A Taxonomy for Mechanical Design

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Abstract. This paper presents a taxonomy that provides a basis for characterizing mechanical design methods and theories. The taxonomy has three primary divisions: the environment, the problem, and the process. Each of these factors is further subdivided into its important characteristics. For example, the process is divided into plan, processing action, effect, and failure action. This paper discusses the options for each characteristic. An overview of the proposed taxonomy is given in section 2 of this paper. Section 3 describes details of the design environment; section 4 gives details on the description of the design problem itself; and section 5 provides details on the design process. In section 6, the taxonomy is applied in two ways: it is first used to clarify the meaning of differing, commonly used design terms, such as selection design, configurational design, parametric design, and redesign; and, second, the taxonomy is used to classify a representative sample of design process research efforts.

1 Introduction

Over the last several years, mechanical design has been an active area of research. In large part, this activity has been motivated by the perceived lack of efficiency and quality of products designed in America compared to those designed in Japan and Europe. The research has been diverse—including the development of domain-specific computer codes using AI techniques, the commercialization of parametric design tools, and the modeling of the cognitive design process. As research results have been published, it has become obvious that the term "design" has different meanings to different researchers. The field is now mature enough to allow techniques and results to be classified, compared, and contrasted; however, these comparisons are difficult because the field lacks a commonly accepted description of design methods, types, and theories. There is a need for a taxonomy to charac-

terize the mechanical design process and the research that accompanies it.

Traditionally, the mechanical design process is divided into stages based on the requirements of project management. This division is usually some variation along the lines of problem definition, conceptual design, layout design, detail design, and manufacturing design. Unfortunately, this taxonomy provides little information on what is being accomplished in each stage of design or on who or what is performing the design. In fact, research by Hales [6] and by Ullman [17] has shown that it is not possible to follow a design in progress using these stages.

Taxonomies for mechanical designs and artifacts can be found in both the European literature (Hubka [7], Pahl and Beitz [11], VDI-2221 [18]) and the American literature (Dixon [4]). In these efforts, the state of refinement of the object being designed is identified and described; however, an understanding of mechanical design requires more than a classification of the object. In reviewing the recent literature it is evident that, to classify design techniques, a taxonomy must include not only information about the object but also information on the design environment and the design process. Like Dixon's work, this paper can be seen as an attempt to classify an evolving field; thus, this paper represents an interim step that will be refined further as our understanding of design matures.

Section 2 of this paper gives an overview of the proposed taxonomy; section 3 describes details of the design environment; section 4 gives details on the description of the design problem itself; and section 5 provides details on the design process. In section 6, the taxonomy is applied in two ways: it is first used to clarify the meaning of differing, commonly used design terms, such as selection design, configurational design, parametric design, and redesign; and, second, the taxonomy is used to classify a representative sample of design process research efforts.

ENVIRONMENT	PARTICIPANTS		1.
	CHARACTERISTICS		2.
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4.
		REPRESENTATION	5.
	FINAL STATE	REFINEMENT LEVEL	6.
		REPRESENTATION	7.
	SATISFACTION CRITERIA		8.
PROCESS	PLAN		9.
	PROCESSING ACTION		10.
	EFFECT		11.
	FAILURE ACTION		12.

Fig. 1. Taxonomy form.

2 An Overview of a Design Taxonomy

To characterize mechanical design, three factors must be described:

* The *environment* in which the design occurs, including *who* is performing the design—their characteristics and the constraints on them.
* The *problem* being solved, as evidenced by *what* the initial and final states are.
* The *process* itself, that is, *how* changes from the initial to the final state occur.

To be useful for classifying mechanical design, these factors must be refined into a more detailed classification scheme. The refined scheme is shown in Figs. 1 (as a table) and 2 (as a tree). When complete, the slots in Fig. 1 describe a specific design method or tool. The tree shown in Fig. 2 presents

the options for filling the slots in Fig. 1. The following sections present the rationale for these slots and options.

3 The Design Environment

As shown in Figs. 1 and 2, three characteristics of the design environment must be classified to provide a complete descriptions: the participants in the design process (item 1 in the taxonomy); their characteristics (item 2); and their resources (item 3).

In reviewing current research and design tools, many categories of potential design participants can be identified (e.g., a sole designer, a group of designers, CAD, etc.). The options, as given in Fig. 3, provide the information necessary to classify the participants for most design methods and theories. As the field progresses, other, less common design participants may need to be added.

Methods for use by *individual designers* solving a design problem can be found in Jones [9]. Much of the recent work on single designers focuses on understanding how a designer performs as a basis for improving the design process (see, for example, Ullman, Stauffer, and Dietterich [14, 17] and Waldron and Waldron [19]). The model presented in [17] is used as an example in section 6 of this paper.

Techniques for *groups of designers* can be found in Jones [9] and VDI-2221 [18]. Recently, researchers have begun to look at design as a group activity. Some of these research efforts use video techniques to study the design environment (Tang [16] and
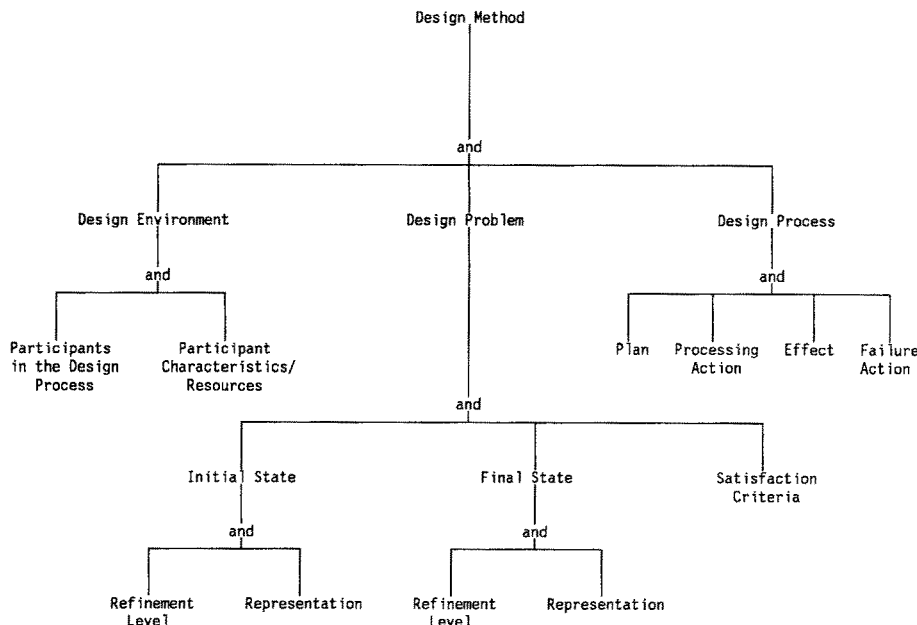
Fig. 2. Top level of taxonomy.
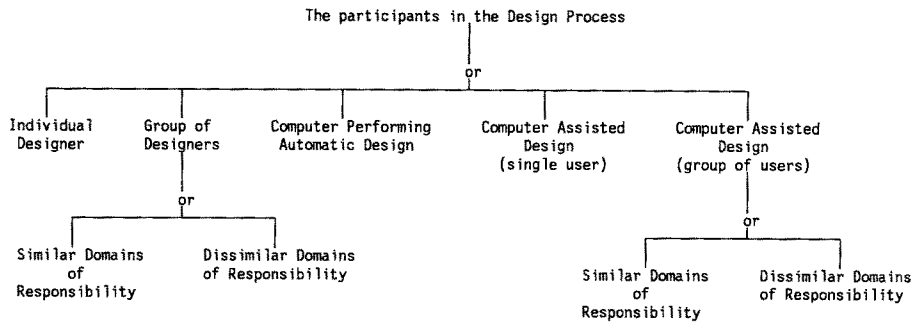
The participants in the Design Process

Fig. 3. Potential options for participants in the design process.

Waldron and Waldron [19]), while others rely on sociological or ethnomethodological techniques (Bucciarelli [2]).

Group design efforts can be differentiated into two subclasses. In groups with similar domains of responsibility, all the participants work on the same project from a similar point of view (e.g., airframe designers may all work on designing similar components of new aircraft subassembly).

In contrast to these homogeneous groups are groups in which individuals have dissimilar domains of responsibility and each member represents a different view (e.g., design, manufacturing, maintenance, etc.). To date, there has been little or no research studying the different types of interactions in homogeneous and inhomogeneous groups.

Many design research efforts focus on *computer-automated design* of a limited design problem. In these batch systems, initial state data is given to the computer and the resulting final state is output without human interaction. Typical among these programs are some expert systems and many optimization techniques. Straight analysis tools and mechanical testing are not included in this discussion as they, by themselves, do not make design decisions.

Many computer-based design systems require human intervention to make decisions. These *computer-assisted design* systems have the added burden of requiring interactive interfaces between the human users and the computer. As shown in Fig. 3, human-computer systems can be classified in the same way as the human-only systems. There are many examples of single-user systems (Brown and Chandrasekaran [1] and Pahl and Beitz [11]), but the only published information on a multi-user system is on Xerox's COLAB [20]. COLAB allows multiple users to share the same data and to collaborate to solve a problem. It is debatable whether COLAB should be classified as computer-assisted design or as a "group of designers," since the computer provides a means of communication and all the design decisions are made externally.

Little work has been done in characterizing the characteristics and resources of design participants. Waldron and Waldron [19] have shown that experts chunk data along functional lines more than novices do. Expertise is a combination of knowledge about the processing techniques and knowledge about heuristics and analytical methods; however, we do not know of any research on characterizing design expertise nor do we know of any on the effects of personality and culture problem-solving strategies.

Another measure that characterizes human designers is their *job responsibility*. Members of a design team may represent many different points of view (i.e., materials, manufacturing, reliability, maintenance, etc.) and thus, the behavior of each may be influenced accordingly.

The characterization of the computer's role in the design process depends primarily on the information flow between the computer and the human. The available computational power is also important for automatic and assisted design. In design, the information flow depends on the interactivity capabilities, the graphical capabilities, and the computing power.

The resources important to the design environment can be categorized as other equipment and/or organizational and management factors. Equipment factors may include video media, such as that used in Xerox's COLAB [20], or special worksheets for performing part of the design. Organizational and management factors may include the organizational support of the design process in terms of technicians, working conditions, development of design teams, library facilities, etc. Other management factors include management style, demand for rapid results, requirements for paper work, etc.

Figure 4 summarizes the characteristics of participants and resources in the design process.

4 The Design Problem

Mechanical design is the problem-solving process that transforms an abstract stated need into a prod-

Participant Characteristics/Resources

and/or (as warranted)

Human Characteristics   Computer Characteristics   Resources

and/or

Domain   Personality   Job
Expertise   Measures   Responsibility

and/or   and/or   and/or

and/or   and/or   Interactivity   Graphical   Computing   Other   Organizational/
                                Capabilities   Capabilities Power   Equipment   Management
Procedural Heuristic Analytic Thinking Cultural   Factors
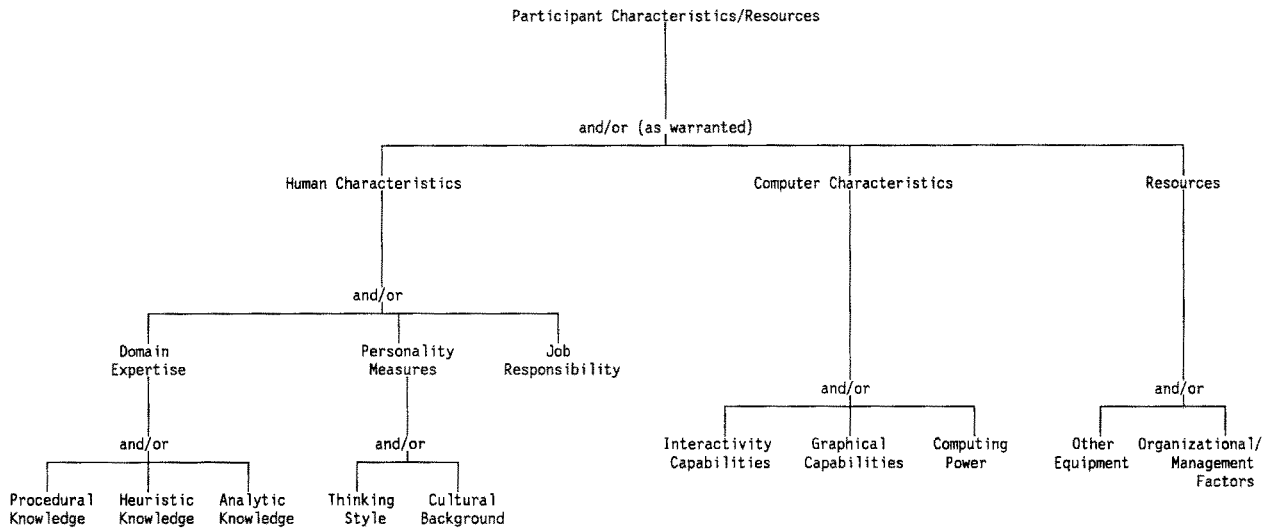Knowledge   Knowledge Knowledge Style   Background

Fig. 4. Options for participant characteristics and resources.

uct. However, no currently available design tools or methods begin with abstract-stated needs to produce a product. Each design tool or method solves some subproblem (i.e., only one part of the total design problem). It is important to characterize the subproblem being solved for each method or tool. Here, as in Dixon et al. [4], Jones [9], and VDI-2221 [18], the *design problem* will be characterized by the design's initial and final states, its refinement level, and its representation language. Options for these refinement levels are presented in Fig. 5.

The following definitions for the refinement levels are taken from Dixon et al. [4], with some modification:

• *Perceived needs:* The perceived needs are the conditions or problems that provide the motiva-

tion for design. This is the most abstract level of the design. Not all design problems begin here, as many have more refined initial states (e.g., concept or artifact type).

• *Specifications:* A specification is a design requirement or goal, based on the perceived need. Although many of the specifications are for functional performance, others relate spatial constraints, manufacturing and/or material requirements, code and standard requirements, and sociopolitical issues.

• *Function:* A function is the most specific statement of the need that still does not refer to a particular physical phenomena or conceptual form. A clear definition of product function is often impossible because function is hopelessly intertwined with artifacts. Function is what the design must
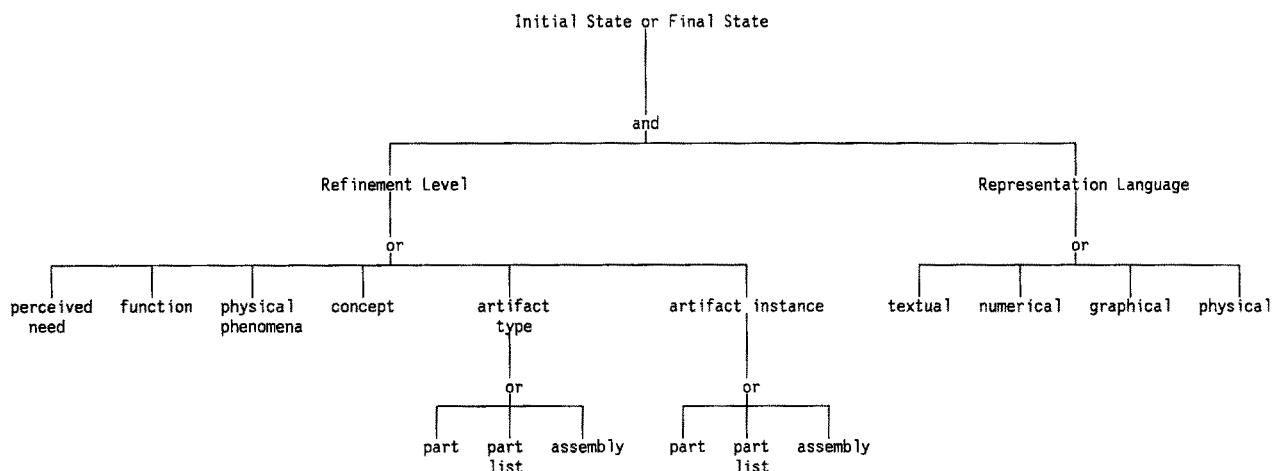
Initial State or Final State

and

Refinement Level   Representation Language

or   or

perceived function physical   concept   artifact   artifact instance   textual numerical graphical physical
need   phenomena   type

or   or

part part   assembly   part part   assembly
      list   list

Fig. 5. Options for initial and final design state.

do to meet the needs with no reference as to how to accomplish it. Many functional representations for a design may exist for a given set of needs.

- *Physical phenomena:* A physical principle can be used to fulfill a function without reference to any specific concept. In Pahl and Beitz [11] and VDI-2221 [18], this is called the working principle.
- *Concept:* A concept, or embodiment, is the generalized physical form that fulfills the function. Concepts are the most abstract physical forms considered.
- *Artifact type:* An artifact type is a concept with defined features (or with defined feature parameters) without specific values assigned to the features or parameters.
- *Artifact instance:* An artifact instance is an artifact type with values specified for all parameters.

Within both artifact type and artifact instance, finer classifications can be made. Specifically, many design process schemes are directed at the design of a single part, while others deal with the selection of parts from a list, and still others deal with assemblies. Thus, it may be important to further classify the artifact's characteristics. Many examples of using this classification scheme are given in Pahl and Beitz [11], VDI-2221 [18], and Dixon et al. [4]. For completeness, a simple example follows:

Perceived need: Move air

  Function: Convert electrical energy to mechanical energy (one of many functions)

Physical phenomena: Ohm's law, Helmholtz's law, etc.

  Concept: A motor and a fan blade assembly (for one part of the concept)

  Artifact type: Can induction motor

  Artifact instance: Granger catalog number A504985C

Many of these levels of refinement are not used in actual problem-solving due to the existence of domain knowledge. Here, an air-moving system may be virtually equivalent to a specific type of fan in which the above motor is a component. Additionally, as discussed in section 6, many techniques do not refine the design to a new level.

Another aspect of the initial and final states is their representation language. The initial state in many design processes is represented differently from the final state. In an ideal design tool, the initial textual statement of the perceived need would result in final designs composed of hardware artifact instances.
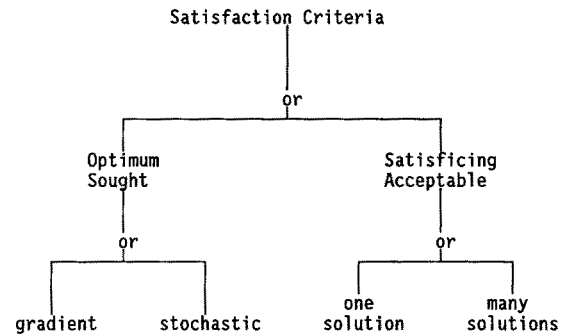

Fig. 6. Options for design problem satisfaction criteria.

Knowing the level of refinement and representation language of the initial and final states does not fully define the design problem. Many different solutions could meet the final conditions; it is important to know what satisfaction criteria are to be used and to know when the final state has been reached. Possible satisfaction criteria are given in Fig. 6. In many design processes, the *optimum* solution is sought, for example, Papalambros [12] and Johnson [8]. Traditionally, gradient optimization schemes have been used to find the optimal solutions. Recently, stochastic methods, often called *robust methods*, have been used in mechanical design, for example, Taguchi [15].

Design methods that consider suboptimal solutions to satisfy the goals are less restrictive than formal optimization schemes. This *satisficing* is the methodology of human designers studied by Ullman et al. [17]. When using satisficing techniques, the issue of the number of solutions required must be addressed; this could arguably also be part of the optimum classification. Often only one solution is needed, but some techniques have as their goal the generation of many, alternative solutions.

5 The Design Process

An appropriate taxonomy for the design process is still emerging because design process understanding and design-processing techniques are both areas of intense research. This taxonomy will continue to evolve as the research matures; however, four essential components are clearly needed to characterize the design process: the *plan*, the *processing action*, the effect, and a *failure action*. Options for these are shown in Fig. 7.

5.1 Plans

The *plan*, or control strategy, for how the design process is to proceed is the focus of many computa-
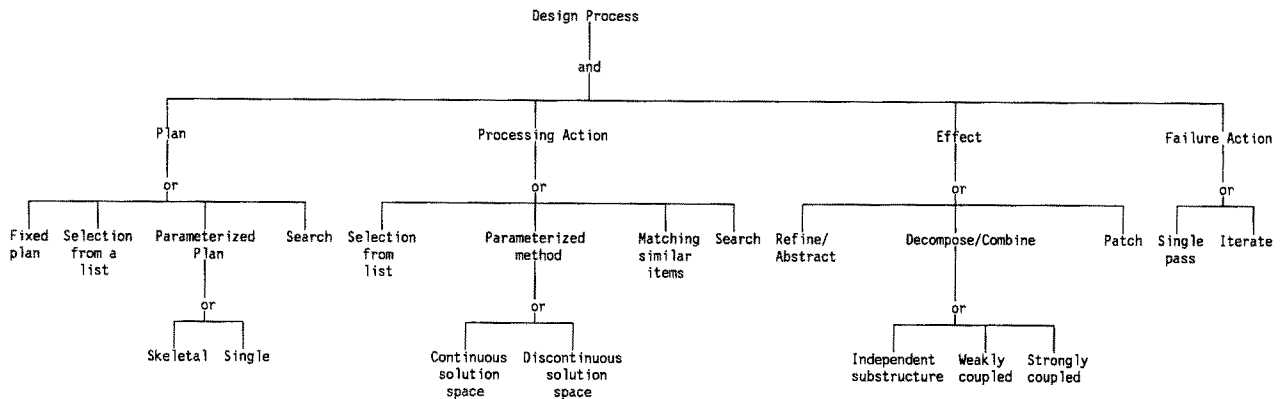
Fig. 7. Options for the design process.

tional design tools. Not enough is known now to create a full taxonomy of mechanical design plans; however, a review of the literature shows four major categories:

- A *fixed plan* implies that the design steps are cookbook oriented. These types of plans are known for well-understood design domains, such as belt and chain selection [5].
- It may also be possible to *select from a list* of plans. Human designers seem to have a number of plans or strategies at their disposal. They choose a plan depending on their domain knowledge [17].
- More sophisticated planning occurs when plans are *parameterized*. Parameterized plans may be skeletal plans (i.e., specific major steps defined but details supplied by the designer) or a single plan with a control strategy based on the values of the design parameters.
- Finally, if no parametric plans exist, then *search* must be used. Search methods can be broken down into weak methods, means-ends analysis, etc., but for our purposes, they are grouped under a single heading.

5.2 Processing Actions

Once a plan is generated, it must be executed using a processing action. The options for the processing action are almost the same as those for the plan:

- *Selection from a list* implies a list from which potential design solutions can be chosen (i.e., the space of design possibilities is known prior to initiating the problem solution).
- With *parameterized methods*, the problems can be represented as a set of equations to be solved. The solution depends on the value of parameters that describe the initial state of the problem. Parameterized methods are typical for the design of

well-understood design domains, such as most machine elements design (Juvinall [10] and Shigley and Mitchell [13]), pump and heat exchanger design [20], and piping design. In the taxonomy of parameterized processing actions, a division is made between continuous and discontinuous solution spaces. Many design techniques, that are successful in continuous solution spaces, fail at discontinuities, and many design problems require investigation over these discontinuities.

- *Matching of similar items* is a form of search but is considered separately because of the strong interest in design by analogy and the importance of this form of problem-solving observed in human designers [1].
- Finally, there is *search*. Again, we leave search as a single undivided category.

5.3 Effects

We have identified three different effects that design processes can have on the design: *refinement, decomposition,* and *patching.*

The primary goal of many design processes is to *refine* the design (i.e. to change the design's state so that the final state is more detailed than the initial state). This does not necessarily mean moving from one refinement level to another (see section 4), as the design can be further refined without progressing to a new level. Conversely, the process may be to abstract the design and to generalize some aspect of it. This is usually associated with learning and is an integral part of the design process.

A second effect of the design process is to *decompose* or *combine* some aspect of the design problem (usually artifacts or functions). This is part of the technique used to solve routine design problems (as discussed in section 6). An important feature of decomposition problems is the coupling of

the subparts. In some design domains the subparts of a design can be broken out, solved independently, and the solutions combined to solve the overall problem. This is not true in many mechanical engineering problems where the ideal would be to functionally decompose the problem, find hardware to satisfy each function, and then to recombine the hardware for the total design. Some research efforts, such as that by Brown and Chandrasekaran [1] are oriented toward weakly coupled problems where the amount of interdependence is small. However, many problems are strongly coupled and, with these types of problems, data management becomes a major problem.

The final effect of the design process may be to *patch* the design. Patching means to change the design in some way, while not actually refining it. For example, if a 1-inch screw is too short, then it might be feasible to try to use a 1.5-inch screw in its place. This is an example of a patch, as both screws are at the same level of refinement. Design is a mixture of refinements and patches [1].

5.4 Failure Actions

The fourth and final component of the design process classification is the failure action. What if the process does not result in a satisfactory result? There are two failure actions possible: to iterate or to completely halt the design process. Specifically, some design methods and tools are only single-pass systems: they produce a single response and any iteration is accomplished externally. Others have an internal logic to iterate toward a more satisfactory solution.

6 Application of the Taxonomy

The previous three sections have presented the taxonomy that is the focus of this paper. In this section, the taxonomy is used to classify a number of design processes. There are two loose groupings of examples here: first, common terms associated with the design process are classified; and, second, we provide some classifications of specific research projects.

6.1 Preliminary or Conceptual Design

The terms "preliminary design" and "conceptual design" are often used interchangeably. Conceptual design can be defined in terms of the design problem alone without reference to the environment or the processes. Figure 8 shows a simple example of the

ENVIRONMENT	PARTICIPANTS		1.
	CHARACTERISTICS		2.
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Perceived need or function
		REPRESENTATION	5. Textual
	FINAL STATE	REFINEMENT LEVEL	6. Concept
		REPRESENTATION	7. Textual or graphical
	SATISFACTION CRITERIA		8.
PROCESS	PLAN		9.
	PROCESSING ACTION		10.
	EFFECT		11.
	FAILURE ACTION		12.

Fig. 8. Conceptual design.

taxonomy's use with the slots for the initial and final states being filled for conceptual design. In Fig. 8, the unfilled slots imply that conceptual design does not require the definition of the environment or the process.

6.2 Layout and Detail Design

Layout design usually begins with a concept and ends with artifact types and instances that form an assembly. Thus, layout can be shown on the taxonomy as a mapping of concept to artifact instance. Similarly, detail design transforms concepts to artifact instances but is focused on specific parts. The taxonomies for these terms are similar to the example above and thus are not shown.

6.3 Selection Design

Selection design is a basic form of design. It encompasses the selection on one (or maybe more) item(s) from a list, such that the chosen item meets certain criteria. The human data on which this example is based is from unpublished observations made as part of the research reported in [17]. In this research, five designers of both men and women with various backgrounds were videotaped performing design from an abstract problem statement to a final, detailed design. In the protocols, the designers used catalogs to select components of materials. It also appeared that each designer had a set plan for how to read through the data to find a satisfactory artifact instance. In terms of the taxonomy, these observations are shown in Fig. 9.

6.4 Parametric Design

The taxonomy developed in this paper can help to classify three different meanings for the term "parametric design." In one sense, as Dixon et al. [4]

ENVIRONMENT	PARTICIPANTS		1. Individual designer
	CHARACTERISTICS		2. Mixed domain experience and sex
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Artifact instance, part list
		REPRESENTATION	5. Textual or graphic
	FINAL STATE	REFINEMENT LEVEL	6. Artifact instance, part
		REPRESENTATION	7. Textual or graphic
	SATISFACTION CRITERIA		8. Satisficing acceptable
PROCESS	PLAN		9. Fixed plan
	PROCESSING ACTION		10. Selection
	EFFECT		11. Refine
	FAILURE ACTION		12. Iterate

Fig. 9. Selection design.

state, the term "parametric" means the design problem of refining an artifact type to a specific artifact. This seems reasonable, as the major difference between type and instance are specific values for the parameters that describe the artifact. However, the term *parametric* can have other meanings, as evidenced by its use in the design process plan and the design process action: it can imply that the plan of how to proceed through the design process itself is parameterized, or that the actual design work accomplished may be parameterized.

Every time engineers use analysis to determine the value of a variable in a design, they are utilizing parameterized actions. Thus, the use of handbook or textbook equations to design a gear (transform from a type of artifact to a specific instance), for example, is the use of a parameterized action in the design process. Note that in the sense that Dixon uses the term, only the fact that there has been a transformation from type to instance is important. However, it may be that there is a parameterized technique for transforming function into artifact types or even needs to some refined forms.

It could also be that the process plan is parameterized, for example, as in the design of a simple gear set. Here, the order in which to design the

gears, shafts, and bearings themselves can be a set of parametric equations. For example, whether to design the shaft next (the next step in the plan) may be a function of the state of knowledge about the gears, bearings, and other components. Thus, if a computer program could perform gear shaft design by automatically utilizing parametric plans and actions to find values for the dimensions of all the components, the taxonomy for it might look like the taxonomy presented in Fig. 10.

6.5 The TEA Model

Research at Oregon State University has focused on designers performing design from initial problem statements to final detailed drawings. The result of this effort has been the Task/Episode Accumulation model (TEA model), which describes the entire design process. This research, a part of which was used in the example above, can be classified as shown in Fig. 11.

6.6 VDI-2221

The German design guideline, VDI-2221 [18] which is referenced throughout this paper, is a prescriptive method for transforming needs to final designs. Its classification is easy using the taxonomy. Consideration of the guideline as a whole is shown in Fig. 12. The VDI-2221 guideline suggests many methods for refining the design. The guideline lists seven stages for transforming the needs to product designs; at each stage, many different techniques for completing the stage are suggested. Thus, the taxonomy can be refined to classify each technique at each stage. For example, the second stage of the design process is to determine functions and their structures. One technique is to first abstract the functional requirements to find the overall function of the device then to decompose the overall function into subfunctions. This decomposition is a

ENVIRONMENT	PARTICIPANTS		1. Computer performing automatic design
	CHARACTERISTICS		2.
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Artifact type, assembly
		REPRESENTATION	5. Numerical
	FINAL STATE	REFINEMENT LEVEL	6. Artifact instance, parts
		REPRESENTATION	7. Numerical or graphical
	SATISFACTION CRITERIA		8. Satisficing acceptable??
PROCESS	PLAN		9. Parameterized, fixed
	PROCESSING ACTION		10. Parameterized, continuous
	EFFECT		11. Refine
	FAILURE ACTION		12. Single pass

Fig. 10. Parametric design.

ENVIRONMENT	PARTICIPANTS		1. Individual designer
	CHARACTERISTICS		2. Mixed domain experience and sex
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Perceived need
		REPRESENTATION	5. Textual
	FINAL STATE	REFINEMENT LEVEL	6. Artifact instance, part
		REPRESENTATION	7. Graphical
	SATISFACTION CRITERIA		8. Satisficing acceptable
PROCESS	PLAN		9. Mixed
	PROCESSING ACTION		10. Mixed
	EFFECT		11. Decompose and refine
	FAILURE ACTION		12. Iterate

Fig. 11. The TEA model.

ENVIRONMENT	PARTICIPANTS		1. Individual designer or group of designers
	CHARACTERISTICS		2. Mixed domain experience and sex
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Perceived need
		REPRESENTATION	5. Textual
	FINAL STATE	REFINEMENT LEVEL	6. Artifact instance, part
		REPRESENTATION	7. Graphical
	SATISFACTION CRITERIA		8. Satisficing acceptable
PROCESS	PLAN		9. Mixed
	PROCESSING ACTION		10. Mixed
	EFFECT		11. Refine
	FAILURE ACTION		12. Iterate

Fig. 12. VDI-2221.

ENVIRONMENT	PARTICIPANTS		1. Computer assisted design: single user
	CHARACTERISTICS		2. Unknown
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Concept
		REPRESENTATION	5. Textual
	FINAL STATE	REFINEMENT LEVEL	6. Artifact instance, assembly
		REPRESENTATION	7. Textual
	SATISFACTION CRITERIA		8. Satisficing acceptable
PROCESS	PLAN		9. Mixed
	PROCESSING ACTION		10. Mixed
	EFFECT		11. Refine
	FAILURE ACTION		12. Iterate

Fig. 14. Routine design, the whole model.

manual search, with a suggested checklist search–processing technique (see Fig. 13). Other techniques for other stages of the guideline can similarly be represented in the taxonomy.

6.7 Routine Design

Brown and Chandrasekaran [1] have developed an expert design system that is oriented toward routine design. Routine design "follows a set of relatively well-established design alternatives which are reasonably well-understood." These design problems begin with knowledge about various component types can be used to create a desired assembly. The overall object to be designed is decomposed into these components. Each component has a "design specialist": a system that knows how to evaluate the specific part. A planner suggests the order in which to evaluate the components. For example, in designing a table (a concept), the table must be refined and decomposed into a structure with a top and a support. The human designer accomplishes this task and a plan is chosen by the computer system. The plan might suggest to design the tabletop

first and then the support; if failure occurs due to constraint violations, the plan iterates back to the top. The human designer may also take part in the control of the iterative activity. Analysis may be required within each specialist, and the results are compared to the existing constraints to determine success and also to produce new constraints for following specialists.

Viewing Brown and Chandrasekaran's model as a whole, the classification scheme appears as in Fig. 14. This classification scheme does help clarify the design problem, but the design process is too complex for this level of dissection to be too revealing. With a finer cut, Brown and Chandrasekaran's method shows two major parts of the methodology. The first is the human's role in the decomposition, and the second is the refinement caused by the computer design specialist. In the human decomposition (as shown in Fig. 15), the human designer generates an assembly of artifact types as a refinement and decomposition of the concept. Often in mechanical design, humans jump from a function or a concept to an assembly of artifacts; this is the case here in transforming from a "table" to a "top" and

ENVIRONMENT	PARTICIPANTS		1. Individual designer or group of designers
	CHARACTERISTICS		2. Mixed domain experience and sex
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Function
		REPRESENTATION	5. Textual
	FINAL STATE	REFINEMENT LEVEL	6. Function
		REPRESENTATION	7. Textual
	SATISFACTION CRITERIA		8. Satisficing acceptable
PROCESS	PLAN		9. Search
	PROCESSING ACTION		10. Search
	EFFECT		11. Decomposition, different levels of coupling
	FAILURE ACTION		12. Iterate

Fig. 13. Decomposition in VDI-2221.

ENVIRONMENT	PARTICIPANTS		1. Individual designer
	CHARACTERISTICS		2. Unknown
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Concept
		REPRESENTATION	5. Textual
	FINAL STATE	REFINEMENT LEVEL	6. Artifact type: assembly
		REPRESENTATION	7. Textual
	SATISFACTION CRITERIA		8. Satisficing acceptable
PROCESS	PLAN		9. Search
	PROCESSING ACTION		10. Matching similar items
	EFFECT		11. Refine and decompose: weakly coupled
	FAILURE ACTION		12. Iterate

Fig. 15. Routine design, human decomposition.

ENVIRONMENT	PARTICIPANTS		1. Computer performing automatic design
	CHARACTERISTICS		2. Unknown
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Artifact type
		REPRESENTATION	5. Textual
	FINAL STATE	REFINEMENT LEVEL	6. Artifact instance
		REPRESENTATION	7. Textual
	SATISFACTION CRITERIA		8. Satisficing acceptable
PROCESS	PLAN		9. Parameterized: template
	PROCESSING ACTION		10. Parameterized method: continuous solution space
	EFFECT		11. Refine
	FAILURE ACTION		12. Iterate

Fig. 16. Routine design, the specialists.

"leg(s)" (there may be one or more). The authors do not make clear the designer's process in arriving at this decomposition and thus guesses have been made in generating the above taxonomy.

The heart of the technique is in the design specialists. The essence of this is caught in Fig. 16. Obviously, the simple list presented in the figure does not take into account all of the method's details. However, it does catch the important points in enough details to allow for comparison to other similar design systems.

6.8 The Cognition System

A number of design tools that act as computer-based assistants have appeared on the market in the last few years. One of the first was Mechanical Advantage, developed by Cognition [3]. This computer tool was originally intended as a conceptual design tool, but it was soon apparent that it was best suited for refining conceptual designs. The Cognition system allowed the creation of dependent drawings and equations, with geometric features in the drawings appearing as variables in the equations. The flow of

ENVIRONMENT	PARTICIPANTS		1. Computer assisted design: single user
	CHARACTERISTICS		2. VAX/IBM-PC or SUN 3
	RESOURCES		3.
PROBLEM	INITIAL STATE	REFINEMENT LEVEL	4. Artifact type
		REPRESENTATION	5. Graphical, textual and numerical
	FINAL STATE	REFINEMENT LEVEL	6. Artifact instance
		REPRESENTATION	7. Graphical, textual and numerical
	SATISFACTION CRITERIA		8. Satisficing acceptable
PROCESS	PLAN		9. Parameterized
	PROCESSING ACTION		10. Parameterized
	EFFECT		11. Refine
	FAILURE ACTION		12. Iterate

Fig. 17. Cognition's system.

information was two ways—from geometry to equations or equations to geometry. Changing the value of one parameter, say a dimension in the drawing, caused other parameters to change to meet the geometric or analytic constraints imposed by the formulation. Figure 17 shows the classification of Mechanical Advantage in the taxonomy.

7 Conclusions and Recommendations

This paper presents a taxonomy for mechanical design which categorizes and organizes mechanical design tools. The taxonomy has the potential to become the basis for classification of mechanical design research methods and tools. Specifically, if research efforts on the mechanical design process could be classified according to a taxonomy such as the one proposed here, then the appropriate tools and techniques necessary to carry out the research would be clearer. In addition, by categorizing the design problem space, the contribution of each research effort would be easier to place in perspective. It must be reiterated that this taxonomy is seen as a refinement on earlier work and as work to be further refined. The author hopes that the community adopts the taxonomy presented here and refines it as the discipline of mechanical design becomes better understood and progresses toward a more formal science.

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