Title:
Graphical Representation of Parametric Feature-Based MCAD Model Characteristics

Authors:
Harald E. Otto, h.e.otto@univpm.it, Polytechnic University of Marche
Ferruccio Mandorli, f.mandorli@univpm.it, Polytechnic University of Marche

Keywords:
MCAD Model Analysis and Assessment, Formative Feedback, Competency Development, Visual Analysis, Radial Visualization, Knowledge Discovery

DOI: 10.14733/cadconfP.2022.72-76

Introduction:
The overall checking, detailed analysis, and subsequent assessment of CAD models within an educational context are different from their counterparts in commercial and industrial settings in regard to both the goal and the assessment criteria. This is most evident within skill and competency development, which benefits considerably from reflecting on, and thus learning from, errors and mistakes. However, to accomplish this, formative assessment and feedback are essential prerequisites. To promote and advance formative feedback in computer-aided design for mechanical engineering (MCAD) education, feature-based model and geometric model assessment needs to consider the quality of a model not only in terms of the absolute criteria that are associated with technical domain knowledge, but also by applying criteria related to model deficiencies that are the result of wrong or inappropriately applied system commands and partial or entire modeling strategies. Deviations from computer-aided design and modeling guidelines and best practices, as taught in the CAD course and expected to be reflected in the structure and properties of student-created CAD models, also need to be included in the assessment and feedback process. This represents a task that is not only comprehensive and complex, but also considerably knowledge intensive. This is related to the fact that analysis and assessment require not only the detection and identification of deficiencies that in many cases do not violate general normative knowledge about feature-based modeling and geometric modeling, but also knowledge about the modeling goals and how they have been translated into strategies and actions.

Within the context of MCAD education, parts of the latter can usually be associated with learning goals and outcomes related to particular exercises and course assignments. In the context of parametric feature-based solid model assessment, analysis and evaluation need to be based on both feature-related properties and characteristics and the topology and geometry of the final modeling result. In particular, properties of individual features, links and relationships among features, and characteristics of feature sequences and modeling histories — that were created for producing the final model shape — can be used as a proxy for assessing models and particular modeling steps in a reflective and ex post facto manner. Currently, most commercially available CAD systems that support feature-based modeling provide interactive commands at the user interface to allow for some basic form of inquiry about model properties and the characteristics of both feature entities and topological and geometric model entities such as feature modeling tree, feature type, and related shape defining elements. However, performing a purely manual feature-based solid model assessment by using such kinds of generic system command is in many cases a sensitive task, and not only can this devolve into quite a convoluted and time-consuming process, but it is also likely to result in neglecting to capture many student failures within individual assignments.

Scope and Objectives:

The basic goal and purpose of any learning experience are seated in acquiring the skills, knowledge, and competency to change and improve an existing behavior or create a new one. Those changes in behavior should have measurable impacts that relate to key metrics indicating success in achieving the desired learning outcome. Within the context of CAD education, those metrics are, in most cases, directly linked to the assessment criteria for CAD models created by students and submitted to teachers for grading. This approach has several shortcomings. Firstly, feedback is usually delayed due to the complexity of CAD model assessment and the rapidly increasing number of students in CAD courses at institutions of higher education. Secondly, the structure and quality of feedback based exclusively on CAD model grading is usually insufficient to support learning from errors and developing metacognitive skills related to self-assessment, and subsequent self-improvement. Recent efforts to reform an actual CAD course for mechanical engineering at the institution represented by the authors, addressed, among other matters, the development of modeling competencies with particular reference to the strategic knowledge required to create usable MCAD models (for more details see [12]). In particular, this major course-specific learning goal, i.e., development of the strategic knowledge and modeling skills indispensable for producing usable MCAD models, requires better teaching techniques that reach beyond the usual lecture-based presentation of domain-specific factual knowledge with students mostly in the role of passive learners. Moreover, it especially requires assessment techniques and feedback which are capable of adequately and frequently measuring the gap between actual student learning outcomes as achieved and learning goals as pre-assigned, while also providing high quality and timely feedback for both teacher and students. Within this setting, and in the context of higher education, as outlined earlier, the assessment of student performance and results produced in CAD laboratory exercises and course assignments needs to be conducted in a computer-aided manner. This will support actual implementation, while also improving the scope and overall quality of formative assessment and feedback, but it requires new approaches and tools for feature-based solid model assessment.

Efforts and recent approaches dedicated to the automation of CAD model analysis, assessment, and grading are obviously capable of considerably reducing the time required for analyzing and assessing CAD models created by students, though the type and complexity of CAD model that can be analyzed, as well as the quality of the feedback that is generated, are still quite limited. This is apparent, for example, in approaches for technical drawings and 2D CAD files that can be found in [3,7,8]. Examples of recent approaches for 3D CAD models and related empirical studies are reported in [1,6,10]. An interesting approach to providing visual feedback for automated CAD model grading using heat maps is reported in [9]. Further discussions on the subject of automated CAD model grading, including a summary of the literature and pointers to gaps in research, can be found in [5]. Another major limitation of those approaches to the automation of CAD model grading is the inherent functional structure of having scripts and other pre-defined computerized means that are capable only of comparing submitted student work with a reference solution and determining what is correct or not in an inventory-checking-like manner. Hereby, the data space of errors, mistakes, and deficiencies — that were introduced into the CAD models by students during model creation — remains largely ignored. However, that is presumably where potentially valuable knowledge can be extracted to gain insight into the shortcomings and difficulties with which students may have struggled. However, analyzing this side of the data space during CAD model analysis cannot be carried out purely with predefined queries and scripts, because a part of this intrinsic and non-trivial information and knowledge needs first to be discovered, before means to look for it can be codified. Here, the authors believe, visual analysis has great potential, due to its ability to combine the creativity, vast knowledge, and visual perception system capabilities of the human user with the enormous computational power of computing machinery, to further insight into data and discover valuable, previously unknown, knowledge.

The aim of the current paper is two-fold. Firstly, it presents a novel approach to enhanced feature-based MCAD model analysis in the educational context, which is based on deficiency analysis using interactive visualization of feature-based model characteristics. Secondly, it reports on the structure and concrete implementation of an advanced graphical representation of feature-based model

Proceedings of CAD'22, Beijing, China, July 11-13, 2022, 72-76

characteristics that is integrated into a software tool to enable and put into practice this novel approach supporting and elevating computer-aided feature-based solid model analysis and assessment, and the subsequent provision of timely and high-quality formative feedback.

Approach, Development and Implementation:

Visual analysis represents a powerful means of understanding complex data, as visual displays allow humans to make use of their cognitive capacity to perceive and study various aspects of complex information and issues simultaneously. Hence, it supports the discovery of intrinsic, non-trivial and potentially valuable knowledge hidden in the data sets being visualized. To facilitate this, an advanced graphical representation of parametric feature-based MCAD model characteristics has been developed and deployed within a modularized interactive visualization environment, which has been engineered and integrated into the architecture of the feature-based CAD model analysis module. This, in turn, is an integral part of the CAD model analysis and assessment software tool system developed by the authors. Although graphical representations are a comprehensive aid, their efficiency and effectiveness strongly depend on both the data to be visualized and the information and knowledge to be communicated. Within the context outlined in this paper, a particular form of radial visualization is used, namely *Kiviat diagrams* [11], in the literature also referred to as *star diagrams* and *radar charts* (see [4]). In MCAD model deficiency analysis, the information subject to visualization can be structured into data that are associated with objects and data that are associated with processes. The former represents the relationships between, and the basic data for, the feature types, the feature scope, and the number of entities that were used to create the MCAD models. The latter relate to the basic tenets of best practice and various aspects of feature entity creation and CAD modeling sequence planning and execution. Based on these data, certain characteristics of trends, patterns, critical situations, and deficiencies can be visually represented and analyzed.

Current design of the Kiviat diagrams is based on the visual encoding of feature-based characteristics that results in certain aspects of the MCAD models being visually represented in the form of closed polygonal profiles defined by polylines of definite size, position, shape, and color. Those colored polylines are then the representative feature-based characteristics profile, which translates into a graphical representation within the visual space through encoding and mapping of spatial properties, color, and layout design of the Kiviat diagrams. The unique polygonal structure of those feature-based characteristics, and their visual encoding, allow for an effective and efficient approach to visually representing and analyzing the relative multidimensional data space of feature-based MCAD model characteristics. To improve the efficiency of the graphical representation, the layout design of the Kiviat diagrams has been optimized through superimposed property profiles, structured diagram sector sub-division, and diagram axis rearrangement. This rearrangement is based on finding an axis permutation that results in a combination of polylines with a shape easily and quickly recognized and understood by the human visual perception system. For this endeavor, Prägnanz and related grouping principles [2] were used as heuristics to approximate a good Gestalt for the shape representing feature-based characteristics based on property profiles defined by their respective polylines. As the prototype implementation of the visualization environment module needs to be integrated with previous work of the authors on MCAD model software assessment tool development (cf. [12]), data management and transformation within the visualization pipeline have to operate through the CAD model and feature entity (CMFE) repository that in turn facilitates the import from and export to different parametric feature-based solid modeling environments. Within the CMFE inventory, the results are used to compile model entity analysis reports.

The newly developed prototype implementation features a technical architecture that leverages API-based functionality provided by commercially available CAD systems to support a modular and highly cohesive system architecture. In the current implementation, the CAD modeling environment deploys a commercially available parametric feature-based solid modeling system, namely *SolidEdge* from Siemens AG. At present, the CMFE repository is compiled by extracting CAD data from the *SolidEdge* part models using Visual Basic for Applications (VBA) functions. This extracted data is then further processed and stored in structured *Excel* files. Next, those structured *Excel* files are imported into the Microsoft *Access* RDBMS (relational database management system) by means of macros, to facilitate the creation and build-up of the CMFE inventory. Currently, the modularized visualization environment is implemented using *Excel,* the VBA environment, and a data pipeline to the CMFE inventory that is channeled through compiled subsets of query reports.

To process and visualize data correctly, compilation, export, import, and filtering within the information visualization pipeline (see Fig. 1) in regard to the CMFE repository and inventory are organized as follows. All feature-based solid models that have been created by students are compiled and stored in the CMFE repository. This repository is structurally sub-divided into various sets of folders, with one set of folders for each exercise or course assignment. During the compilation process, information on feature entities and their related properties and meaningful characteristics, such as feature type, shape-defining topology and geometry, is extracted from the parametric feature-based solid models, codified, and stored in the form of structured files, with one file for each model. Data on parametric feature-based model entities and their properties and characteristics stored in the model repository are processed and imported into the CMFE inventory. This inventory provides a lattice-based data structure, which is structurally organized as various linked entity tables. Data compiled from CAD models associated with a particular exercise or course assignment are assigned to one particular cluster of entity tables. It should be noted that table entries for each feature entity in the model repository contain also an identifier-based link, which connects them to the geometric modeling system. Note that this link mechanism is essential to enable the implementation of a cross-linked view supporting linking and brushing.

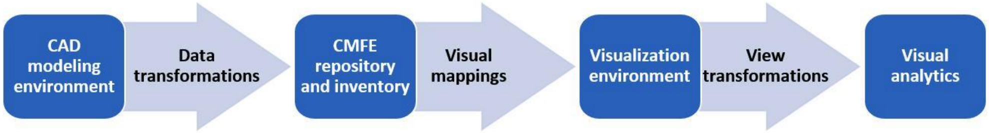

Fig. 1: Overview of the information visualization pipeline and central system components.

During the software tool evaluation, various checks regarding functionality, reliability, and effectiveness, as well as the expressiveness of the novel and newly developed graphical representation of parametric feature-based MCAD model characteristics, were carried out on a wide selection of parametric feature-based CAD models that had been created and submitted by students during exercises related to CAD laboratory and course assignments in the last academic year.

Conclusions:

Within the work presented, the approach, framework, and structures used for the design and development of a novel and advanced interactive visualization system for feature-based MCAD model characteristics have been outlined and discussed. Promising outcomes achieved, based on the assessment of empirical results from functionality and reliability checks and experimental evaluation, were as follows. First, the graphical representation of feature-based MCAD model characteristics, as implemented and provided within the interactive visualization tool component, supported efforts to increase cognitive productivity and throughput during model analysis and assessment. With the interactive visualization serving as an interface between the human MCAD model assessor and the computer system, casting of visual patterns, which is required for visual queries, enabled model analysis in a way that would be impossible to achieve without such a computerized visual aid. Second, the interactive visualization-based approach also facilitated the discovery of meaningful and previously unknown knowledge during computer-aided MCAD model analysis and subsequent formative feedback creation. In particular, insight on data related to model deficiencies and errors was considerably increased, as well as elevated, through enabling the detection of relations, patterns, and trends which otherwise would have remained largely overlooked. Third, in regard to these discoveries, unprecedented possibilities were opened by revealing links between individual types of MCAD model deficiencies and particular patterns and trends that could be associated with errors and mistakes committed by students during model creation. This, in turn, enabled the formation of pointers toward more evidence-driven and student-needs-oriented improvements to the current MCAD course and its exercise and CAD laboratory assignments. Based on the promising outcomes achieved so far, an experimental full integration of the approach, with implementation within the model analysis and assessment processes of the current MCAD course, is planned for the next academic year.

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