Assembly Oriented Design

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Abstract

The paper focuses on the development of a prototype assembly oriented CAD environment as opposed to the more common component based approach, as an evaluation tool for early product introduction. It introduces the notions of proactive DFA and assembly sequence construction as the underlying methodologies, with geometric reasoning and expert system tools employed in support. A case study example illustrates the benefits gained by this approach.

Introduction

It has long been accepted that product assembly considered at an early stage of the design, promotes study of the design as a whole which has been proven to improve overall costs, quality and time to market. Unfortunately this is contrary to the component focused approach of current CAD systems. Consequently, there is a requirement for computer-based systems to consider assembly issues early in the design process, providing the functionality to support design evaluations in terms of manufacturability and assemblability.

Design for Assembly (DFA) procedures [1],[2],[3] can help engineers achieve these measures. Indeed, the methodologies claim proven success in reducing part count, improving product quality and minimising assembly problems. However, the current methods are reactive tools, time consuming and are, at best, applied towards the end of the design process. Refinement of DFA to cater for its application in a more proactive manner would assist the designer to develop a product which is configured for ease of assembly and manufacture. While this is not altogether a new idea [4][5], relatively little work has addressed the problem of realising assembly-oriented design and proactive DFA due to its complex and demanding nature. Recent developments in design of information systems and computer technology, and advances in product modelling now suggest that a solution may be within reach.

Little research has been directed at generating suitable assembly sequences for use with DFA. Both Li *et al* [6] and Sturges *et al* [7] proposed frameworks for automating the DFA evaluation procedure linked with a CAD system. Neither considered the potential benefits to be gained from analysing products concurrently within the design process. Kim *et al* [8] presented their system INSPIRE-2 which integrates assembly planning, DFA and redesign. This system takes a finished design and its assembly operations and reconstructs a default design process in stages. However, there is no defined methodology for the designer to construct the sequence whilst the design is progressing.

In this work, enabling assemblability analysis of a developing design, requires concurrent assembly sequence construction. The sequence then forms the basis of the proactive analysis. As the designer manually specifies mating conditions and sequence data, the proactive DFA analysis provides a quantitative view on the assemblability of the product in relation to the amount of available data. This paper describes work towards such an environment and builds upon previously reported work [9].

Industrial Assembly Planning

The actual processes of assembly planning must be understood and clarified to successfully develop a simple methodology which assists the designer to build an assembly sequence alongside a developing design. Much of the assembly planning literature focuses upon developing the algorithms [10],[11] for the automatic generation of sequences. The human involvement in the process has largely been ignored. There are a few studies aimed towards understanding the processes involved in assembly sequence planning to try to enhance the process, using computers as an aid rather than a solution [12],[13].

Many automated assembly sequence generation systems developed to date [14],[15] rely upon complex algorithms to generate the geometric or ‘hard’ constraints and thus present feasible sequences. Heuristic-based or ‘soft’ constraints are then implemented by the user to identify the most practical sequence based upon prior knowledge. This method was not observed by Ye and Urzi [12] during their experiment. They found that, in contrast to automated systems, planners integrate the application of the hard and soft constraints throughout the process to define a good assembly sequence. Our industrial investigations carried out across 10 diverse companies ranging from automotive to medical equipment have confirmed this. In all cases the assembly planner used experience of the product and assembly equipment in conjunction with geometric data from the CAD models to produce the best assembly sequence.

Sequence Construction Methodology

The assembly based CAD system, has been developed to demonstrate simultaneous component design and assembly sequence construction. It combines the benefits gained by the early evaluation of assemblability with conventional design measures. In order to facilitate this, a methodology for sequence generation was developed, allowing for the integration of the hard and soft constraints chosen for the particular assembly situation.

Support for generating an assembly sequence is offered in two tiers:

- Assembly Structure Definition
- Sequence Generation

Assembly Structure Definition

This tier interactively defines product structure, building upon the function structure as defined in the concept design stage. Thus consideration and documentation of proposed component and subassembly partitions is achieved. This allows the exploration of differing levels of parallelism in the assembly sequence. Thus, the designer recognises the importance of a suitable assembly structure and by applying heuristics, is ensuring it is optimised in terms of ease of assemblability.

Sequence Construction

The tools to allow the user to interactively develop an assembly sequence are applied in this tier. It offers the facility to consider assemblability issues for the partitioned subassemblies defined in the Assembly Structure Definition. The whole sequence or a subset of the sequence, dealing with a single subassembly can be considered at any one time..

Integral within the two tiers are systematic validation techniques utilising a set of hard and soft constraints [9]. These assist in the creation of a “good” sequence first time with less errors. Evaluation of the designer’s sequence is provided by the proactive DFA analysis.

These tiers are implemented as discrete but linked workspaces which allow the design to be completed concurrently with the consideration of subassembly partitioning and sequence construction. Hence, any new assemblability issues are highlighted during the design process using the proactive DFA analysis and solutions found before they cause manufacturing ‘head aches’. This is illustrated diagramatically in Figure 1, and shown in relation to the product introduction process (PIP).

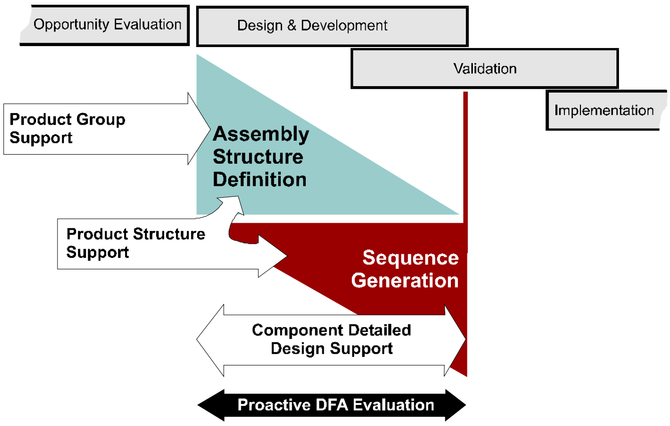

Figure 1: *Sequence Definition and Generation integrated with Proactive DFA Support in the PIP*

Proactive DFA

As the assembly sequence is being generated, a proactive DFA [16] analysis is completed. This can be defined as the integration of process knowledge and experience within the design process to facilitate the generation of design solutions that are amenable to assembly and economic to manufacture. The proactive process has been developed to operate at three levels or layers of support which can be seen in Figure 1 with the assembly definition and sequence. The levels of support are labelled:

- Product Group Support
- Product Structure Support, and
- Component Detailed Design Support

Product Group Support

Before product development commences it is important to decide whether each product is unique and bears no relationship with other products from the business, or whether there are, in fact, similarities and therefore opportunities for rationalisation and standardisation of parts and assembly procedures. The possibility of establishing a product family theme where identical components, a constant assembly sequence, and standard feeding and manufacturing features are used across a range of assemblies should be investigated. If successful, it enables the use of common assembly systems across a range of products.

Supporting procedures available within this level are aimed at minimising the number of variants and facilitating the use of standard parts and features. This is achieved through ‘on-line’ knowledge of high level DFA principles and case based examples, and the easy integration of common and standard parts into the current design.

Product Structure

The main benefit gained from the application of the established DFA evaluation methods results from systematically reviewing a product's functional requirements, in terms of relative motion and materials, and replacing component clusters with single integrated pieces [17]. Until now, this information was investigated after completion of design when all detail was completed. The requirement of earlier (more proactive) assessment has been met through the use of direct interaction with the hierarchy and the assembly sequence diagram during the build. Evaluation of the assembly structure through DFA criteria and knowledge provides an up to the minute account of how successful the product is from an assembly point of view.

Support in this area stems from the detailed DFA cost indices associated with the particular assembly processes. High cost areas are instantly highlighted and where appropriate, action can be taken to 'design out' the current high cost problem. Further detailed DFA information and examples can be accessed, explaining the current assembly problem and providing help for alternative design solutions.

Component Detailed Design

Analysis of numerous DFA case histories indicates that, invariably the success of revised design solutions relies on an understanding of the capabilities of manufacturing processes and the adoption of different materials and/or manufacturing processes. DFA analyses are invoked at the earliest possible stages of the design process, whether there is CAD data available or not. Inference from the components attributes, estimated size and complexity, and default data are used to approximate early DFA evaluation. As the design develops and more detail is accessible, so the DFA evaluations become more reliable and accurate.

Proactive Design Evaluation

Traditional DFA and DFM analyses provide cost estimates for component parts and the techniques are designed to be applied to detailed component parts. This environment brings a more proactive approach to DFA and to foresee many of the assembly problems, requires some geometric reasoning to assist the designer. This may be simple analyses for, say, volume or size, where the manufacture of a certain component may exceed the capabilities of its manufacturing process or more complex geometric reasoning where the stability of a stack of parts may be called into question.

Assembly Oriented Design Support

The underlying data structure for this computer based environment uses a Four Layer Model [18], which comprises a component (CAD) model, assembly representation, component interaction data and an assembly plan. To incorporate the assembly sequence generation and proactive DFA methodologies, there is a requirement for expert knowledge representation and where appropriate, geometric inference from CAD model data. Support for these are provided by geometric reasoning and expert system technology.

Geometric Reasoning Support

A previous paper [9] describes the need for novel geometric reasoning techniques to provide a means of interrogating model data to determine required DFA criteria. These included insertion trajectories, symmetry, shape complexity, cross-sectional areas and degrees of freedom.

The imprecise definitions of the DFA criteria leave them open to interpretation and thus, rather subjective in nature. This highlights the need for mathematical definitions to specify the required model interrogations, tightening up the definitions and providing more consistency. In order to achieve this, there is a long list of model interrogations algorithms which can be utilised. The key requirement for DFA is the determination of axes of symmetry, of which the first reported work can be found elsewhere [19].

Expert System Support

As detailed data is not always available, any decision making process during the early design stages, must cope with indeterminacy. It is here that expert systems incorporating heuristics and expert knowledge with reasoning ability are best able to give guidance and suggestions on how to create an easy to assembly and manufacture product. There are many aspects in this environment which can benefit from expert system support, such as in the generation of the assembly sequences. It is here that the so called *Expert Assembler* [20] can advise and help with which part(s) to start with, the *Starting Component Advisor* and which part(s) you should choose next, the *Next Component Advisor*.

The *Starting Component Advisor* provides suggestions on which part or parts should not be used as the base component(s). It is then easy to deduce which part(s) can be used as a starting component. Based on various attributes, a number of rules have been extracted from case studies and knowledge engineering exercises with experts in industry.

The *Next Component Advisor* highlights the best possible next part to add to the assembly. It provides suggestions based on component group information in the assembly structure, the assembly strategy preferred by designer (such as bottom up, inside out), and some general rules extracted from case studies and industrial experts.

Both advisors are transparent to the user and are continually updated as more information becomes available. The reasoning behind the advisors is accessible and secondary to the user's decision making. The advisors are working with incomplete data as only the designer is aware of data unavailable to the system.

Assembly Oriented Design Environment

Realisation of an assembly oriented CAD environment is performed through the integration of the ACIS solid modelling kernel embedded within Visual C++. The Access database provides a means to store the Four Layer Model information and CLIPS provides the expert system support. The overall structure comprises a number of workspaces:

- *Structure-Builder* - a window to develop assembly structures comprising the assembly definition tier
- *Sequence-Builder* - a window to build assembly sequences comprising the sequence generation tier and a window containing the parts ready for insertion into the assembly sequence.
- *CAD Solid Modeller* - a CAD window for designing each component, defined subassembly and overall product assembly.

Sequence Representation

Any assembly sequence definition involves the embodiment of much data. Conventionally, the *Sequence Builder* diagramatically represents the temporal data as the order in which the components are shown on the screen from left to right. The act of assembling one component to another involves a number of distinct stages. There are tasks which must be performed on particular components prior to insertion; for example placing in a workholder. Figure 2 shows this as an addition to the *Pre Process Box*. Other tasks represented in the *Sequence Builder* form part of the insert process itself, for example by default, an insertion, plus a non permanent mechanical fastening. These are added to the top of the *Insertion Box* (shown in Figure 2). Some tasks associated with a liaison are completed after the insertion, such as welding or adhesive processes. These are shown at the bottom of the *Insertion Box*.

The tasks involved with the liaison can also be further sub-divided into *Assembly Actions* and *Joining Processes* *Assembly Actions* are those needed to physically join the two components and are associated with the proactive DFA analysis. They include insertion, gripping, workholding, disassembly, and turnovers. *Joining Processes* are those tasks which involve the constraining of the two components. These processes are categorised into non permanent mechanical fasteners, permanent mechanical deformation, welded joints, adhesives and soldered and brazed joints. The user may define particular types within these broad categories for more detailed analyses.

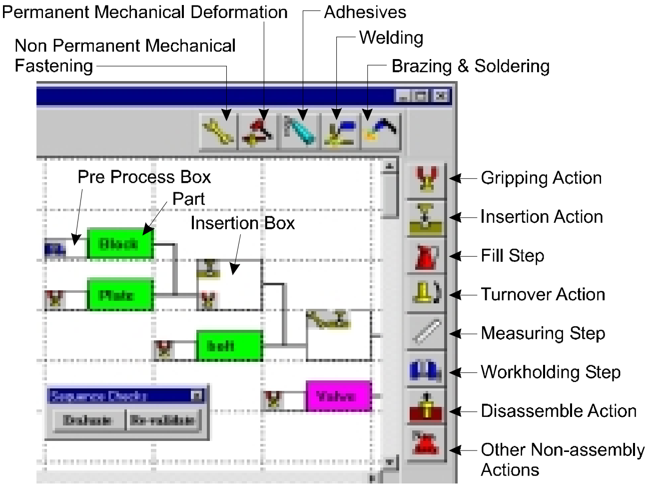

Figure 2: *Assembly Sequence Representation*

Example: Air Pump

An example is developed using a typical assembly of an air pump at an intermediate stage of design, Figure 3. The product has been functionally defined prior to input into the system. The assembly structure has been partially defined in the *Structure Builder* workspace and the designer has started to develop a suitable assembly sequence.

With the addition of new or existing standard parts, the designer is prompted to consider where the component fits into the assembly structure (this can, of course be edited at a later stage if necessary). Distinctions are made between a number of different component types listed below:

- *New Component* - a part which has not existed prior to the conception of this particular design.
- *Existing Component* - a part which is common to a number of products, often a standard /bought in part
- *Existing Subassembly* - similar to existing component but comprising more than one part
- *New Subassembly* - a sub assembly created by combining a user defined selection of components/ subassemblies.

When new or existing components or subassemblies are added, they are represented in the *Structure Builder* and the 'holding bay' of the *Sequence Builder*. The holding bay, labelled "Components To Be Added To Sequence" (see Figure 3), ensures that all parts are incorporated into the assembly sequence and it is here that the current results of the *Starting Component Advisor and Next Component Advisor* are indicated by different border colours. At any stage in the design process, the sequence can be interactively constructed, picking components from this list and placing them in their required positions in the sequence. Given the fact that all components may not yet be added or created, the user is able to develop the sequence in a non-sequential manner.

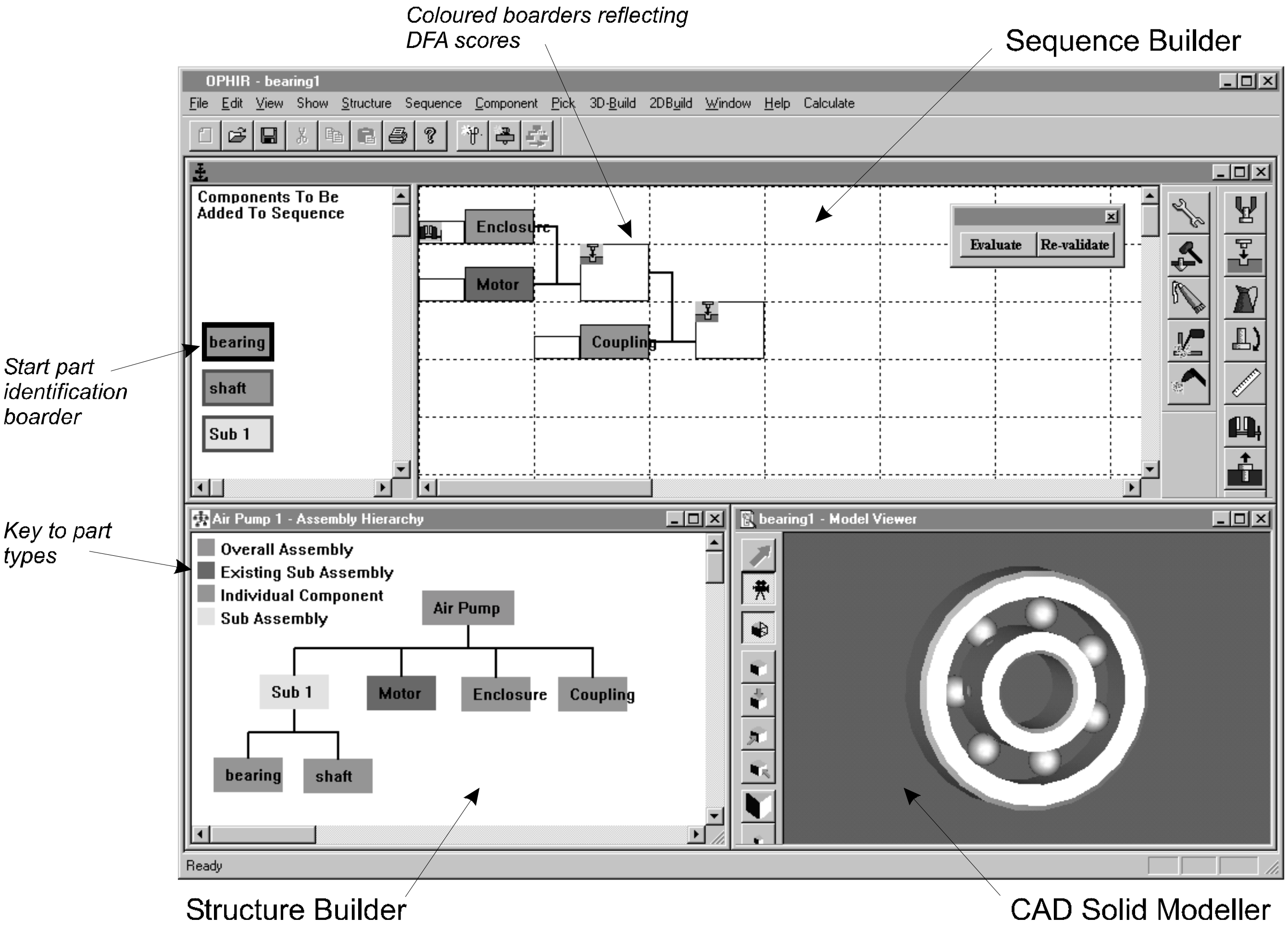

Figure 3: *Assembly Oriented CAD Environment*

Attributes are attached to the components by inference from the expert systems, geometric reasoning if there is appropriate CAD data available, and by user input. Any lack of data will not stop the designer from progressing as it is still possible to add components to a sequence when there is little data, but this will affect the accuracy of the DFA/DFM evaluations.

For a new component, the DFM data initially relies on defaults based on best practice and requires the user to make changes according to their particular requirements. Existing components have detailed CAD model data and DFM evaluations so no manual intervention is not necessary here. All parts are evaluated for their manufacturability, whether their complexity and size are estimated by the designer, reasoned from geometric data or previously defined. The resultant high cost items are singled out at this early stage through different border colours whilst it is still easy to make design changes.

Prior to the first part being set in the *Sequence Builder*, the *Starting Component Advisor* continually investigates new component attributes and/or newly added components/ subassemblies for the best possible starting part. In the case of a newly defined subassembly, such as ‘Sub 1’ in Figure 3. The *Starting Component Advisor* assists with the choice of starting component for that particular subassembly as well as for the overall assembly.

The *Next Component Advisor* is also working throughout the design session. The choice of next part in an assembly can change according to updated component attributes and newly added components and subassemblies. This again is reflected in the software by colour co-ordinated borders on the part names. In the given example (Figure 3), *the Next Component Advisor* has determined that the next component to be added is ‘Sub 1’. As it is a newly defined subassembly, it must be built before it can be added. The *Starting Component Advisor* is then invoked to determine which of its constituent parts is the most suitable as a base part for this subassembly.

Toolbars provide the facility to further define the sequence in terms of relevant assembly processes (e.g. gripping, turnovers, workholder required, etc.) and in terms of joining processes (e.g. adhesives, mechanical deformation, etc.). Attributes can also be added to these processes to further define the sequence (Figure 2) which increase the accuracy of the analyses.

Evaluation and support for the assembly sequence through proactive DFA is performed whilst the assembly sequence is being constructed. Potential assembly problems are highlighted through colour changes of the insertion boxes and where necessary, corrections can be made.

The facility to save a number of candidate assembly sequences are also available. This provides an environment in which comparisons can be made, allowing the user to explore many options and deliver the sequence most suited for the circumstances involved.

Conclusion

A computer-based system is described which supports assembly oriented design. A methodology has been developed and implemented which supports the construction of the assembly structure and sequence concurrently with the design. Taking advantage of the information provided by the assembly sequence, enables the earlier implementation of DFA, the so called proactive DFA and the benefits it provides.

The paper demonstrates manual assembly sequence generation, together with expert advisors and geometric reasoning to support the proactive DFA, to achieve a realistic method of quicker assembly and manufacture evaluated designs. Through a case study example, this paper has demonstrated a successful way to practically progress CAD tools for assembly oriented design.

Further work to make the approach yet more useful, requires more validation and evaluation criteria based on expert knowledge, and the addition of functional model representations.

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