Interface Based Design, A Method For Detailed Design Execution

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ABSTRACT

Tremendous efforts have been devoted to establishing a high-level methodology in the development of engineered products. These efforts provide a philosophical foundation for both corporate America and its educational institutions in developing overall system evaluations prior to detailed design. The general approach at times has been called “simulation based design”. Unfortunately, a minimal amount of material is available which presents a simple execution plan for the detailed design aspects of product development to ensure form, fit and function are met on the production line. In today’s ever growing fast paced multi-disciplined product design teams, a concise, simple method for ensuring overall design intent is met has become even more important.

The simplest form of the problem, a part not fitting in an assembly on the production line, is explored and then related to system level design failures. The contributors to this problem from collegiate education, corporate training and corporate culture are reviewed at a high level. A pedagogical approach currently employed is presented that has proven itself in both corporate and academic environments to specifically address the detailed design execution aspects of current philosophical approaches to product design and production.

INTRODUCTION

As a recent industry veteran turned collegiate educator, I can tell you that simulation based design is alive and well during the initial stages of a product development cycle. Some companies are even practicing a form of concurrent engineering to aid in the transition to production. I have one question, if this is true, why at times do parts not fit together on the assembly line? Why aren’t products meeting functional specifications all the time? Why are production lines delayed in new product release? How is this possible when the up front system analysis on the product was so positive.

Something was lost in the transition from system and subsystem analysis to detailed part design. This elusive something is called design intent. How can this be if we employ our concurrent engineering practices and use computer aided design (CAD) systems? Our solid models on the latest 3-D CAD system seem to show all parts fitting together yet the pin just simply does not fit in the hole on the production line. These parts were intended to slide together and they work in CAD but why not on the production line. This paper proposes a simple process that ensures design intent is maintained in the production environment.

NOMENCLATURE

- CAD: Computer Aided Design Or Drafting
- FEA: Finite Element Analysis

PROBLEM STATEMENT

The problem stated simply is; parts don’t fit all the time on the assembly line, systems do not meet performance expectations. How is this possible when prototypes were built that seemed to work? There must be a better way, so what are we overlooking? Shouldn’t CAD make these problems go away? Why
are failure analysis efforts indicating component interference or loss of design intent in production documentation?

REVIEW OF EXISTING EDUCATIONAL PRACTICES

How are we educating our young engineers? Classical education methods in design development provides the overview of the whole process from product need assessment to end of life through system analysis. Training the young engineer in detailed design implementation is left to future employers. The classical approach is well described in Voland’s “Engineering By Design” (Ref 1) that I believe is well written and currently used at my institution.

The development process is divided quite eloquently into 5 phases as follows: Needs Assessment; Problem Formulation; Abstraction / Synthesis; Analysis and finally Implementation. This of course is not a unique approach. Most approaches in various company development processes utilize the similar methods only disguised under the buzzwords of the week. Let’s examine the philosophical guidance provided under Voland’s 5 phases.

A needs assessment identifies as clearly as possible what basic void is going to be fulfilled by a technological development. For those actively participating in product development this is better known as a Market Analysis or Business Plan. This new product proposal or idea has various noble starting points but a beer stained napkin with some sketching that occurred during the last airport layover is also an appropriate beginning.

While this may seem whimsical, it is the foundation for the beginning of a communication journey through the product development process. If there is no identifiable need, why are we expending the energy and effort to develop a new product? Clearly stating what void this product will fill is in fact the cornerstone of achieving a product to fill that void.

Problem Formulation is the first step in developing detailed definition of the product’s functionality and appearance. Clearly, this is the most critical part of the philosophical phase of the development process from a system functionality or design intent perspective. It is during this phase where detailed functional specifications are developed and compared to the needs assessment to ensure the proper technological direction is charted. Form, fit and function must all come together in the detailed definition of the new product.

During the Abstraction and Synthesis phase, preliminary concepts are developed in an effort to satisfy both the problem formulation and needs assessment. During this phase various forms of modeling are employed; mathematical, computer simulation, physical representations from cardboard or clay etc. Critical items may also be analyzed using Finite Element Analysis (FEA) or even a mock up breadboard fabricated to validate computer simulations all in an effort to verify that design intent of an idea can be made a reality. From these efforts, final system design options are synthesized from successful analysis of components.

The Analysis phase is typically the tie back with a company’s marketing department to evaluate the final options with regards to meeting the needs assessment or business plan. The various design options are evaluated relative to a prioritized needs assessment goals to select a final product design specification for implementation or transition to production.

The Implementation phase is where design intent is usually lost. Most textbooks address concurrent engineering, getting an appreciation for all aspects of the product life cycle and designing them into the product. Several books have been devoted to this effort such as reference 2, Turtle’s “Implementing Concurrent Project Management”. Relative to our design text’s efforts most of the requirements are put forth in this phase:

- Maintainability
- Reliability
- Manufacturability
  - Machine ability
  - Assembly
- Recycle-ability
- Component Interchangeability

The textbooks are quite detailed with respect to what these requirements are, but they do not provide any detailed methods for transferring the design intent developed during our extensive modeling and
analysis efforts to a meaningful set of production drawings that will work with typical tolerances of a modern production line.

I would also propose that the introduction of technological tools such as CAD and FEA have lead to the educational community focusing too much on the tools rather than what the output from these tools should be. A wonderful article appeared in the American Society Of Mechanical Engineering (ASME) magazine titled “CAD Jockey or Engineer” (ref 3) which also describes the current trend of focusing on engineering tools and the diminishing engineering capabilities of the “new breed” of engineers.

Typical engineering and technology students are required to take an Engineering Graphics course which describe the execution of drafting practices to quasi conform to engineering standards such as ANSI series Y14.XX. The educational efforts are usually focused on the appearance of the drawings; orthographic projections, line weights, text styles and borders for the various drawing sizes and how to get the various CAD packages to produce such results. Small sections of these textbooks, if at all, are devoted to evaluating tolerances, fit issues or maintenance of design intent associated with multiple parts working in concert to produce a viable, functional system. I will describe in detail later why I believe tolerance analysis and design intent to be the corner stone of “interface design” practices.

TYPICAL EMPLOYER TRAINING PRACTICES

Many engineers with 20 plus year experience remember their first on the job mentor, but where have most of these mentors gone? Is mentoring dead? I would venture to say that a combination of 401K-retirement plan, changes in corporate culture, combined with newer generations sense of entitlement, have killed the traditional mentoring and training in most companies. As a result, department managers today need to plan for continuous turnover of employees, which in turn has reduced the willingness for companies to fund organized mentoring and or training programs.

In addition to a significant reduction in formal on the job training, there is currently a metamorphosis occurring in the work force very similar to the changes that occurred when secretaries were slowly eliminated and administrative assistants were born. Unfortunately, the evolutionary process has not been so kind to a group of industry veterans, the draftsman and traditional designers. More and more demands are being put upon the engineers to communicate their design ideas from initial concepts all the way to production quality blueprints. As for the drafting board designers, some have made the transition to CAD operators but lack the educational background to make detailed design decisions based on engineering and technology fundamentals to ensure integrity of the design is achieved. What essentially is lacking is the ability to define component or system design intent.

In this situation, as described in reference 3, an employer is faced with a substantial dilemma; do we need someone who can document a design using CAD or someone who can define what the design should be. Corporate America is looking for engineers who can do both but the primary training being provided is how to use the company’s particular CAD tool. Worst scenario of all is when something goes wrong and the company blames the CAD tools and or user’s lack of CAD experience. The typical knee jerk reaction is inundating the staff with training in the use of the tool.

However, being able to produce drawings with CAD does not ensure what is documented will work! The heart of the problem, i.e., what needs to be in the design, is never communicated. The nuances of detailed design development are not being stressed. Where then does the detailed design execution training occur? Is it being left to trial and error? The main problem is the old time draftsman that has worked at the same company with 25 years production design experience is being replaced by a 0-4 year experience engineer who is an expert using the company’s CAD tool.

A TYPICAL PRODUCT FAILURE

Probably the most common problem encountered in a production line failure is parts not fitting properly. This in turn can have unwanted deleterious effects, high component rejection and or failure of a system to operate properly. This does not necessarily mean the system cannot be assembled, as it may in fact be the cause of the poor system performance.

The engineering staff is puzzled by this phenomenon because the CAD tools indicated all parts worked in the assembly. A typical misconception by management is “Why is this new CAD tool making our engineers look so bad.” In reality the design mistakes occur long before CAD is brought into the picture by not clearly identifying the design intent of the system and its components.
DESIGN INTENT DEFINED

What is design intent? Quite simply, it is “the translation of the design engineer’s vision into components and systems that function as he or she intended them to function.” Well now isn’t this obvious! Let’s first consider a single component product to build our design intent concept before we pursue complex multi component, multi designer scenarios.

Let’s evaluate a chisel for cutting soft thin metals. The primary design function is to cut metal by being propelled through the material by a hammer. The design must be capable of maintaining an edge and made of a material harder than that which we are cutting and also withstand the blows imparted by the hammer.

We will assume that we have defined: the needs assessment; formulated the problem; analyzed and synthesized various design options; and are now left with implementation, i.e., creating the production documentation and processes. What are the pit-falls in execution? Maybe incorrect documentation of materials, but no other component depends upon the chisel’s tolerances.

Would using this chisel as a screwdriver work? Maybe. Did our philosophical process ever intend this product to perform this function? Would it work well or not at all or break? What if the design intent was to build a screwdriver instead and a wonderful soft plastic handle was fashioned to a slotted steel bit. Could this be used in accordance with the design intent of the chisel? Most likely not! The handle could break or the tip chip.

Let’s now consider a multi component system, a soft drink cup, lid and straw. In this situation, each component has distinctly different functions that must work in concert to fulfill the end users need of holding the liquid, preventing spills and having a means for delivering it on demand. Each part is required to meet a predetermined design intent or function in order for the whole system to operate in accordance with the overall design intent.

The cup’s design intent may have several high level components such as, volume, construction material and ergonomic features like maximum diameter. The lid’s design intent would require it to provide a minimal leak seal around the cup and straw. The straw would have design intent such as fit to the lid, maximum diameter and nominal length. All of these component level design intents must work together to ensure the whole system also works.

Let’s broaden the system design parameters even further. Consider a series of cup volumes from small, medium, large to extra large that use the same lid and straw, as one encounters in most fast food restaurants. For the sake of time to market a team of engineers are assigned to the project each with a different part to design. How and where do we begin?

I will propose in order to maintain system performance each interface has in fact a design intent associated with it. The interface design intent definition is the foundation for multiple engineers working on one project but designing components independently and is the first step in achieving the ultimate goal of a working system the first time.

INTERFACE DESIGN PRACTICES EXPLAINED

Hopefully what is beginning to become apparent is the need to define and control how two parts interact. We will define this interaction as the interface design intent. This interaction extends into the various disciplines since purely mechanical system rarely exist today. I provide the following to my students, “The last purely mechanical system widely used in our society was the steam locomotive.”

While working at a small start up engineering company, a colleague and I were faced with the exact dilemma described above in that we only had a 0-4 year experience engineering pool without any true production veterans. Due to the small size of the company, our job descriptions required us to be program manager, system engineer, mentor and quality managers. We were faced with a major problem in that we could only provide system level direction and could not be looking over every young engineer’s shoulder to ensure design intent was maintained. With the help of my colleague, I developed a detailed design training session to ensure design goals from the system simulations were achieved. This method is described below.

1. Create hand drawn system sketches.

Once all the system analysis is complete, the design team uses a system sketch as the fundamental beginning of a sound detailed design. During the sketching phase, a couple of things are accomplished; all
team members work together to get a broad picture of the components and individual component detailed design responsibilities are assigned.

2. Identify and number interfaces

Anywhere two or more parts or subassemblies interact, needs attention because defining the interface upfront will allow a concurrent design with the most flexibility in the main body of the component. The soft drink container for example could have additional engineers added to the project to design various size cups with absolutely no impact on the lid or straw designers, provided the interface is fully defined using steps 3 thru 6.

3. What type of interaction is desired / required / design intent definition
   i. Fixed
   ii. Rotational
   iii. Translation
   iv. Positional
   v. Fasteners / Retention

4. What tolerance is needed / positional accuracy at each interface
   i. Clearance
   ii. Interference
   iii. Transitional Fit

5. Interface functional stiffness / allowable stress / displacement limits
   i. Positional Encoder Requirements
   ii. Maximum Loading Requirements
   iii. Maximum Deflection Requirements
   iv. Range Of Motion
   v. Etc.

6. Allocations for electrical interconnect
   a. Assembly method including Isolation / grounding
   b. Access / Serviceability
   c. Test and Debug methods

This detailed interface definition is considered critical to provide direction for the entire cross-functional team of engineers in the final selection of components. For instance a major problem with the typical 0-4 year engineer is grasping the notion that nominal dimensions don’t exist.

   Every dimension on a component found on a production line falls into a range of dimensions or tolerance about a “theoretical” nominal. If this is true, there can never be a line-to-line interface when one views a CAD model.

   Unfortunately, the most visually pleasing view and easiest to model in CAD is a part that would have line-to-line fit at all interfaces. Sometimes, we may want an interference fit and need to account for these areas. Global interference checks with advanced software may also cause design intent to be lost when an uninformed designer tries to resolve the problem identified by CAD. Defining and documenting interface requirements will ensure these areas are identified and unwanted changes of intentional clearance or interference prevented to preserve design integrity.

   These steps also allow the mechanical, electrical and software engineers a chance to exchange detailed design concepts and to verify that system simulations will make it into the production documentation.
7. Assembly methodology / cycles during life
   a. Initial assembly / procedure outline
   b. Set up adjustment procedures
      i. Setup defined tolerances
      ii. Setup after assembly – gages, masters, etc.
   c. Maintainability / Serviceability
   d. Disassembly

8. Component selection for:
   a. Fasteners / Pins / Hardware
   b. Bearings
   c. Slides
   d. Raw material
      i. Sheet metal
      ii. Fabricated metal
      iii. Plastic
      iv. Other
   e. Actuators

Steps 7 and 8 set up a loop back to step 1 as we ensure the requirements are designed into the product. In our quest for the optimum design with the fewest parts, we must consider the assembly and set up requirements, which at times may necessitate break up of a single component into multiple parts. This step also brings in additional analysis and interface tolerance requirements based upon “off the shelf” components. Note that all this work occurs before any CAD efforts begin.

We must accept that CAD is the tool we use to document our design intent, recognizing that it is only minimally at best responsible for determining it. The next step, documenting our design, is definitely dependent upon the company’s CAD system. We must develop 3-D models that are robust and capable of being manipulated to accommodate design refinement during a normal production process.

9. Modeling flow chart
   a. Assembly datum’s
   b. Manufacturing / Inspection datum’s
   c. Potential feature changes / impact on (CAD) model usability / functionality

10. What is the final tolerance stack at each interface – does it meet design intent both geometrically and structurally

   This is a verification step performed at every interface using production documentation with the results compared to the design intent developed in previous steps. The results are documented and used for the presentation in design reviews.

11. Design Reviews / Presentations / Sign-off

   The design review phase is the last stage prior to purchasing prototypes or transitioning to production manufacturers. This step can occur multiple times as each iteration of the design is fabricated. After all, no matter how thorough we are in our efforts, there is a reason why philosophical design methods advocate build- test- correct cycles.

INTERFACE BASED DESIGN EDUCATION

How does one get the above concepts across to junior engineers, engineering and technology students. I believe the first step is awareness of the need for maintaining design intent and second is design intent definition. If engineers or students are not aware that interface definition must be communicated to production prints, why would they take the time to define the requirements up front.
This has lead me to develop a pedagogy for teaching interface design concepts. After basic 2-D graphics and mechanical design courses, the first phase comes during a 3-D CAD course in which the fundamentals of 3-D design tools and interference analysis are introduced. The second phase occurs in a simulation based design course that focuses on establishing design intent using different available computer tools such as Excel, Math CAD, FEA, etc. for determining preliminary thermodynamic, thermal growth and structural design parameters.

Both courses utilize a simplified miniature steam engine as the design project under consideration. A cut away view of the engine is provided as figure 1 and the names of the parts as table 1.

This simplified design gives rise to at least 21 interfaces that must be considered in both the design documentation and development of design intent process. The completed list is provided after the students attempt to create it in the first course and the list is developed jointly along with the necessary analysis to determine the necessary fits during the second course. The power source, for thermodynamic analysis conducted in the second course, is derived from a steam source at 200 pounds per square inch and 500 °F.

Figure 1: Cut Away View Of Engine Used In Courses
<table>
<thead>
<tr>
<th>Part Number</th>
<th>Part Description</th>
<th>Component Or Material Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crank Shaft</td>
<td>17-4PH Stainless</td>
</tr>
<tr>
<td>2</td>
<td>Connecting Rod</td>
<td>6061-T6 Aluminum</td>
</tr>
<tr>
<td>3</td>
<td>Piston</td>
<td>A356 Cast Aluminum</td>
</tr>
<tr>
<td>4</td>
<td>Piston Pin</td>
<td>17-4PH Stainless</td>
</tr>
<tr>
<td>5</td>
<td>Cylinder Block</td>
<td>6061-T6 Aluminum</td>
</tr>
<tr>
<td>6</td>
<td>Crank Support</td>
<td>6061-T6 Aluminum</td>
</tr>
<tr>
<td>7</td>
<td>Rear Crank Case</td>
<td>6061-T6 Aluminum</td>
</tr>
<tr>
<td>8</td>
<td>Forward Bearing</td>
<td>Std Catalogue Part</td>
</tr>
<tr>
<td>9</td>
<td>Rear Bearing</td>
<td>Std Catalogue Part</td>
</tr>
<tr>
<td>10</td>
<td>Cylinder Head</td>
<td>6061-T6 Aluminum</td>
</tr>
<tr>
<td>11</td>
<td>Cylinder Head Gasket</td>
<td>Copper</td>
</tr>
<tr>
<td>12</td>
<td>Screw #1</td>
<td>High Strength Steel</td>
</tr>
</tbody>
</table>

Table 1: Engine Initial Parts List

In the first course, after some basic 3-D modeling proficiency is developed, the interface checklist and awareness of the requirements to ensure parts fit with intended tolerances are introduced. A completed interface table is provided to the students after they attempt to identify and characterize each interface on their own. Table 2 is a partial listing of the interfaces considered during the courses. In the second course, the students are required to develop and/or verify that the tolerances provided are in fact correct and determine what impact if any the tolerances will have on the performance of the engine.

In the first course, we introduce a generic 7-step process for modeling parts as follows:

1. Identify Design Intent, Shape, Size, Fit, etc.
2. Create Basic Work Planes Or Select Sketch Plane
3. Rough Sketch A Closed Profile
4. Add Or Modify Geometric Constraints
5. Add Driving Dimensions To Maintain Design Intent
6. Create 3-D Solid By Extrusion, Revolve, Etc
7. Add Child Features As Necessary To Achieve Design Intent

We try to stress the process of thinking about and defining what should go on the model before actually starting to model in CAD. Again, awareness is the first step in becoming a better design engineer.

Next, we introduce the concept of basic tolerance analysis. We must emphasize that nominal dimensions are used as a convenience in developing production drawings and as engineers we must consider the impact of part size variation on the design. Additionally, it is OK and in fact required to have our CAD models reflect the design intent of clearance, line-to-line or interference at interfaces, provided that is what the design requires. Line-to-line fits are when the edges of components reside on the same line. For example a pin outside diameter is exactly the same as the inside diameter of the hole that it fits inside. The following equations and graphical representation of tolerances are then introduced:

1. Min Hole – Max Shaft = Tightest Fit
2. Max Hole – Min Shaft = Loosest Fit
3. The Sign Of The Fit Determines Type
   a. Positive Fit Is Clearance
   b. Negative Fit Is Interference

![Graphical representation of clearance and interference](image)

This graphical representation is then related to how the interface will appear to the user on CAD. By using graphical means, the point is also driven home that the dimensions fall into a zone and are not discrete numbers. The students must accept how the model will look when there is an intended clearance or interference between two parts. Also, utilizing the full capability of the software, each interface that should have interference is identified when a global assembly check is performed.

### Table 2 Examples of Interfaces Considered In Course

<table>
<thead>
<tr>
<th>Interface Number</th>
<th>Interface Description</th>
<th>Interaction Type</th>
<th>Tolerance Allocation</th>
<th>Final Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crank To F. Bearing</td>
<td>Position</td>
<td>Transition +.0002 to -.001</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Crank To R. Bearing</td>
<td>Position</td>
<td>Transition +.0002 to -.001</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>F. Bearing To Support</td>
<td>Position</td>
<td>Transition +.0002 to -.001</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>R. Bearing To Support</td>
<td>Position</td>
<td>Transition +.0002 to -.001</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Crank Support To Cylinder</td>
<td>Position, Fixed</td>
<td>Clearance .001-.003</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Crank Support Sub Assembly To Cylinder</td>
<td>Alignment, Position</td>
<td>Maintain Crank Flange Position within .005 Total Variation</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Crank To Rod</td>
<td>Rotation</td>
<td>RC 5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Rod To Cylinder</td>
<td>Clearance</td>
<td>Verify .005 Min Clearance</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Rod To Piston Pin</td>
<td>Fixed</td>
<td>FN 5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Rod To Piston</td>
<td>Clearance</td>
<td>.001 to .005 clearance</td>
<td></td>
</tr>
</tbody>
</table>
The basic tolerance analysis is developed as part of the course work including discussing which points will be used as measurement and assembly datum planes along with the impact of poorly chosen planes. This is considered a crucial step in the execution of the interface checklist to ensure final inspection requirements are developed.

As mentioned earlier, the basic instinct of the uninformed designer is to design everything line-to-line. Interface 7 is shown in figures 2 and 3 with the typical line-to-line and exaggerated clearance respectively. This example provides the basic views of an established interface clearance for our young engineers and students to become accustomed to seeing on CAD.

Figure 2: Interface 7 With Line-To-Line Fit

Figure 3: Interface 7 With Exaggerated Clearance

SUMMARY

The advent of CAD on every engineer’s desktop has dictated a new mindset for today’s engineers. In the strictest sense, they must be both engineers and documentation developers. These CAD tools are both powerful and difficult to master. Unfortunately, the current trend in both academia and industry is to focus on the tool rather than the role of the tool in the product design process.
I for one believe that we need to stress the philosophy that “design integrity happens way before the documentation is ever initiated on CAD”. Once the transition to CAD has begun, it should become a documenting and drafting exercise as described in the interface checklist. The final phases of the checklist can be supported by CAD by evaluating the structural integrity through FEA or interference / clearance analysis if available on the particular CAD system.

Detailed engineering documentation notebooks in addition to engineering notebooks should be maintained. The first notebook is to ensure design integrity and the second is to document when designs are invented for legal purposes. The documentation notebooks will enable easy manipulation of the model by explaining how the interfaces were derived and how components were modeled.

This new approach is being used at Wentworth Institute of Technology with great success. We are currently stressing the development of documentation notebooks to ensure product maintainability. Since our students are being taught with the interface checklist as part of the curriculum, they seem able to accept interfaces when modeled as they should be rather than line-to-line.

I feel strongly that program managers and department heads can benefit from this philosophy as a roadmap to ensure success. The checklist concept is invaluable by allowing us to measure meaningful progress rather than how much effort has been spent on the CAD tool. For instance, if the young engineer is on CAD and does not have an initial part sketch with interface tolerances, you know immediately the design intent has not been defined.

REFERENCES
1. Engineering By Design, Gerald Voland, Addison-Wesley 1999
2. Implementing Concurrent Engineering Management, Quentin Turtle, PTR Prentice Hall, 1994
3. CAD jockey or Engineer?, Jean Thilmany, March 2002 Mechanical Engineering Design