Mapping Multi-Disciplinary Design Processes

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This paper describes research in progress whose goal is to synthesize design methodologies for rapid product development in multi-disciplinary design situations. The potential outcome is superior design methodologies that facilitate integration and collaboration between different disciplines, conduct design tasks concurrently, and apply to a wide range of design problems, thus reducing costs and time-to-market.

The approach is based on simulating the design process using a multi-agent system that mimics the behavior of the design team. The multi-agent system activates the pieces of design knowledge when they become applicable. The use of knowledge by agents is recorded by tracing the steps that the agents have taken during a design project. Many traces are generated by solving a large number of design projects that differ in their requirements. A set of design methodologies is constructed by using clustering and abstraction techniques to generalize the traces generated. These methodologies then can be used to guide design teams through future design projects.

1. Introduction

The general scope of this research is the multi-disciplinary design of engineered systems. This work extends the concept of analysis-by-simulation to the area of engineering design research. Analyzing the behavior of physical systems in engineering applications by computer simulation using mathematical models has been a powerful tool in engineering, reducing costs and time in comparison to physical prototyping and experimentation.

In this work the same concept is applied to the design *process* instead of the design product. A computational model in the form of a knowledge-based multi-agent system is built that simulates the design process. By running the simulation under different conditions, and examining the performance, detailed understanding of the design process is gained [12]. As for simulations of physical systems, the computational model of the design process is a simplified one in which the design activities that are usually carried out by humans are performed by software agents in a slightly simplified manner. We have developed these ideas using the multi-disciplinary domain of robot arm design [11].

The current practices of multi-disciplinary design are based on ad-hoc strategies for handling the complexities that multiple points-of-view bring to the design process. These techniques solve the problem of complexity at the expense of giving up the potential advantages of diversity. The common methodologies for multi-disciplinary design are based on compromising between different disciplines rather than collaborating between them. These methodologies do not use a systematic, holistic approach to the problem of multi-disciplinary design and thus these approaches to multi-disciplinary design are not as efficient and effective as they could be.

The most common strategy to overcome the complexities of multi-disciplinary design is sequential design, in which different disciplines take part in the design process sequentially. In sequential design, information sharing between different disciplines is limited to the interfaces between disciplines [8]. As a result, conflicts between disciplines are not discovered until they are very expensive to resolve, because their resolution may need to destroy the partial designs generated by the previous discipline.

"In sequential design, a tentative design synthesis is developed by one designer, often acknowledged as the *lead discipline* designer, which address some of the key performance specifications and constraints for the artifact" [8]. Having a lead discipline that makes some of the key decisions reduces the number of conflicts. The other disciplines conform to the decisions made by the lead discipline. However, that may prevent them from producing their best solutions. In a lead-discipline approach a single point-of-view dominates the decision making process and therefore constraints from that discipline are favored. This produces a lower quality design product and increases the number of iterations required to reach an answer.

2. Simulation of the Design Process

We have proposed a new approach to the problem of producing better design methodologies for multi-disciplinary design based on the integration of different disciplines. The discipline-sequential approach, while poor, is quite simple. Integration tends to make the design process more complicated. To overcome this complexity, a computer system is developed based on a multi-agent systems paradigm in order to automate the simulation of the design process.

The system simulates examples of multi-disciplinary design processes while applying integration principles to the problem. These include common design knowledge representation schemes and common communication mechanisms; design knowledge sharing among participants; cooperative problem-solving strategies among participants; simultaneous design process where possible; and comprehensive mechanisms for conflict discovery and resolution.

The large chunks of discipline-specific knowledge are broken into small pieces and are represented in the system by agents. Agent activation is triggered in an opportunistic manner and is unaffected by discipline boundaries. Agents might participate sequentially or in parallel.

The traces of the agent activations (i.e., knowledge use) during the course of the design process are recorded. The recorded traces consist of orderly patterns of different design tasks that have led to the solution. Some candidate design methodologies are extracted by generalizing the patterns using clustering and inductive learning techniques. Some of these candidates will be reinforced by solving more examples and accepted as design methodologies for that particular class of problems.

A design methodology is a scheme for organizing reasoning steps and domain knowledge to construct a solution. It provides both a conceptual framework for organizing design knowledge and a strategy for applying that knowledge [13]. A design methodology can provide the knowledge for decomposing the problem into sub-problems, synthesizing partial designs, evaluating and then combining them into more complete partial designs, ordering design tasks by considering proposals from all participants, and discovering and resolving conflicts. Figure 1 shows one of the methodologies generated by the system for robot design.

IF

- constraints on deflection and the gain are both tight, and
- requirements on workload is rather “easy”;
- workspace is of type “small-M”;

THEN

- **choose** the location of the base of the robot: “left or below of the workspace length”
- **choose** the material: “steel stainless AISI 302 annealed”
- **select** the shape of the cross section of the link: “hollow round”
- **choose** the structural safety factor: “3”
    - **do** the design and proceed to the next step
- **choose** the link 2 to link 1 length ratio: “0.5”
    - **do** the design and proceed to the next step
- **pick** the configuration of the arm: “left-handed”
- **select** the ratio of section dimension to min required: “4”—if it fails select “3”
    - **do** the design and proceed to the next step
- **find** the accessible region: use Equation 2-4
- **find** the deflection of the tip: use Equation 2-14
- **choose** the type of controller: “PD”
    - **do** the design and finish the process.

FIGURE 1. A Methodology Discovered

3. Related Research

Recently there has been increasing recognition that multi-disciplinary design is important. A large amount of very good research has been focused on Multi-disciplinary Design Optimization (MDO) [14]. MDO tries to produce an effective product by recognizing and using appropriate combinations of parameters to be controlled and optimized by the designer. A key part of the process is the use of decompositions (see the discussion of decomposition in [14]) [3] [9].

In multi-disciplinary design problems the values of design parameters may determine what design method will be employed, as methods may have applicability conditions. As different design methods may introduce different dependencies, dependency chains, and potentially problem decompositions, can be dynamically determined. Hence the sequencing of design tasks can also be dynamically determined. Some approaches provide some user interaction to help determine what task sequence will be used [5] [4] [17]. However, while Multi-disciplinary Design problems often require the user's investigation of design trade-offs, for each problem and related set of requirements, there are a number of common design task sequences that are used. Such sequences form the basis of a design methodology for that problem or class of problems.

Our work requires that the results of the discovery process be well integrated and concurrent. Fine-grained tasks are needed, as opposed to the large grained tasks used by some research [4] [16]. Our agent-based approach can accommodate qualitative, experiential, and heuristic knowledge. Lander [6] provides a detailed review, while other work on multi-agent Systems in Concurrent Engineering is reported in [1].

The use of Machine Learning methods in support of design has been well documented [2]. While the use of Case-Based Reasoning (CBR) and inductively formed user (i.e., designer) models is becoming familiar, our method for generalizing design traces is not. Depending on what is included in the design traces, and its representation, we can take advantage of work on clustering and on induced finite-state transition networks, inductive learning for state-space search, or flexible macro-operators [7, pp. 258, 304, 348].

4. The System and the Results

A knowledge-based model of design is adopted in order to implement the proposed strategies for integration. To implement the proposed model a knowledge-based design tool based on a multi-agent architecture is developed that simulates the design process. The multi-agent paradigm intuitively captures the concept of deep, modular expertise that is at the heart of knowledge-based design [6].

An agent as a self-contained problem solving system capable of autonomous, reactive, pro-active, social behavior is a powerful abstraction tool for managing the complexity of software systems [15]. A multi-agent system is composed of multiple interacting agents, where each agent is a coarse-grained computational system. Agents are used as an abstraction tool for conceptualizing, designing, and implementing the knowledge-based design approach.

A Java-based computer program called RD (Robot Designer) has been implemented for parametric design of a two degrees of freedom (2-DOF) planar robot arm. We used RD to solve a set of 960 design projects. Figure 2 shows how many projects followed a specific trace. The promising results is that the distribution of the traces is quite scattered—that is, many projects followed similar traces. The total number of possible traces is the product of the number of design approaches of all the designer agents. For the experiments shown in Figure 2 the total number of possible traces is 2304. Among all 2304 possible traces only 84 were followed to generate successful designs, i.e., less than 4%.

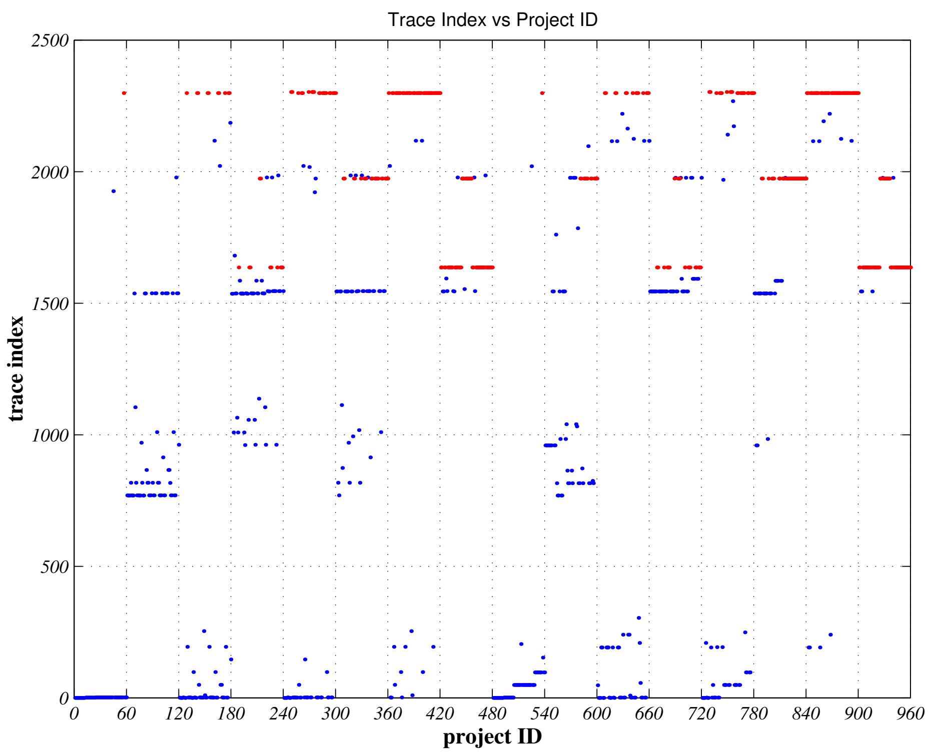

FIGURE 2. Distribution of Traces versus Projects

The low percentage of successful traces indicates that for each group of projects that followed a particular trace there is a unique combination of approaches leading to successful designs, hence there is a high chance that if similar projects follow the same trace they will succeed in generating a successful designs. As a result, the path followed by those projects can lead us to formulating a design methodology for the projects that followed that trace as well as projects that are similar to those projects.

The traces in the set of successful traces that are close enough can be clustered together to form a generalized trace. A generalized trace covers all the projects that followed each of the traces incorporated in the generalized trace. Design methodologies are formulated by extracting the correlation between a generalized trace and the design projects that followed that trace. The sample design methodology that is shown in Figure 1 is the English translation of the correlation between design projects and the corresponding traces.

5. Importance of this Research

Using system-developed methodologies allows effective and efficient practices to be used from the start of a project instead of being learned from experience. These new methodologies are radically different from the sequential, discipline-based ones. They also reduce time-to-market and save resources. To be able to compete in today's global market, companies need continuous improvements in product quality and improvements to the performance of their design and manufacturing processes. Integration reduces the number of failures and backtracking by facilitating information sharing, thus saving resources and reducing design time. Integration also provides collaboration between different participants that, as a result, enhances the quality of the design.

Agent-based systems allow the incorporation of new technologies systematically and quickly through the addition or deletion of agents. Thus new knowledge can be added, and old knowledge removed rapidly. Running the system with the new set of agents will result in new traces and thus new and different methodologies. In addition, design processes can be biased toward more environmentally friendly products, as the alternative methods that are built into each agent are tried in a preferential order, and as each method tends to contribute differently towards the final properties of the design.

The research attacks the problem of integration in multi-disciplinary design. The number of specialists is increasing, while the number of generalists, capable of doing system integration, is decreasing. Also the knowledge burden on the designer keeps increasing due to more materials and more options [10]. Thus it is becoming harder to develop methodologies for the integration of multiple disciplines in design. An increasingly specialized technological environment tends to force designers to concentrate on some disciplines more than others. This research allows designers to see the whole design problem.

Computers have mostly been used to support the manipulation and analysis of design product information. This work focuses on the design process, an aspect that has not benefited from computers very much. It applies computers to new areas of engineering design by incorporating new software methods. Simulation of design processes based on a multi-agent paradigm is a new area of research that has a high potential for practical as well as theoretical impact on the design of products. This research has produced convincing, preliminary results. The use of multi-agent systems technology is growing rapidly with the development of Java-based systems and agent access across the world-wide web.

The research incorporates judgement and experience. "System integration, many consider, is an ill-structured problem... No specific rules have to be followed when doing integration... Experienced designers deal with system integration using judgement and experience. Knowledge-based programming technology offers a methodology to tackle these ill-structured integration and design problems” [13].

This work benefits from inter-disciplinary contribution from the state-of-the-art in both Artificial Intelligence and Engineering Design. According to NSF’s report on Research Opportunities in Engineering Design [10], “research areas that will have greatest impact on engineering design over the next 10 years are: Collaborative Design Tools and Techniques, Perspective Models/Methods, System Integration Infrastructure/Tools, and Design Information Support Systems”. This work covers all of these areas of research and hence is expected to have a strong impact.

6. Conclusions

The potential applications of this research are in multi-disciplinary design situations, such as those that occur throughout the automotive industries, where large gains can be achieved with integrated methodologies. In addition, current methodologies can be analyzed for flaws and bottlenecks, and necessary refinements made. New methodologies can be customized so that they are biased toward specific objectives such as manufacturability or being environmentally friendly. By applying this approach the response time for the incorporation of new technologies in design processes will be reduced. Methodologies can be refined as soon as a change occurs in the market or in the organization of the company.

This research has proven that the following hypothesis is true: *Computers can provide us with better ways of doing design by discovering superior design methodologies that integrate different points-of-view of multiple disciplines in the design process.* It has been shown that it is possible to use the computers to simulate the design process. We can then analyze the results of the simulation to synthesize design methodologies that have superior features. The approach that we have proposed has been developed based on parametric design problems. Applicability of the approach to other types of problems needs to be investigated.

7. References

[1] BROWN, D. C., S. E. LANDER & C. J. PETRIE, “The Application of Multi-agent Systems to Concurrent Engineering”, Editorial: *Concurrent Engineering: Research and Applications*, Technomic Publ., V.4, N.1, (March 1996), pp. 2-5.

[2] DUFFY, A. H. B., “The ‘What’ and ‘How’ of Learning in Design”, *IEEE Expert: Intelligent Systems & Their Applications*, Vol. 12, No. 3, (May-June 1997), pp. 71-76

[3] GEBALA, D. G. and S. D. EPPINGER, “Methods for Analyzing Design Procedures”, *Proceeding of ASME Design Theory and Methodology Conference: DTM’91*, ASME DE-Vol. 31, (1991), pp. 227-233.

[4] HALE, M., J. I. CRAIG, F. MISTREE, D. P. SCHRAGE, “DREAMS and IMAGE: A Model and Computer Implementation for Concurrent, Life-Cycle Design of Complex Systems”,

Concurrent Engineering: Research and Applications, Vol. 4, No. 2, (June 1996), pp. 171-186.

[5] KROO, I. and M. TAKAI, "Aircraft Design Optimization Using a Quasi-Procedural Method and Expert System", *Multidisciplinary Design and Optimization Symposium*, (Nov. 1990).

[6] LANDER, S., "Issues in Multi-agent Design Systems", *IEEE Expert: Intelligent Systems and their Applications*, (March-April 1997), Vol. 12, No. 2, pp. 18-26.

[7] LANGLEY, P., *Elements of Machine Learning*, Morgan Kaufmann, Inc., (1996).

[8] LEVITT, R. E., Y. JIN, and C. L. DYM, "Knowledge-Based Support for Management of Concurrent, Multidisciplinary Design", *AI EDAM*, Academic Press Ltd., Vol. 5, No. 2, (1991), pp. 77-95.

[9] LIU, J., and D. C. BROWN, "Generating Design Decomposition Knowledge for Parametric Design Problems", *AID-94: Artificial Intelligence in Design'94*, (Eds.) Gero & Sudweeks, Kluwer Academic Publ., (1994), pp. 661-678.

[10] NATIONAL SCIENCE FOUNDATION, *Research Opportunities in Engineering Design*, NSF Workshop Final Report, (April 1996).

[11] RIVIN, E. I., *Mechanical Design of Robots*, McGraw-Hill Book Company, (1988).

[12] SHAKERI, C., D. C. BROWN, and M. N. NOORI, "Discovering Methodologies for Integrated Product Design", *Proceedings of 1998 AI & Manufacturing Workshop: State of the Art and State of Practice*, (Aug. 31-Sept. 2, 1998), Albuquerque, NM, pp. 169-176.

[13] SOBOLEWSKI, M., "Multiagent Knowledge-Based Environment for Concurrent Engineering Applications", *Concurrent Engineering: Research and Applications*, Technomic Publ., V.4, N.1, (March 1996), pp. 89-97.

[14] SOBIESZCZANSKI-SOBIESKI, J. and R. T. HAFTKA, "Multidisciplinary Aerospace Design Optimization: Survey of Recent Developments", *34th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, AIAA Paper No. 96-0711, (January 15-18, 1996), pp. 32.

[15] WOOLDRIDGE, M., "Agent-based software engineering", *IEEE Transactions on Software Engineering*, (1997), 144(1): 26-37.

[16] WOYAK, S., B. MALONE, and A. MYKLEBUST, "An Architecture for Creating Engineering Applications: The Dynamic Integration System", *Proceeding of ASME Computers in Engineering Conf.*, Boston, MA, (September 1995).

[17] WUJEK, B. A., J. E. RENAUD, S. M. BATILL, and J. B. BROCKMAN, "Concurrent Subspace Optimization Using Design Variable Sharing in a Distributed Computing Environment", *Concurrent Engineering: Research and Applications*, Vol. 4, No. 4, (December 1996), pp. 361-377.