Visits to Prof Kimura's CAD Research Lab July 5 and July 19 for Discussions about Product Realization, IMS, and Product Development Cycles

The general topic of research in the lab is product realization via computer. The work is currently sponsored by the Japan Society of Precision Engineers, of which Prof Kimura is a prominent member. Similar research has been going on for at least 5 years under the original leadership of Prof Sata (now retired) and Prof Yoshikawa, now Vice President of Todai. Prof Kimura said that he expects a new large government grant starting this fall.

Sata and Yoshikawa apparently are responsible for the highest level view of this topic. It has matured from long-standing research by them and Kimura on numerical control machining of complex surfaces into the notion of CAD systems that contain engineering knowledge, capture the designer's intent, and connect design and manufacturing. Its most recent manifestation is in Yoshikawa's proposal for internationally supported research on Intelligent Manufacturing Systems (IMS).

Note: on the second visit I was accompanied by two researchers from Hitachi Production Engineering Research Lab.

New Approach to Manufacturing

"Manufacturing" often connotes fabrication of single parts, typically by metal cutting. Interpreting IMS in this way seriously misses the point. Taking the more general view that "manufacturing" means fabrication, assembly, test, and logistics activities in factories also seriously misses the point. It is important to realize that the idea of IMS extends well beyond "manufacturing" all the way back to conceptual design.

Therefore, IMS is the same as "product realization," which encompasses all of the processes, intellectual and physical, that are undertaken as an idea for a product is hatched, refined, turned into design data, analyzed and simulated, cost-analyzed, turned into process plans and instructions, the parts made, assembled, tested, and shipped, the factory designed and operated, customer responses factored into the next design, and so on.

Prof Kimura's career illustrates the process by which these ideas have grown and matured. His background is in 3D modeling of complex shapes such as car bodies and creation of computer software for representing these shapes. He was involved in several MITI projects that created GEOMAP I in the late 1970's and GEOMAP II in the early 1980's. This software was taken up by Toyota and used in their car design CAD software. Kimura consults regularly for Toyota.

Such software ultimately must represent two distinct but mutually indispensable components: 1) the mathematics of the surfaces themselves, so that they can be displayed realistically and manipulated into the desired shape; and 2) the physical processes by which metal will be pressed and stamped into those shapes, so that the designer can find out if the shape is possible to make and how much it will cost. A complete design system must therefore contain a great deal of manufacturing process knowledge. Developing this knowledge has been a 20 year effort for most automobile companies but is only being integrated into design software in the last 5 years or so at the most advanced companies. On the other hand, software to represent the shapes mathematically has existed in various forms and levels of sophistication since the 1950's.

The above pattern (namely that computer-aided design software is incomplete without manufacturing / assembly / test process knowledge) is at the heart of a new wave of research and commercial progress in CAD. It is redefining the meaning of CAD, once embodying only making mechanical drawings of single parts, into someday representing all the knowledge needed to design, analyze, make and even sell entire products.

State of the Art in Different Design Domains

The use of computers in design has grown rapidly in the last 30 years, but the most complete representation of product and process design methodologies is in the domain of micro-electronics. Here, the products are so complex that they are impossible to design without pervasive use of computers. A typical microprocessor design looks like the map of a city's streets. Recent designs contain as much information as the entire New York metropolitan area including much of western Connecticut and northern New Jersey. Because microelectronic designs consist of layers of 2D information, mostly in the form of circles and straight lines, they are easy to represent mathematically. Similarly, all the manufacturing tooling consists of photographic replicas of exactly this information. Thus the conversion of the design into manufacturing equipment is relatively straightforward in the sense that no further complex mathematical processing is required to convert the design data.

By contrast, the shapes of car bodies cannot be made by making the press die the same shape as the mathematical model because of the mechanical properties of the sheet metal (spring-back) and the behavior of the metal-die interface during stamping. Accurate models for these factors are difficult to create. Bridging this design-process gap is the essential obstacle in car body design- manufacturing. The trial and error involved here is responsible for much of the time needed to design cars, and thus better prediction and less error are of extreme competitive value as well as being an extreme intellectual challenge.

The conversion of micro-electronic designs into working manufacturing processes is not straightforward either, but the obstacles are in keeping the processes free of contamination and in learning how to make the patterns of lines and circles smaller and smaller. The limits of the manufacturing processes create "design rules" that must be followed, but these are relatively simple to state and to check for during design. This is not to say that making microelectronic products is easy but rather that representing the designs in the computer in ways that translate directly into manufacturing instructions is relatively straightforward.

In addition, the geometric layout of a micro-circuit determines its electrical behavior, so it is relatively straightforward to obtain a computer simulation of the behavior during design.

On the other hand, drawings and mathematical shape representations of mechanical items contain no clue at all as to how they will operate and little about how they should be made, except when their shapes are simple circles, cylinders, and so on. On the contrary, most mechanical drawings and CAD versions of them are merely symbolic notation that refers to both physical things (circles that refer to circular holes) and nonphysical things (arrows pointing to extensions of surfaces that represent measurements between those surfaces). Drawings thus represent a well developed language that people know how to interpret. Many statements in this language are inferred and do not appear directly on the drawing.

Another difference is that in electronics most of the parts are standardized. In larger parts, the externals are designed almost exclusively for handling. In smaller items like microcircuit elements, the shape completely determines the performance, but these shapes are simple and are also standardized. The behavior of each item has been well modeled and the behavior of both single elements and large systems of them can be predicted with excellent accuracy.

By contrast, the shape of mechanical items must be tailored specifically for each item to the tasks it must perform. Rarely does a part do one thing. Most items do several, such as provide strength, electrical or heat conduction, and geometric arrangement. All of these functions can be difficult to model and predict accurately even when performed in isolation. Little modeling capability exists for sets of mechanical items operating together as a system except if many simplifying assumptions are made.

Thus the essential elements of a complete design-manufacturing system are in many ways much easier to establish for microelectronic items than for mechanical items.

Research Activities at Todai

Prof Kimura has two bright assistants, Prof Suzuki and Prof Inue. In other labs there are additional faculty with similar aims. Kimura and his assistants have 12 graduate students, 8 undergraduates, and 13 visiting researchers from industry. Their research breaks down into three main categories: geometric modeling, product modeling, and design / manufacturing. Their participation in the IMS is in such areas as concurrent engineering, virtual manufacturing (meaning wide use of simulation of product and processes), design by customers, information transparency (meaning good user interfaces) and self- organizing and distributed systems.

Prof Kimura also divides up the topics into objects, processes, and environments. All three are essential, he says. In this sense, he reflects his machining and NC background. "There is nothing without understanding of the basic processes," he says, and I agree. Yet right now their research tools consist entirely of workstations, due to lack of space, funds, and a process-oriented colleague to replace Prof Sata.

1. Geometric Modeling

The lab has a long history of studying geometric modeling. Recently they have been overtaken by developments in commercial software and by the fact that students do not like software thesis topics. So he is using commercial solid modelers as the basis for additional work. This work is heavily related to constraint-based modeling and design. A typical project is on use of constraints to determine the size or shape of an item based on a statement of its performance requirements. Feature-based design is another related topic.

A typical project involves allowing the designer to call forth standardized elements such as shaft ends and their mating bearings, which together form a functional feature made of several geometric features. These functional features can be given specific dimensions, or some larger requirement such as a torque or side load can be given by the designer and the computer will resize the parts. The example shown was hardwired (i.e. preprogrammed in LISP) by the student. There is no graphic design interface.

Another project is design of sheet metal parts based on partial input of geometric constraints. These include locations of holes, portions of the part's outline, and areas the part should avoid. The computer draws the rest of the outline. This project is similar to others where the spirit is to permit partial information to be used effectively.

Another series of projects deals with tolerances. These include use of solid modeling methods to predict all the possible mating arrangements of parts with deformed mating features, such as machine tool ways or peg-hole mates. These methods are enumerative rather than statistical so they are threatened with combinatoric explosion.

Another series of projects involves specification of geometric constraints. The portion that accepts 2D constraints has probably been overtaken by commercial modelers such as SDRC's I-DEAS Level 6. Three D constraints are much harder to deal with and include lining up features on different parts in order to describe constraints in an assembly.

2. Product Modeling

Several of the above projects could fall into product modeling, since the line is rightfully indistinct. The goal in product modeling, however, is to work top-down from specifications toward assemblies and finally to parts, with the computer progressively doing more and more of the routine work. Prof Kimura wants to capture what he calls "product structure," something he distinguishes from assembly structure or machining structure, which have their own geometric features.

Product structure is about function and its relation to technological knowledge: kinematics, dynamics, dimensions, and tolerances. In one form of this idea, a product model is realized as a set of objects (in the database sense) together with object models of the tools that make them. To these models must be linked models of the processes (machining, assembly, test) that will make the parts and the product. He agrees that "this is a quite difficult topic."

Clearly, AI has deeply penetrated this lab. One can see it in the magazines the group subscribes to. They cover robotics, graphics, CAD, AI, graph theory, UNIX, and a wide variety of non-mechanical engineering topics.

He is also interested in modeling the design process. He does not approach this directly by observing the behavior of designers but rather by observing the work they do. He was inspired by how Toyota did this. It is very pragmatic and seeks to identify what takes the designer's time that could be computed readily, or what tools the designer uses (colors, multiple views of solid examples) that the computer could reproduce. Right now he has identified "routine design" as an approachable topic. An example is the feature- constraint-driven model of shafts and bearings mentioned above.

He notes that such models are easy to construct so as to obey physical laws. The same is not true of more innovative design. This is not a linear process dominated by well-trod paths and procedures. Here he suggests that the computer models not be bothered by physical reality, as indeed perhaps the designers' thoughts are not either. When something useful emerges, the designer can impose reality. The likelihood of the computer's suggestions being real is enhanced if they are built up from verified elements.

Thus his model is that the designer can manipulate such elements in what he calls a "virtual factory" that contains models of machining, molding, and assembly processes. These models may be approximate but that would be good enough for preliminary design.

Aside on Model Accuracy

The idea that a rough model with imprecise or incomplete data should be sought for early design is consistent with Toyota and Nissan being willing to launch downstream design tasks when only partial information is available. Body styling data accurate within 1 mm is available months before the last mm is pinned down. Yet nearly all of the design of dies can be done within 1 mm and finalized at the end. None of the stamping simulations is likely to be affected by a 1 mm change.

Thus a major component of research in support of early design should focus on determining just what information is of real value in launching any given step in the design, and the level of accuracy at which this information must be provided. Such a study will likely reveal that much of the demanded perfection of data is not needed right away and that a preoccupation with perfection and finality is a time waster in many design processes. It also may be a time waster in many searches for good computer models of products and processes.

He cited Toyota's method of evolving design tools: make a simple tool that helps a specific design step; observe how the designers use it and get their suggestions for improving and broadening it to cover more of the steps. This way the tools grow organically and no useless tool is pursued or imposed on the designers. It is an example of a larger difference identified to me last year by Mr Hazeki of IBM Tokyo Research Lab: Americans jump too quickly into system software (equivalently are too top-down oriented) without thinking the process through first, whereas Japanese are too slow and spend too much time figuring out their processes and perfecting them manually before daring to put in any software (too bottom-up oriented).

I am also reminded of the difference in approach between Toyota and GM regarding die design software. Toyota has a series of elementary analyses that the designer can ask the computer to perform on a die shape. These are quite approximate but can avoid every known disaster. The totality of the programs is an end-to-end system for turning designs into finished dies. GM critiques this system (privately to me and to others) as not having any real engineering analyses or accurate simulations of the metal deformation process. GM has delayed implementing a similar system pending completion of accurate models, a step Toyota gave up on immediately as requiring too much computer power. Thus Toyota can be said to value integration over accuracy, while GM favors accuracy over integration. Toyota appears to be ahead, although Prof Kimura jokes that CAD-designed cars seem to look alike.

3. Design and Manufacturing Problems

In this area, there is little work so far. It covers concurrent engineering, parametric design of routine objects, machining simulation, design for machining, assembly process planning, and standardization of CIM data. The group is active in STEP and other standards activities.

The Relative Importance of CAD/CAM/CAE and Management in Product Development Strategies

As a researcher in CAD/CAM/CAE, Prof Kimura feels that these topics are central to any successful product development strategy. Thus it was interesting to hear this topic discussed by him and two researchers from Hitachi, Mr Ohashi and Dr Taniguchi. Both have advanced degrees from US universities and are active in PERL developing software to aid manufacturing engineering, assembly evaluation, and concurrent engineering.

The Hitachi people reflect the opinion of the Nissan people, namely that "90% of problems in product design methods can be solved by management, and only 10% can be solved by computer tools and computerized knowledge bases." They base this opinion on observing their company designing really new products for which there are no established procedures or tools. Especially important is the lack of corresponding manufacturing processes. Experiments, communication, redesign, and feedback are the essential elements, and the success of these is mostly influenced by management.

The main problem in complex design is that different groups or tasks have conflicting goals and there is no standard way to work these out. The team design method brings the issues out sooner but that only causes embarrassment. Hitachi's big point of pride is the "user first" slogan, which supposedly focusses the team on the customer and makes them forget their internal conflicts. What solution to conflict X will benefit the user the most? The fact that design tools could explore many possible answers faster is not appreciated. The reason may be that it does not seem to be a real option. It is just a promise by researchers.

In this context, what is concurrent engineering? Is it any different from simultaneous engineering? Are they just the team design method with computer support? Isn't concurrent engineering just something that Japanese companies have done for a long time?

Discussion on these points reveals little consensus except that all is not rosy inside Japanese companies. Some people refer to "big business syndrome" in which top managers want to interfere and decisions take too long to make. Mr Ohashi cites a recent Business Week article on concurrent engineering as a clever way to convince managers that communication is really important.

Prof Kimura feels that computers cannot by themselves shorten the design cycle although they can improve quality and help improve the technological level of products. But shortening the cycle is almost exclusively a management factor. Thus concurrent engineering can help shorten the cycle.

The Hitachi people feel that concurrent engineering could help improve quality because they see the current push to shorten the cycle as threatening quality. There is too little time to do the necessary analyses and tests. Thus providing knowledge bases, integrating design and test data, and improving information flow are all ways that concurrent engineering could help the design process move faster.

Now that the US seems to be catching on to the big secret of communication and team design, will Japan have to invent something better? They secretly worry about this but have no answer. It is the big debate inside Hitachi right now.

Closing Comments

Prof Kimura's view of design research is both impressively broad and very pragmatic. His topics seem to be aimed directly at the main needs of mechanical design: higher levels of modeling that include symbolic components such as constraints, maintaining the link between design and manufacturing processes, and striving to support design in fuzzy situations like early design where answers are needed but data are limited.

The IMS idea was born in this environment and thus it has a very sophisticated intellectual base. Prof Kimura surprised me by asking me a "very general question:" How can the IMS project achieve its main goal, which is for Japan to relieve many international trade problems by giving its advanced manufacturing technology to the US and Europe? Why are there so many political problems over IMS? Surrounding this question are his wonderment that the US can develop advanced ideas like CAD and concurrent engineering with computers and still not spread them around adequately.

In one sense Kimura answered the question himself but I also offered an answer. The US is behind Japan in its sophistication regarding manufacturing. It is not clear if we could adequately absorb Japanese technology if it were "given" to us. Thus I said that successful international projects must have well-defined technology transfer mechanisms built into them. Such mechanisms must include long-term hands-on contact with the technology and cannot be confined to delivering reports or presenting papers. Such conditions should apply to any kind of "manufacturing" technology, including management techniques, computer software, robots, sensors, and so on.