other hand, in engineering, traditional tools are in place to represent objects and their shapes using two-dimensional means such as technical drawings. These combine with proven methods and standards that define how to map three-dimensional object shapes onto two-dimensional representations employing orthogonal projection, and which graphical elements are to be used to represent both shape and related dimensions and tolerances. In this context, design intent is expressed using functional dimensioning where 2D dimensions and tolerances are added onto technical drawings to unambiguously specify the functional meaning of the geometric elements that compose the shape of a part of the component.

Just as a designer is able to recognize the design intent by looking at a component represented on a 2D mechanical drawing, there is no reason to believe that (s)he will not be able to recognize the design intent on a 3D model, assuming that the 3D model contains the same information as that contained in the 2D drawing. It seems evident that if the information about the component shape is equally represented on a 3D model and on a correct 2D drawing, then the 2D drawing will also contain a lot of additional information that needs to be mapped onto the 3D model, and the most important of this information is the functional dimensions.

However, a simple transfer of the methods and elements of representation used in two-dimensional functional dimensioning straight into the three-dimensional domain of modern MCAD systems and their user interfaces and geometric models is bound to fail. There is a host of differences between the two approaches, with some difficulties being more obvious than others. It is in this context that motivation arose for work on an approach where design intent in the form of semantics related to component shape could be specified in terms of functional dimensions similar to those used in mechanical engineering drawings. These in turn could be described, implemented and preserved within MCAD systems using a novel framework for 3D functional dimensioning and explicit modeling technology. The objective of the work presented in this paper is to develop concepts, structures and mapping functions for a framework which can be used to implement and translate into practice 3D functional dimensioning employing modern MCAD systems and explicit modeling as envisioned above.

Background and Scope:

When we use an explicit modeling approach, geometric constraints between model entities, as well as shape dimensions, are directly linked to the 3D model and they determine (drive) the way the model can be altered. However, in contrast to the feature-based approach, explicit modeling considers the model shape as a whole at each stage of the modeling process, without any reference to the sequence of previously executed operations. Hence, explicit modeling is history independent in the sense that the order of modeling operations used to create a model does not directly impact the way a model can be altered. By using explicit modeling, users can literally perform any kind of geometric model alteration. Hence, appropriate modeling strategies and constraints (definitions) are required in order to ensure that alterations are not only consistent with model functionality, i.e. the design intent, but also performed in a transparent, easy, and more intuitive manner than with other modeling options made possible by direct manipulation of object geometry.

In order to succeed in this direction, users should adopt a systematic and coherent modeling approach, paying attention to dimensions and constraints that are finalized for the preservation of the design intent, as those will also preserve the function related to the model shape if model alteration is later required. One way to achieve this goal is oriented on the careful use of 3D dimensions and constraints as is done in the field of technical product documentation. In this context, the traditional means used to transfer a solution from design to manufacturing is technical drawings. In particular, the mechanical drawing of a component must contain the information necessary to enable a univocal interpretation of the depicted shape, which includes all dimensions and tolerances required for manufacturing. In this sense, the technical drawing is a graphical language which is based on commonly accepted rules and criteria, most of which are now specified by international standards. Those standards, together with standards on geometric product specification, introduce ideas, principles, and definitions which highlight characteristics of the distinctions among different types of dimensions. For example, a preliminary concept introduced by the standard ISO17450-1 [8] is the difference between an integral nominal element and a derived nominal element. An integral nominal element is a basic geometric element such as a line or a surface belonging to the shape of the ideal (nominal) representation of a part or component being designed. A derived nominal element is a geometric element such as a point, a medial axis, or a medial surface, which is computationally extracted (derived) from an integral nominal element. In particular, the ISO 129-1 standard [4] introduces general syntactical rules and principles for the indication of dimensioning and tolerances on technical drawings, whereas the ISO 129-2 standard [5], currently under development, is expected to introduce specific cases of particular interest for the field of mechanical engineering.

Functional dimensioning represents one out of several methods of determining the dimensions and tolerances to be added on mechanical drawings. The tenet central to this method is to unambiguously specify and communicate the functional meaning of the geometric elements that compose the shape of a part or component. In this context, explicit modeling supports a more intuitive way of managing the model during the design process, by facilitating a method for users to iteratively refine CAD models from a roughly defined geometry into a final detailed geometry. Additionally, this modeling paradigm provides a new perspective to 3D modeling by facilitating functionality to globally add and remove dimensions and geometric constraints to/from the shape of the model at any time during the modeling process. This allows for the direct application of functional dimensioning criteria while modeling in 3D. In such a scenario, the application of functional dimensioning criteria within explicit modeling will offer various interrelated benefits. Characteristics intrinsic to functional dimensioning will result in a fully constrained 3D model, which in turn, when associated with the functional dimensions, will be able to communicate the design intent.

Outline and Approach:

Concepts, structures, and mappings, as defined within the framework described in this paper, aim at providing a means to investigate and enable novel ways of directly placing functional dimensions of mechanical components as 3D driving dimensions within the MCAD systems that provide explicit modeling functionality. Such functional dimensions will usually be the functional 2D dimensions in mechanical drawings. Design and formulation of the framework and concepts are oriented on the set of international standards for Geometric Product Specification and Technical Drawings and best practices, which provide definitions, general principles, and strategies for 2D dimensioning and its consistent representation within technical documentation such as line drawings for mechanical engineering.

Central concepts such as integral element and derived element, introduced and defined in [8], are used in ISO 14405-1 [6] and ISO 14405-2 [7] to define the classification of different types of dimensions. The set of standards on the general principles of presentation in technical drawings specified under ISO 128 (cf. [3]) defines rules on how to use orthogonal projection and how to represent contours and axes within technical drawing employing the concepts of integral and derived elements. As the geometric product specification standards aim at defining an homogenous framework to relate dimensioning to control procedures, general syntactical rules and principles for dimensioning and indication of tolerances on technical drawings are defined in ISO 129-1 [4].

We intend, therefore, to implement and translate into practice an approach to 3D dimensioning which employs explicit modeling within the objectives and scope presented earlier. However, we need not only structures and elements for representing the nominal shapes of objects and the related functional dimensions in the three-dimensional domain, but also a correspondence that maps functionality between elements of the 2D dimensioning domain and the 3D dimensioning domain, as shown in Fig. 1. In the framework developed, concepts, structures, and correspondence relationships are designed as follows. Geometric features being defined and used within traditional 2D dimensioning as outlined above are related to the concept of explicit 3D entities, which in turn corresponds to actual elements of the geometric model of a MCAD system, which nowadays can be considered in most cases to be a boundary-representation (Brep) based model. Explicit 3D entities are comprised of explicit topological entities and related geometric information pertaining to the Brep model. In addition to explicit 3D entities, geometric constraints need to be considered as a means of providing the mechanisms required to maintain consistency between associated driving dimensions and resulting CAD model geometry. Geometric constraints are also required to provide functionality for consistent model alterations during CAD model exchange and re-design.

Elements for 3D dimensioning are represented using the concepts of explicit 3D entities (as previously outlined) and implicit 3D entities. Implicit 3D entities are comprised of topological entities and related geometric information as used within a Brep model. However, due to their structural properties, actual elements of this entity domain are not an explicit part of the set of topological and geometric model entities used to represent the three-dimensional shape of an object. To provide functionality for placing 3D dimensions correctly and consistently within a MCAD system that is supporting explicit modeling, so-called *dimensioning correspondence mapping* (DCM) has been developed and implemented. This maps individual 2D dimensioning elements to 3D dimensioning elements. DCM considers linear dimensions and angular dimensions as defined in [4]. In accordance with ISO 14405-2, for the case of linear dimensions correspondence mappings are provided for dimensions comprised of one feature and two features. Linear dimensions for transitions are also supported. For linear dimensions with one feature the mapping is based on relating specific entities from the 2D entity representation domain corresponding to a contour outline to specific entities from the 3D entity representation domain corresponding to either a boundary edge or a silhouette edge. For linear dimensions with two features the mapping is based on relating geometric point spaces of spatial intersections of specific entities from the 2D entity representation domain, corresponding, for example, to a contour outline or to an axis of a geometric feature, to geometric point spaces of spatial intersections of specific entities from the 3D entity representation domain, corresponding, for example, to a boundary edge or to a snap point. For angular dimensions and dimensioning of transitions the mapping is based on combinations of the previously mentioned two mapping scenarios, additionally considering correspondences to projections of contour outlines for geometric point spaces of spatial intersections of specific entities from the 2D entity representation domain and correspondences to trimmed (implicit) edges for geometric point spaces of spatial intersections of specific entities from the 3D entity representation domain.

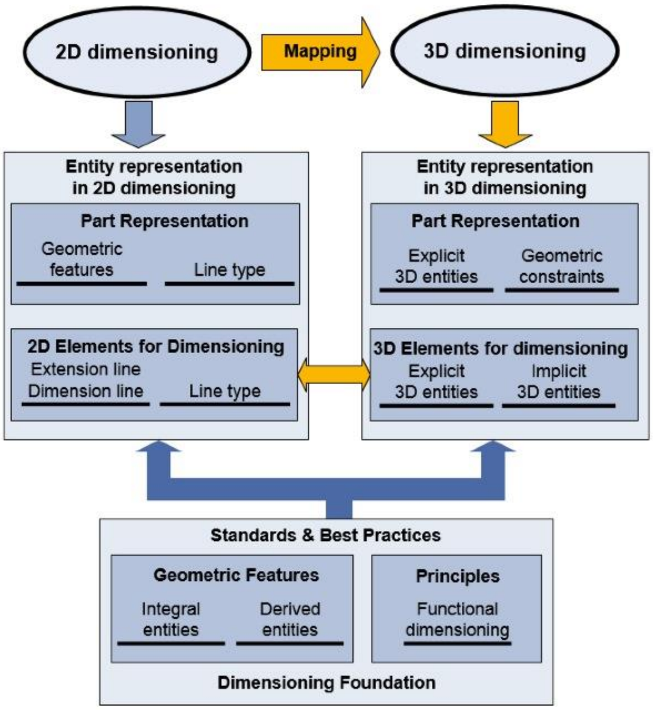

Fig. 1: Frame and outline of concepts and relationships.

The work presented in this paper is part of a larger research project aimed at research into and development of 3D functional dimensioning as a novel, consistent and systematic way to define and implement design intent representation and robust model alterations of CAD models by making use of emerging opportunities provided by modern MCAD systems and explicit modeling. Theoretical and empirical work has been pursued in the following directions. Firstly, development of concepts and structures that take into account traditional 2D functional dimensioning as used in mechanical engineering, with an orientation consistent with definitions and methods as given in the standards for technical drawings and geometric product specification. Secondly, formation of a framework based on those developments. This was applied as a means for the implementation of 3D explicit functional dimensioning using a commercially available parametric MCAD system with explicit modeling capability. It was also applied as a means of locating and assessing the conceptual and application-related limits encountered during translation of this approach into practice. Thirdly, experimental work was conducted to provide empirical input for approach evaluation and framework improvement. Empirical results were obtained by conducting implementations of various modeling situations within part and component design, which are considered representative examples, using actual industrial MCAD case samples.

Conclusions:

As became evident during both theoretical analysis and empirical work, at present the dimensioning concepts, as defined by the standards, and the explicit modeling functionality available within the MCAD system and used as an enabling technology to translate and implement 3D dimensioning, are neither sufficiently structured nor coherent enough to allow for sound and complete 3D functional dimensioning, as traditionally applied in mechanical engineering. In particular, it could be shown that several shortcomings of the explicit modeling functionality as provided within most of today's MCAD systems are related to either an incomplete access to, or even the total absence of, geometric elements such as the referenced or implicit entities that are required to support 3D functional dimensioning. As could be demonstrated in some cases, though, modifying or adjusting the definition and implementation of the DCM and related sets of 3D elements for dimensioning can overcome the shortcomings arising from the absence of proper entity access or the actual absence of elements. However, a more appropriate and sound solution in this context lies in the efforts to improve and extend current user interface functionality of commercially available MCAD systems in respect to their explicit modeling capabilities by adjusting their current inadequate levels of usability and affordance to current needs in practice.

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