Automated Reference Model Generation and Utilization for Dimensional Control of Large Scale Assemblies and Assembly Processes

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***Abstract*—A lot of manual user interaction with computer aided design and analysis software is currently needed for dimensional control of large scale assemblies. This user input is required for both selecting the vital entities to be measured and analyzing the results of the measurements. In this paper an automated approach for reference model generation and vital entity selection is presented. The reference model generation is guided by user editable knowledge base and it is based on data extraction from computer aided design data. Prospects to utilize the generated reference model for automated manufacturing accuracy analysis are also outlined. The software implementation made has proved to be feasible for different kinds of dimensional control needs of large scale assemblies, and outweighs the current state of the art both in speed, completeness, and versatility.**

Keywords-accuracy control; large scale assemblies; data extraction; dimensional inspection

I. Introduction

A modular construction is today a typical way to build large scale objects like ships, submarines, offshore platforms, airplanes, and bridges. In this manufacturing approach, the final product is assembled by joining separate, large subassemblies (blocks) one after another.

One of the main interests in the assembly process of large scale objects is how different blocks can be fit together optimally. If the two blocks to be joined do not fit properly, corrective reworking is needed, causing extra costs and time delays [3]. In order to expedite the joining process, the geometry of the blocks is measured and verified (as-built to as-designed) before the joining.

It is common in modern industry that the dimensions and the shape of the objects to be manufactured are designed computer aided. Thus geometrical design data of parts and products is almost always available in the form of computer aided design (CAD) files. These files can be used directly as sources of geometric information and thus the idea to use CAD data as a reference for as-built to as-designed verifications has been brought forth, see e.g., [1]. However, the CAD data typically contain a lot of unnecessary information from the dimensional accuracy control viewpoint. Thus the extraction of the essential data out of CAD data is needed. Currently, this vital entity selection and extraction is performed by using different kinds of interactive approaches requiring a lot of manual work, caution, and time.

In the case of large scale objects, the implementation of an automated vital entity (e.g., point to be measured) selection seems to remain an extremely challenging and thus an unsolved task. Reasons for this comprise

- The differences in the CAD data and systems: an approach designed for a certain CAD data format or CAD system is typically not feasible with another
- One of a kind manufacturing -property of large scale objects: vital entities are neither the same nor in the same place on the object
- The rules, principles, and practices to choose the vital entities are different in different applications and in different organizations: the expertise to select vital entities is undocumented tacit knowledge of the personnel.

There are few papers addressing automatic vital entity extraction and the generation of a reference model for as-built to as-designed verifications of large scale objects (readers interested in computer aided inspection planning for smaller sized objects are referred to [10]). Manninen et al. [4] seems to be the first and only paper in which a workable implementation (for shipbuilding) was presented. However, even though the basic ideas and principles presented in [4] have been proven to be feasible, it has been noted that the implementation is not flexible enough for different kinds of (complicated) blocks, different kinds of practices for choosing the vital entities, and different kind of measuring and as-built to as-designed analysis needs in different shipyards. The main drawback of the implementation presented in [4] is that it analyzes only planar surfaces of CAD data leading both instability and incomplete reference models in case of CAD models comprising curved surfaces. The implementation is also slow, restricted to only one CAD format (dxf) for input, and comprises no support for automatic manufacturing analysis.

In this paper, a knowledge base guided approach to automatically generate reference models for dimensional manufacturing accuracy analysis of large scale objects is proposed. This reference model generation comprises the reduction of CAD data and selection of vital entities essential and sufficient for dimensional control purposes. The automatic reference model creation and vital entity selection processes are controlled through a set of parameters. The identification information and values of these parameters

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form an information source, which is called a knowledge base in this paper.

Some prospects to utilize the generated reference model for manufacturing accuracy analysis are also presented. The main new idea in this sense is the automated manufacturing accuracy analysis. It comprises computation of quality figures for a certain set of user defined structure types and combining these quality figures to form a comprehensive quality database (quality figure tree) of the object manufactured. In addition to be used in analyzing the dimensional accuracy of the object manufactured, this quality data is intended to be utilized for monitoring the manufacturing and assembly processes.

The rest of this paper is structured as follows: In Section II, a new approach is presented at the general level. Some implementation issues are commented on as well. Then, in Section III, some results of our experiments with shipbuilding data are presented, and finally, in Section IV, we conclude by summarizing the results and presenting ideas for further study.

II. Description of the Approach

In this section, we present our approach at the general level with some examples. First, the general flow of the reference model creation is given, and then, in subsections II.A to II.C, the utilization of the knowledge base, the recognition of vital structures, and the automated manufacturing accuracy analysis are presented.

The creation of the reference model and vital entity selection is purely based on geometric information. The process progresses through the following steps (see also Fig. 1): First, the file containing the CAD data is read into the system and all geometric data is converted to a boundary representation (see e.g., [5, 8]). We utilize Open Cascade Technology [6] for this step, since it provides ready-made interfaces for this operation. Then, each face of the boundary representation is analyzed to find out, which side (nominal side, non-nominal side, thickness side, see Fig. 2) of a structure (e.g., steel plate) the face represents and classified on the basis of this analysis for further processing. After all faces have been "side-classified", the nominal side faces are studied once again in order to find out whether bigger structures can be constructed by stitching a set of faces together. The results of the stitching phase are either planar or curved surfaces. These surfaces are then checked against size limits for acceptable objects, and either accepted or excluded. If needed, the application specific recognition of vital structures can be performed in this phase. Finally, a reference model of "intelligent objects" (see [4]) is created and finalized by dividing the points of the model into vital (to be measured) and non-vital points according to the instructions given in the knowledge base controlling the reference model generation.

A. Utilization of knowledge base

The end-user is able to guide the automatic reference model creation and vital entity selection processes through a set of parameters. The identification information and values of these parameters form an information source, which is called a knowledge base.

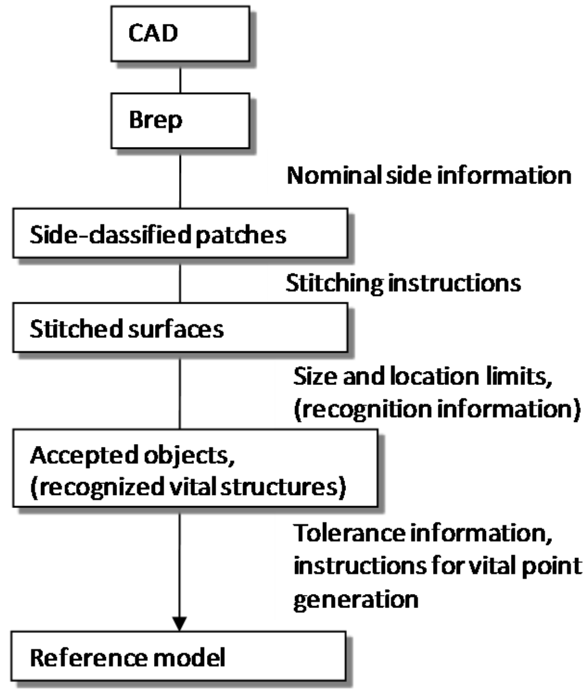

Figure 1. Reference model generation process.

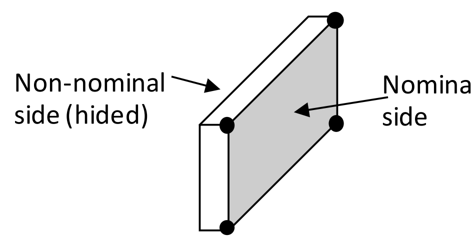

Figure 2. Nominal and non-nominal sides of a steel plate. Besides the nominal and non-nominal sides there are four thickness sides in this example. Vital points (points to be measured), shown here with black dots, should be generated on the nominal side of the plate.

The structure of the current knowledge base has been developed together with several dimensional control and shipbuilding experts. Currently, it comprises two main sections: a general section and an application specific section. The end-user can edit the values of the parameters in the general section but otherwise (identifications, the structure of the knowledge base) the general section of the knowledge base is meant to be edited only by the software engineer. The general section of the knowledge base currently comprises

- Tolerance information to be assigned to the various objects in the reference model
- Information for selecting correct nominal side for each structure to be included into the reference model

- Size and location limit information to control whether a CAD structure is to be accepted to or excluded from the reference model (see Fig. 3 for example of the effect)
- Information where to generate vital points (points to be measured) in some special cases (see Fig. 4 for example of the effect)
- Information whether some of special details, like holes or curved structures are to be included into the reference model (see Fig. 3 and Fig. 4 for examples of the effect)
- Information for automatic alignment of the measurement data to the reference model

The application specific section of the knowledge base is used to define the vital structures to be recognized and to be used in manufacturing accuracy analysis. This section is completely user editable even though some keywords need to be used in order to guarantee the knowledge transfer between the knowledge base and the software. This section includes information for

- Recognition of the vital structures
- Vital structure -wise selection of the quality figures to be computed
- Combining the lower level quality figures to upper level quality figures
- Constructing the quality figure tree of the quality figures computed (see Fig. 6 for an example).

B. Recognition of vital structures

Vital structures are different for different large scale assembly applications. Thus application specific knowledge to recognize the vital structures from CAD data is needed. Currently, this information is given in an interchangeable recognition data module of the knowledge base. Thus different applications can be handled easily by changing the contents of this module to be suitable for the application.

In the recognition data module identification (name), recognition, recognition process and quality figure type information is given for each structure wanted to be recognized and further used in the manufacturing accuracy analysis. The recognition information is simple geometric data to classify a structure, and could currently comprise size, location, and orientation limits. The recognition process information is used to control the classification process. It informs the system in which order the recognition information should be applied when trying to classify an input structure. Quality figure type information is a list of quality figures to be computed for the structure after the actual (measured) data are available. A weight, which is used when quality figures are combined in manufacturing accuracy analysis, is given for each quality figure as well.

We have demonstrated the recognition of vital structures in shipbuilding applications. In our demonstrations structures like whole block, decks, bulkheads, stiffeners, block faces, engine foundations, basic plane, centre plane, and special points were recognized. The quality figures computed for these structures comprised flatness, straightness, location, orientation, length, width, height, and cross-measures.

C. Automated manufacturing accuracy analysis

In order to pack the information offered by numerous quality figures computed for each vital structure, these quality figures are statistically combined to form a hierarchical, tree-like presentation of the manufacturing quality of the block. This manufacturing quality tree is saved as an xml-file and can thus be browsed afterwards to check any detail of the manufacturing quality (see Fig. 6).

The vital structure types for which the quality figures are computed can be selected by using the knowledge base. For each structure type, which is identified to be recognized, a set of quality figures to be computed can be selected (from a list of available quality figures).

There are two types of quality figures in our approach. The basic quality figures are the lowest level quality figures obtained by comparing a geometric feature (either directly measured or computed by using measured data) to the corresponding design value for the feature in question. Thus the basic quality figures are direct measures of dimensional accuracy of the feature in question. The combined quality figures are obtained by combining two or more quality figures to a one (higher level) quality figure.

Each quality figure has at least value, weight, and location information assigned to it. Combined quality figures have also statistical data available. Usually, the unit of the quality figure is also given but if the quality figure is a combination of values with different units, the unit is not defined.

The value of a basic quality figure is a deviation of the actual data from the design or desired data. The value may, in some cases, also be negative. The closer the value is to zero the better.

A weight is used when combining quality figures in order to emphasise the significance of some measured data or quality figures more than others. As mentioned above, weights can be given quality figure -wise for each structure to be recognized in the application specific section of the knowledge base. The default weight is one for each quality figure meaning that each quality figure will have equal importance.

Two types of location information is presented: the location point, which is typically a centre point of the input data of the quality figure, and the bounding box, which limits the size of the space from where the input data was obtained. Currently, the main purpose of the location information is to identify to which structure the quality figure in question is related to but later the location information can be used to put the quality information data in the correct place in a graphical presentation.

For combined quality figures, several statistical figures (maximum, minimum, weighted arithmetic mean, standard deviation, and mean deviation) are computed and saved. As a value (result) of a combined quality figure either the root mean square error (RMSE) or weighted arithmetic mean is used. The RMSE, which is related to the arithmetic mean (m_x) and the standard deviation (s) of the sample data (x_i)

$$\mathrm{RMSE}^2 = m_x^2 + s^2 = \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^2 + \frac{1}{n}\sum_{i=1}^{n}(x_i - m_x)^2 \quad , (1)$$

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where n is the number of samples, is used when the basic quality figures are combined. Thus, when the RMSE is used, the value of the combined quality figure includes information of both average error (bias) and deviation of the data. It should be noted that, in our approach, the sample data (x_i) to be used in (1) is derived from actual to design comparisons, and thus, RMSE (not RMS) is indeed obtained.

The weighted arithmetic mean is used, when already combined quality figures are further refined to a higher level quality figures. An example of this is an integration of similar quality figures of different structures of the same type (e.g., flatness quality figures of all block faces of the block). This kind of integration is continued until a quality figure tree, from simple point deviations up to the overall quality of the whole block, has been constructed.

III. Experiments

The approach presented has been experimented in several shipbuilding cases. Separate knowledge base instances have been built for several different kinds of block types from two different shipyards. The CAD data provided by the design department of the shipyard have automatically been reduced to form a reference model by using our software modules, and obtained results have been evaluated together with the personnel responsible for the dimensional control in the shipyard. Then the actual blocks have been measured by the measurement group, and finally, the measured data have been aligned to the reference model and quality figures computed. In the following sub-chapters some detailed observations of the experiments are presented. The overall results of the feasibility of the proposed approach are summarized in Section IV.

A. *Usability of different CAD file formats*

As a CAD data format both dxf [2], iges [9], and step [7] formats were evaluated and each format was found out to be equally suitable. No significant difference was observed either in the generated reference model or the vital entities selected to be measured.

B. *Validity of reference models for dimensional control*

The reference models created automatically were suitable for dimensional control purposes. The amount of detail could be controlled by the values of the parameters in the knowledge base, and thus the data extraction process could be tuned to be suitable for the needs of the inspection task in question (see Fig. 3, Fig. 4, and Fig. 5). Some minor problems were detected in the reconstruction of the curved surfaces (e.g., shell plates of the ships) but the deficiencies, which these problems lead to, were more esthetical than practically meaningful from the dimensional control point of view.

The validity of the vital points, i.e. percentage of the vital points that are actually measured, and percentage of the points that are measured but not classified as vital in the reference model, will be studied later in detail when the approach has been adopted into actual use properly. Preliminary studies indicate about 90% result for both cases, which has been judged to be acceptable at this point of development work.

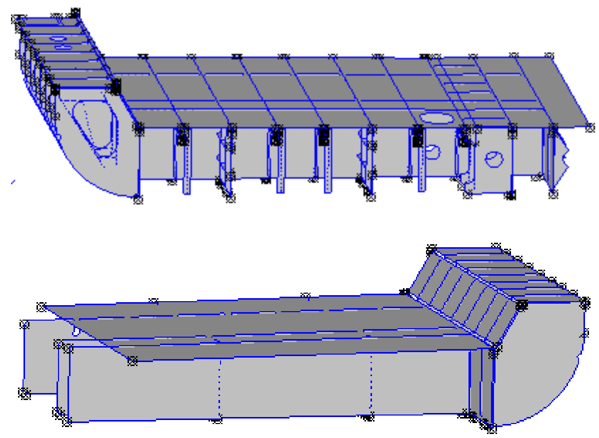


Figure 3. Examples of a knowledge based guided reference model generation: Two halves of the same block imported by using different instructions given in knowledge base. The upper reference model has more details and vital points included (also holes) than the lower model.

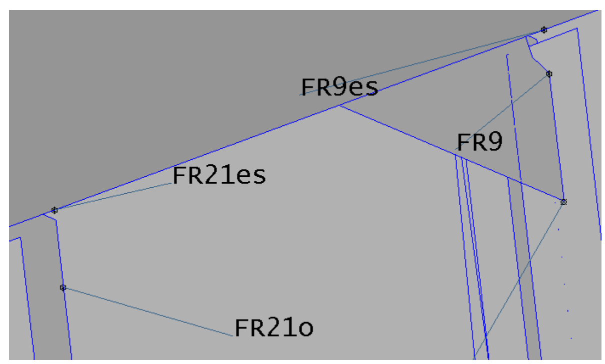


Figure 4. Example of a knowledge based guided vital point generation: “If a bulkhead or a stiffener has a notch (corner cutout), use notch point (FR9), otherwise make an offset point 100 mm from the corner of the bulkhead or the stiffener (FR21o). Create points also on the deck edge in the position where the bulkhead or stiffener goes under the deck (FR9es and FR21es)”.

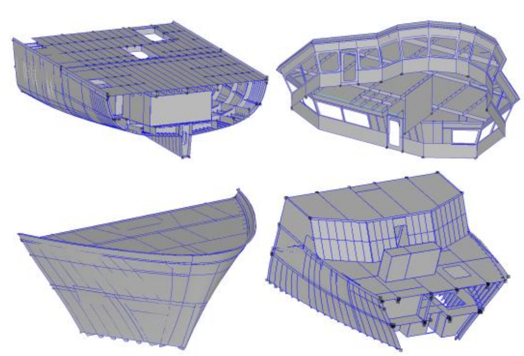


Figure 5. Four examples of generated reference models.

C. Import time comparison

The time to create a reference model depends on the amount of data in the CAD file, the complexity of the 3d structure, and the amount of analysis the knowledge base instructs to be done during the reference model generation process. The reference model generation time with the new approach was compared to the current state-of-the-art approach [4] by creating reference models by using both approaches on the same normal laptop computer. Our approach proved to be significantly faster (Table I).

TABLE I. REFERENCE MODEL GENERATION TIME COMPARISON

CAD-file size [MB]	Generation time [s]	
	Reference [4]	Our approach
2,4	55	4
3,3	65	6
3,7	60	5
4,4	85	6
7,4	240	12
11,3	600	18
21,9	1625	35

D. Data reduction

One purpose of the reference model generation is to reduce the data available in the CAD models. The reference model should comprise all data and structures needed for performing the measurements and visualizing the model judiciously. However, unnecessary data and structures should be excluded in order to offer illustrative and clear model.

All the evaluated models were approved by the measurement personnel and dimensional control management by inspecting the models visually. The amount of data reduced was computed by comparing the number of 3d objects defined in the CAD model and in the generated reference model. The amount of data was reduced typically to less than 2% of the original (Table II).

TABLE II. DATA REDUCTION

CAD-file size [MB]	Number of 3d objects		Percentage
	CAD	REF	REF / CAD
2,4	8515	141	1,66 %
3,3	10875	93	0,86 %
3,7	10500	51	0,49 %
4,4	13687	212	1,55 %
7,4	25431	501	1,97 %
11,3	37890	454	1,20 %
21.9	71707	557	0.78 %

E. Quality figure computation

Quality figure computation was experimented by defining several different structures into the application specific module of the knowledge base. The structures, which were used in all our experiments, comprised block as whole, block face, deck, bulkhead, stiffener, and special points. In some specific experiments some additional structures like foundations, center plane, and basic plane were evaluated. The size, location and direction information was given for the recognition of the structures.

Instead of finding out the actual quality of the blocks measured, the purpose of the quality figure computation experiments was to evaluate the feasibility of the approach. From this point of view, the results obtained from our preliminary experiments were encouraging: The structures were correctly recognized, correct points were used for the computations of different quality figures, and lower level quality figures were successfully combined to the upper level quality figures of the quality figure tree. An example of an automatically generated quality figure tree is shown in Fig. 6.

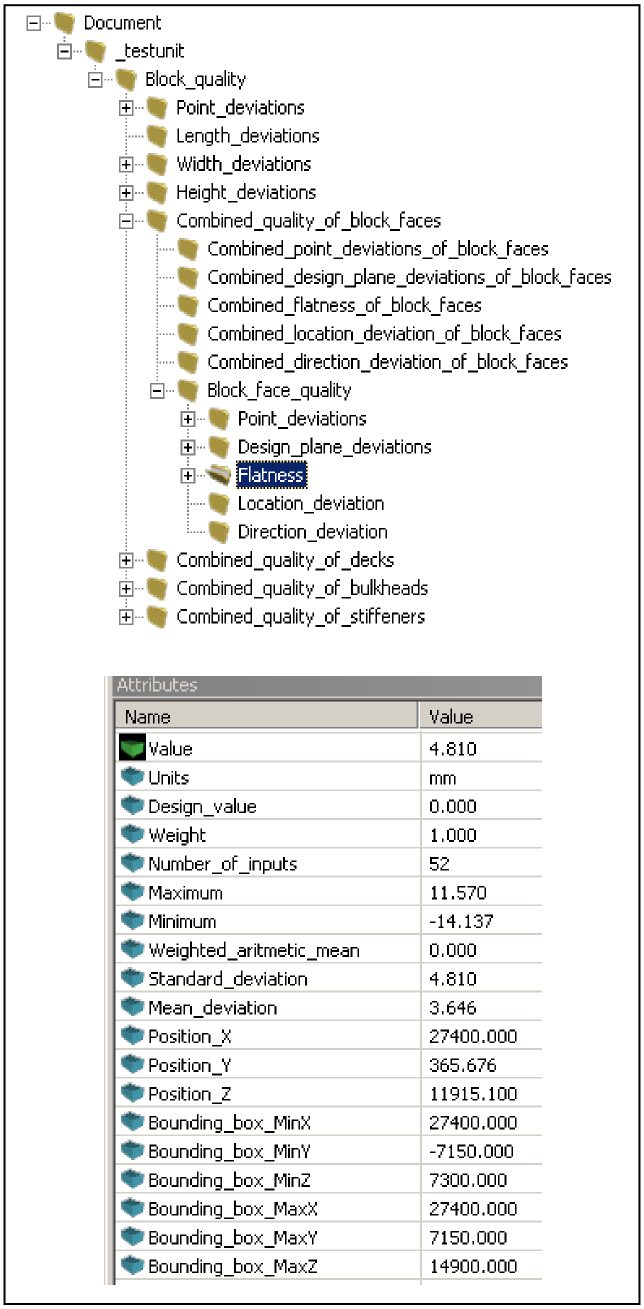
IV. CONCLUSIONS AND FUTURE WORK

The automated, knowledge base guided approach for reference model generation proposed in this paper seems to offer a step forward for the dimensional control and accuracy analysis of large scale objects. The following advances have been accomplished:

- Possibility to use different CAD formats
- Possibility to import more complicated structures than with the current state-of-the-art approach
- Significantly faster reference model generation than with the current state-of-the-art approach
- Significant data amount reduction (compared to the amount of original CAD data)
- Recognition of user defined structures vital for dimensional accuracy analysis
- Creation of comprehensive quality database advantageous to dimensional accuracy analysis of the object in question and for monitoring the assembly process
- Flexibility and better suitability for different kinds of dimensional control needs by using user editable knowledge base.

The usability of the quality data obtained from the proposed automated manufacturing analysis has not been properly evaluated yet. In order to utilize the data e.g., for monitoring the assembly process and long-term statistical process control further studies are needed. For example, it has to be studied, which statistical quality figures need to be computed and how these figures should be combined in order to properly serve the process monitoring. The current implementation serves as a good starting point for these studies.

In this paper, the studies focusing on the automation of the reference model generation and manufacturing accuracy analysis were reported. Even though very promising results were obtained, it should be noted that some amount of user interaction is and will be needed. How this interaction (e.g., for editing the knowledge base) should be arranged, must also be considered properly in the future in order to obtain a useful system for the industry of large scale assemblies.



Name	Value
Value	4.810
Units	mm
Design_value	0.000
Weight	1.000
Number_of_inputs	52
Maximum	11.570
Minimum	-14.137
Weighted_aritmetic_mean	0.000
Standard_deviation	4.810
Mean_deviation	3.646
Position_X	27400.000
Position_Y	365.676
Position_Z	11915.100
Bounding_box_MinX	27400.000
Bounding_box_MinY	-7150.000
Bounding_box_MinZ	7300.000
Bounding_box_MaxX	27400.000
Bounding_box_MaxY	7150.000
Bounding_box_MaxZ	14900.000

Figure 6. Example of an automatically generated quality figure tree.

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