Visit to Prof. Tomiyama, University of Tokyo, Aug. 15, 1991

Prof. Tomiyama and Prof. Yoshikawa share a laboratory devoted to modeling engineering knowledge and design processes. While Prof. Yoshikawa is engaged as Vice President of the university, Prof. Tomiyama is in charge in the lab. His background is mechanical engineering, but his research approach is strongly linked to artificial intelligence. It is an interesting combination with many possibilities.

The research has two related branches: design and maintenance. Each should have a theoretical basis, and he aims at providing the base via representations of deep knowledge about "how things work."

Design

This research has two branches itself: understanding the design process and understanding designed objects. The design process to him means understanding how people think, including cognitive process modeling. His route to a design theory is similar to that of researchers in the US who, like him, use protocol analysis to determine what the designer is doing. (Protocol analysis comprises recording, often with video, what a designer does during an experiment and then analyzing the record - the protocol.) Unlike some US researchers, Tomiyama tries to link the protocols to a computer simulation of the process. However, he admits that the protocols do not really tell him anything about what the designer is thinking or how the process actually proceeds.

Modeling of designed objects comprises "CAD without pictures," a term he uses jokingly but which is quite important. Like others, including myself, he feels that conventional CAD puts too much emphasis on pictures. Fascination with the pictures obscures the fact that no real knowledge has been captured in the design. The challenge is to find a way to capture "deep knowledge," by which he and other AI-based researchers describe knowledge about complex relationships among physical phenomena, for example. Deep knowledge is different from "facts," such as "every screw goes into a hole."

To capture basic knowledge, Tomiyama is using Qualitative Physics (QP) and Qualitative Reasoning (QR). The goal is to represent things symbolically so that facts can be reasoned about. This approach has the promise of creating "intelligent CAD," but in doing so appears to sacrifice many aspects of existing quantitative models. Tomiyama disagrees, saying that QP augments quantitative models because it can be the basis for generating symbolic models.

Long term, the goal is to create a meta-model (literally a model of models) that will contain the usual engineering models as subsets. Products would also be modeled in this way. Other researchers' ideas about product models are too geometry-oriented for him. He would rather model where the geometry comes from. (This means that his goal extends beyond the needs of design to the needs of engineering in general. The utilitarian needs of design may not require the wheels of basic engineering to be reinvented every day.)

A demonstration system (see below) suggested how such deep knowledge might be able to find out behaviors or consequences of a design that the designer had not thought of. This would be a powerful and useful capability. To begin this effort, he put five students to work last year defining all the engineering knowledge chunks they could think of. The result was 3000 chunks. These describe phenomena in hierarchical classes. Under "movement" one finds rotational, straight, oscillating, accelerating, and so on. For each one there is a capsule description using qualitative terms like accelerating, plus, connected_to, and so on.

A moment is described in terms of two objects, one of which exerts a force on the other from a distance; if the moment is applied by one object, the other rotates. Coils and magnets can exert forces. Shafts connected to bearings can rotate. When current passes through a coil, it acts like a magnet. It also gets hot. Things that get too hot can melt. An inference engine browses through a model constructed of such chunks and finds out if the conditions for rotation are satisfied: there is an object containing a coil that can rotate, there is another object that contains a magnet, there is a source of current to the coil, the resulting force can exert a moment, etc.

Qualitative physics sits at the top (currently) of a hierarchy below which are "confluence-based QP" and "Qualitative Simulation." QS comprises a qualitative description of the relationships between variables in equations. Typical output consists of conclusions like "if voltage A increases, current B will decrease." It has been applied by other researchers for at least 15 years to fault diagnosis of chemical plants and is used in the self-maintenance copier described below. C-B QP takes a topological description of a designed object and seeks to derive a qualitative equation description, upon which QS can operate. QP allegedly can generate the topology, but I think the designer currently must input nearly all the information from which the topology is derived. This topology comprises both the physical arrangement of objects and that of the physical principles underlying the object's behavior.

A quantitative version of all this has existed for about 30 years in the form of "Bond Graphs." Bond graphs model the energy flows between fairly general discrete elements like energy storers, transformers, and dissipaters. These elements can actually be electrical, thermal, fluid, or mechanical in underlying nature. The designer supplies the topology, which consists of mapping the energy flows. The equations can be derived algorithmically and are quantitative. The origin of this method is dynamical analogies, discovered when it was shown that the differential equations for many engineering systems had the same form.

Two objections can be raised to the bond graph approach. First, it cannot be reasoned about by existing AI systems. Second, it cannot easily handle logical state changes, such as that once a wire melts, the coil will not conduct electricity any more. This capability is important if one wants to capture the failure modes of a design, especially the unanticipated ones. In addition, some systems undergo logical state changes that are not failures but are merely different normal behaviors. The copier in our office senses the position of the input paper guides, decides which way the original is oriented, and selects the correct paper tray.

Tomiyama feels that these are not drawbacks but merely reflect the fact that Bond Graphs are meant only to model energy flows and fail to represent other aspects of physics that designers must take into account.

I was shown a demo of a QP system for modeling simple discrete physical systems - the same kind that bond graphs model. [Kiriyama, et al] The item modeled is a simple one-, two-, or three-pole motor comprising a shaft on bearings carrying the coils (poles), wiring of the coils to a commutator, and two permanent magnets. Facts about magnetic attraction, moments, rotation, state change of the commutator, and rotary acceleration caused by torque are assembled by the designer into a model of the motor, a portion of which appears in Exhibit 1. The computer knows many side effects of these knowledge chunks and constructs its own extended meta-model.

From the meta-model the designer can elicit simulations of all effects or he can request "aspect" views, such as evolution of rotational states or thermal states. Behavior of the rotational model is started from given initial conditions on pole angle and velocity. Some states permit rotation to start and continue. The computer can deduce that cyclic state behavior exists. Other initial states are neutral; the magnets cannot exert any net torque and rotation does not occur. Instead, coil heating occurs. In the thermal model, states progress from cool to hot to melted. Operation of the motor is henceforth impossible regardless of changes in the initial state.

The dead state from which failure ensued is symmetric, a condition that is impossible for a three-pole motor. Dr. Kiriyama admitted that his system does not know the concept of symmetry and in any case could not generate the three- pole design following detection of the two pole design's shortcoming. He said that QP is not good at such generalizations.

Maintenance Theory

The goal here is to understand how to design things so that they can fix themselves, at least to a limited degree. There are two advantages to such products. First, time and effort are saved. Second, the product may be able to fail soft. That is, degraded behavior may be available as a backup even if the failure has eliminated top quality behavior.

Two issues are involved here: how to design things that have backup modes, and how to equip products to diagnose themselves and bring these backup modes into play. The latter has been explored in a self-maintenance copier. Electrical variables are manipulated to compensate for the degradation of electrically driven components. A publication [Umeda et al] discusses gear-driven devices as well, but the opportunities for functional redundancy are likely to be more limited in such cases.

The central idea is self-diagnosis and generation of a repair strategy using QP. A copier in the lab has been augmented by a monitoring computer, a diagnosis computer, four sensors, and three controllers. One of these measures copy density. A QP model of the elements that affect copy density has been built. Degradation of the halogen lamp was simulated and the system proceeded to determine that raising the lamp voltage was a feasible fix.

The method requires the user to put in the QP model, from which the computer can derive a QS. The computer first reasons backwards from the observed sensor readings to determine possible causes, listed as voltages, resistors, and so on. It then assumes that the causes cannot be changed and identifies variables that it can manipulate, as well as the effect these variables would have given what is apparently broken. Among the available choices, some will produce side effects in addition to the desired one. The candidate with the fewest side effects is chosen. See Exhibit 2.

The diagnosis computer recommends a small voltage increase for the lamp, which is implemented automatically through a controller. The test is repeated, as is the recommended fix, until it cannot further improve the copy density. Either the process halts here or the diagnosis computer shifts to a second variable, the main static charger voltage, and tries to gain further improvements. This is actually a simple axis-by-axis search.

Note that all of this could have been accomplished with a quantitative linear model composed of influence coefficients relating controllable and observable variables. This method is well known and widely used in control, simulation, and optimization. The objection is again that logical state changes are not easy to represent, except by altering the coefficient matrix. However, I do not see why that is difficult. Everything that is called "reasoning" above can be accomplished using linear algebra or circuit theory implementations of it.

Multi-axis solutions can also be readily found, such as simultaneously raising one voltage a lot while lowering another one a little. I do not know if QP can do this.

Tomiyama feels that linear algebra approaches cannot handle noisy sensory data, represent portions of a system that are completely broken, or permit traceability of symptoms to causes that are very subtle. He cites Three Mile Island and Chernobyl as examples of systems that failed for lack of suitable reasoning during their design. [However, the fact that Chernobyl-type reactors are inherently unstable at low power is well known and was known when it was built.]

Comment

Qualitative models appear to have many advantages, among them being the ability to represent important behavior patterns with relatively simple models. However, it remains to be seen whether they can ever attain the sophistication and complexity of well-developed quantitative models, such as those exhibited by the automobile companies for simulating crashes, skids, and air flow. Prof. Tomiyama feels that QP not only can coexist with quantitative models but has the potential to model types of phenomena that cannot be represented in traditional models. My feeling is that augmenting quantitative models with logical state variables could increase their generality and a meeting ground in the middle might be found.

References

[Kiriyama et al] Kiriyama, T., Tomiyama, T., and Yoshikawa, H., "Model Generation in Design," Fifth International Workshop on Qualitative Reasoning about Physical Systems, 1991, pp. 93-108.

[Umeda et al] Umeda, Y., Tomiyama, T., and Yoshikawa, H., "A Design Methodology for a Self-Maintenance Machine," in L. A. Stauffer (ed.) Design Theory and Methodology - DTM '91-, Vol. DE-31, published by the ASME, pp. 143-150.