INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

TOWARDS GENETIC MODELING OF MACHINES FOR ENGINEERING DESIGN SYNTHESIS

Shah, Jami
Arizona State University, United States of America

Abstract

A novel physics based model of engineered artifacts is described analogical to molecular biology which tells us function and behavior are encoded in organisms. Each gene encodes what particular protein is to be made, and the protein performs the same function as part of a cell or organism. In our model a gene is equivalent to a working principle. Combinations of genes appear in chromosomes which makes them equivalent to working structures. Since proteins are the physical function carriers, they can be considered equivalent to physical embodiment of a design, and cells/organs are analogous to machine parts or sub-systems. The amino acids and their arrangement in proteins determines the behavior of the protein. In an abstract sense, this is equivalent to a the behavior of the working structure of a machine component. Each individual organism has unique DNA, so also each designed artifact has a unique working structure (although identical designed and manufactured parts could nominally be considered clones). Each class of designed artifacts can be defined by its genome.

Keywords: Design informatics, Computer aided design (CAD), Conceptual design

Contact:
Prof. Jami Shah
Arizona State University
United States of America
jami.shah@asu.edu

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

The Materials Genome Initiative (MGI) was inspired by the rapid developments in biology (OSTP 2011), such as mapping the human genome (HGP 05), genetic engineering and bio-informatics (Lacroix 03). In this paper we examine whether these ideas could be applied to machines and other engineered artifacts. What kinds of advances can be made in engineering design if such an initiative was to be undertaken by the design research community? What are the similarities and differences between mapping biological genomes, material genomes and machine genomes?

This is clearly a revolutionary, perhaps even a preposterous idea at first glance. One might argue that while biological systems are finite in number, limited to those that nature has created over millennia, artificial systems are potentially unlimited. However, we have seen engineered biological systems created from the combining and structuring existing genes in new ways. Similarly, a vast majority of materials that we use in machines today, do not exist in nature, but have been artificially constituted from naturally occurring elements. In the design of machines, designers are also limited by the laws of nature. The rules of physical sciences, and basic properties of materials, impose constraints on the range of designs possible. The "design" of organisms reflects the inescapable properties of the physical world, even though they were not designed but evolved by natural selection (Vogel 88). This applies both to natural systems and man-made artifacts. Research in biological and medical sciences is relating genes to physical attributes, medical conditions, system properties, etc. MGI is attempting to find genetic structures that could similarly be used as predictors of a materials properties and behavior. Can a genetic model be developed for classes of machines and devices? In this paper, we will show that many pieces needed for such models already exist, though in disparate form.

The immediate benefit from such models is the possibility of creating online databases, similar to those in MGI and bio-informatics, to archive existing devices in a structured way. Such databases could be used for design synthesis and data/knowledge exchange. They could be integrated with various computational tools for simulation. One could study the evolutionary history of classes of devices and perhaps extrapolate from them to invent new ones. As bio-mimicry gains in popularity, machine genetic structures could be related to biological systems to get inspiration from nature.

In theory, we can say that conceptual design involves understanding the design requirements, generating alternative concepts and evaluating the concepts qualitatively or with simplified quantitative analysis. The evaluation is done to determine which concept(s) show the most potential so as to develop them further. However, in practice, the design process in conceptual design is hardly standard – it can vary widely depending on the type of the artifact, artifact complexity, problem novelty and experience of the designer or company with that particular type of design. If a designer encounters a totally unfamiliar need, a new function structure (function hierarchy, sequence) needs to be devised. The new portions of the function structure need to be realized using new working principles and structures (embodying physical principles in different geometries and materials). Some parts of the working structures may correspond to new artifact types. In adaptive design, we may be seeking new solution (alternatives) to an existing design. Thus, the function structure is known and either a new working structure is to be devised, and/or new configurations are to be found. In many types of routine design where a wealth of satisfactory solutions already exists, the designer might skip all the conceptual design steps and go directly to parametric design for sizing (e.g. 5-speed transmission, caliper brakes, McPherson suspension).

2 ARTIFACT MODELS

Surveys of formal methods for conceptual design and synthesis can be found in various publications (Antonsson 01, JCISE 04) We distinguish here between three types of artifact models: pure linguistic, computational and physics based (some overlap is certainly possible). This paper is focused on the last one.

Pure linguistic models contain a vocabulary and syntax that may be directed at requirements, functions, behaviors, or form. By far, functional models have received the most attention (Szykman 99, Kirschman 98, Stone 00). Computational representations define functions in terms of input and output variables and their transformations. For example, Pahl & Beitz (1996) model functions as actions on energy, material and signal. Another popular design representation is FBS or Function-Behavior-Structure (Gero 07, Goel 09, Dorst 05). The three classes (F, B, S) of variables are linked together by processes which transform one class into another. A graph grammar is a computational model for manipulating graphs consisting of domain specific entities and connectors such as mechanical elements or functions (Schmidt 97, 99, 00; Ilies 04). Shapes can be represented as graphs and rules used to manipulate them (Shape grammars). An example application of grammar based computation is mechanism design.

The Modelica® language can support physics based artifact models; it includes definition of algebraic and differential equations that can be used in simulation (Fritzson 14). A number of Modelica libraries of standard components are freely available (OSMC ,2014). Bond Graphs are also physics based artifact models expressed in graphical notation (Thoma 75). BGs can model the energy and signal flows among components in a complex electro-mechanical system using a small set of ideal elements (Karnopp 00, Paynter 61). When modeling with bond graphs each element has two associated variables: an effort and a flow; this allows directed analysis through the concepts of causality and power direction. Bond Graphs have been viewed as front ends to numerical simulations by providing an intermediate level of abstraction to analyze physical causality independently from the underlying math models. Bond Graphs can be used in conceptual design but a limitation is that they can only represent information that can be adapted to the *Power=effort*flow* model leaving out other important information, particularly geometry. Finger (1989) and Rinderle (1991) defined a Bond Graph grammar with the objective of mapping (dynamic) behavior into form.

Two notable physics based models for mechanical design are SAPHIRE (Chakarbarti, 09, 13) and KIEF (Umeda 96, Yoshioka 04). SAPHIRE is a causal model incorporating physical laws, environment and structure to consider change of state. It has been applied to synthesis and analysis based on functions. KIEFF is a meta model based on function-behavior-state to relate diverse and multi-level Knowledge Bases.

3 GENETIC MODELING EFFORTS

The Human Genome Project is a massive and highly publicized international research effort since 1988. Its goal is to determine the DNA sequence of the entire human genome. "The existing and ultimate products of the HGP will give the world a resource of detailed information about the structure, organization and function of the complete set of human genes and other functional elements found in DNA. This information can be thought of as the basic set of inheritable instructions for the development and function of a human being."(HGP 05). Off-shoots of HGP include efforts towards genome modelling of plants (NRC 02) and the advent of the field of bioinformatics (Lacroix 03). Bioinformatics includes the creation and advancement of databases, algorithms, computational and statistical techniques, and theory for analysis of biological data.

A more recent effort, closer to engineering, is the Materials Genome Initiative (OSTP 2011). It proposes to develop new materials through integrated computational, experimental, and data informatics tools. "This infrastructure will seamlessly integrate into existing product-design frameworks to enable rapid and holistic engineering design" (OSTP 11). NIST claims that in contrast to an empirical trial and error approach, multi-scale computational approaches based on physics based material models can reduce development time by orders of magnitude and result in materials of higher performance and lower cost (NIST 2013). The same type of thinking applies to product design and hence the motivation for this paper.

4 TOWARDS ARTIFACT SEMANTIC MODELS

The rapid development and adoption of geometric CAD can be attributed to generalized mathematical models, such as NURBS and B-Rep/CSG. Can this be done for conceptual design in a domain independent manner? There is more to this problem than simply standardizing pure linguistic function ontologies or Modelica models. We propose a genetic modelling approach for artifactual informatics as the science of building multi-level, multi-modal models of artifacts. We take our inspiration from genetics and propose that we think of artifacts in a manner similar to biological systems.

4.1 Quick Review of Molecular Biology

The structure and function of any cell of an organism is determined by the totality of protein molecules it contains. A protein is a large polymer molecule of a linear sequence of amino acids – the particular sequence determines the structure and function of a protein (Haggis 74). So we can think of the acid sequence as information coding for the protein. There are 20 different amino acids that can be combined to produce unlimited number of protein types. Proteins perform a variety of functions; some act as structural components, transport systems, pumps or motors.

Another type of large molecule in cells is the gene. It is also a polymer that is made up of linear sequences of nucleotides. Genes encode the information about what proteins to make, in what quantities, when and where. Genes do not actually make the protein – they just encode the information in the particular sequence of nucleotides. There are just four types of nucleotides: A=Adenene, C=Cytosine, G=Guanine, T=Thymine. Genes are constituents of nucleic acids (DNA, RNA). The difference between DNA and RNA is that the former is double stranded helix while the latter is single stranded. A single strand of DNA is described by its particular sequence of nucleotides (A, C, G, T). For example,

ATGCTCGAATAAATGTGAATTTGA

This is read by arranging in triplets:

<ATG><CTC><GAA><TAA><ATG><TGA><ATT><TGA>

The triplets <XXX> are code for amino acids to be produced or other information. Figure 1 shows the interpretation of the code (genetic code). Because each place in the triplet can be any of 4 letters, there are 4^3=64 combinations – 3 have been found to be codes for stopping production and the remaining for amino acids shown in the Table. There are 20 amino acids, so many are coded multiple times.

We can look at genes as sequences of this code:

{<ATG><CTC><GAA><TAA>} {<ATG><TGA><ATT><TGA>}

Gene 1 *Gene 2*

Using the genetic code in Figure 1, the nucleotide sequence for Gene 1 would map to `<Methionine><Lencine><Glutamic acid><Stop>`

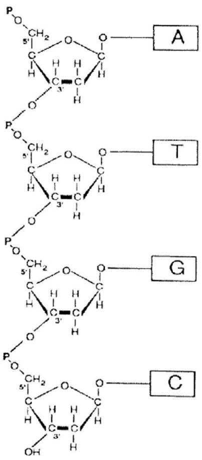
These are instructions encoded in Gene 1 for forming a protein. The particular mechanism for creating the protein via transcription and translation is not relevant to this paper. Typically, proteins have a sequence of 100 or more amino acids.

The totality of all genetic information about an organism is called the genome. The human genome project (HGP 05) found that there are between 30,000-60,000 genes in humans. The full sequence was published in April 2003. DNA is a unique blueprint of an individual while the Genome is the entire collection of genes for a particular species.

Finally, for completeness, we include a definition of chromosomes – it is DNA plus other components. There are 23 pairs of human chromosomes, bundles of genetic information.

First Position	Second Position: T	C	A	G	Third Position
T	PHE	SER	TYR	CYS	T
	PHE	SER	TYR	CYS	C
	LEU	SER	stop	stop	A
	LEU	SER	stop	TRP	G
C	LEU	PRO	HIS	ARG	T
	LEU	PRO	HIS	ARG	C
	LEU	PRO	GLN	ARG	A
	LEU	PRO	GLN	ARG	G
A	ILE	THR	ASN	SER	T
	ILE	THR	ASN	SER	C
	ILE	THR	LYS	ARG	A
	MET	THR	LYS	ARG	G
G	VAL	ALA	ASP	GLY	T
	VAL	ALA	ASP	GLY	C
	VAL	ALA	GLU	GLY	A
	VAL	ALA	GLU	GLY	G

(a) Genetic code



(b) Structure

Figure 1. Interpretation of genetic codes

4.2 Application of Genetics to Engineered Artifacts

An understanding of the relationships and roles of the physical phenomenon and constituent levels of the artifact are fundamental to the development of a model for artifacts. We draw upon molecular biology to propose a model for design. The rules of physical sciences, and basic properties of materials, impose constraints on the range of designs possible. The "design" of organisms reflects the inescapable properties of the physical world, even though they were not designed but evolved by natural selection (Vogel 88). This applies both to natural systems and man-made artifacts.

The German systematic design model of Pahl & Beitz (1999) and VDI 2221(1987) Guidelines provide for design synthesis at three levels supported by paper catalogs: *Components*, *Working principles* (WP) and *Physical effects* (PEs). Examples of working principles are: shrink fit to fasten components; reduce speed to multiply torque. Examples of PEs are Bernoulli effect, photovoltaic effect, Hall effect. This body of literature does not provide any computable semantic model, but only pictorial and textual listings in the form disparate paper catalogs.

It makes sense to start with models of physical effects and move up to macroscopic levels to see how the physical effect is embodied (working principle). At the next level, we can look at how the working principles combine into the working structure of a component to provide one or more mechanical function of the device.

Each gene encodes what particular protein is to be made, and the protein performs the same function as part of a cell or organism. Therefore, a gene is equivalent to a working principle. Combinations of genes appear in chromosomes which would make them equivalent to working structures. Since proteins are the physical function carriers, they would be equivalent to physical embodiment of a design, and cells/organs will be equivalent to machine parts or sub-systems. The amino acids and their arrangement in proteins determine the behavior of the protein. This would be similar to a mathematical behavior model of the working structure of a machine part or component. Each individual has unique DNA, so also each designed artifact has a unique working structure. Its copies or clones would have the same DNA. Each species of organisms are defined by a set of genes – its genome. Similarly, each class of designed artifacts (automobile, airplanes, buildings, etc.) would be defined by its genome. Although physical effects (genes) are universal, not all physical effects are exploited in all artifacts. Lines between species can be drawn as desired; for example, one could map the genome for all mammals, or just dogs. Similarly, one could map genomes for all transportation devices or just bicycles. So we can think in terms of a mechatronics genome, an automobile genome, a planar linkage genome, a structures genome, etc.

In the proposed model, a distinction is made between Design Function or Intent and Mechanical Function. For example, the design intent of an airbag is to "Save Life" while a mechanical function is to inflate the bag. Modeling of design intent and how it is converted to mechanical function(s) are not within the scope of this paper. It will be assumed that the designer arrives at mechanical functions from intent by his/her own ingenuity and experience. Mechanical functions may be broken down into sub-functions in order to make it easier to find solutions. For any given sub-function a solution may already exist in the form of a physical artifact, or a known working structure; in that case these solutions may be used directly or a variant may be created. If no known solution exists, the sub-function may have to be satisfied from first principles by exploiting some physical effect or using a known working principle that is a manifestation of some physical effect, as depicted in Figure 2.

Molecular Biology helps us in three ways. First, we can copy some of the same procedures used in mapping (protein functions, gene coding). We can analyze the chemicals that make up of the genes (physical effects), the structure and function encoded in the gene (working principle), the chromosomes in which combinations occur (working structure), the proteins structure and behavior and biological function served by the cell or organ (part, sub-system physical embodiment). Second, a structured model with properly defined roles of entities, just as those in organisms, adds clarity to the multitude of ideas being put forward for modeling design. Third, in using a common taxonomy of mechanical functions with biology, we may be able to tap into Biomimetic data bases in the future.

5 THE MACHINE GENOME MODEL

We center our artifactual model around the concept of WPs because they include both behaviors and generalized embodiment not specific to a machine component. If WPs can be characterized in generic formal terms, any device or subsytem could be described as a network of WPs, which is more meaningful than describing components in terms of linguistic description of functions. This implies that the WP structure should be amenable to synthesis, both at the behavior level and at the physical level. This is easier to do when there are clean interfaces between components (e.g. oil flowing from a pump to an actuator) but not that easy when there are other types of interactions (e.g., how a snap fit locks in place). Similar complications occur when there is functional coupling within a component.

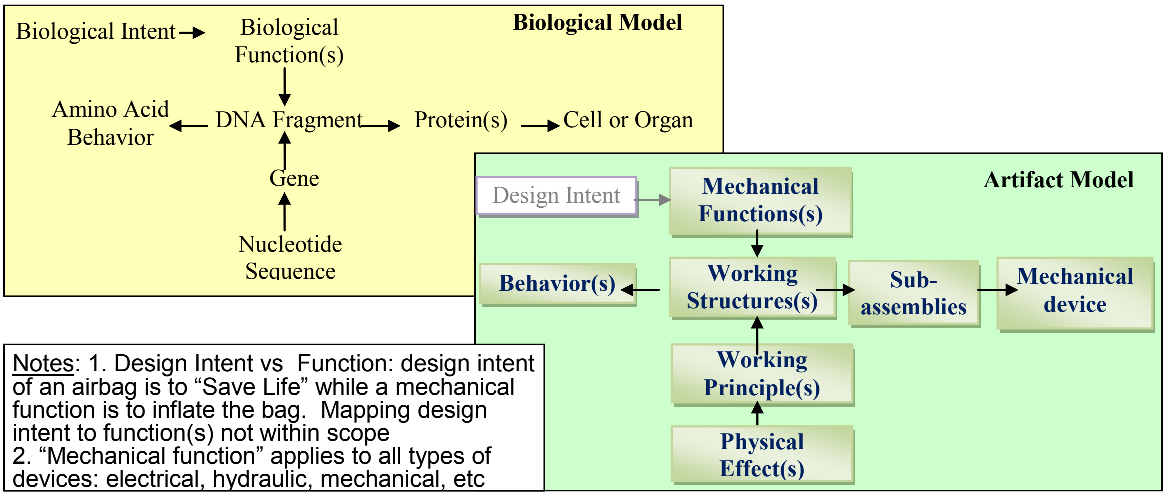


Figure 2. Machine model analogous to biological model

5.1 Modeling Physical Effects

Nearly 200 physical effects have been enumerated in mechanics, electromagnetics, solid state, chemical, thermal, fluid and other areas (Wolfram, Bogatyreva 03), from surface tension to resonance to centrifugal force. Rodenaker is reported to have cataloged physical effects, excerpts of which are found in VDI 2221(1987) and Pahl & Beitz (1996). These catalogs are in the form of annotated pictures for human interpretation and use. Our computer representation of PEs includes the following entities: *Action* (physical variable); *Reaction* (physical variable); *Interacting geometry* (number, type, attributes); *Interacting material attributes; Physical law* (relations between physical, material, geometric variables); *Conditions/constraints*. Physical effects may have side effects such as motion against friction causes heat dissipation. Physical variables and laws governing these side effects must also be included. When multiple bodies are involved in a physical effect, it typically implies interacting features from parts in an assembly. Thus, assembly conditions must also be captured in a formal representation. Finally some physical effects may require specification of temporal relations.

5.2 Modeling Working Principle

A working principle is a functionally relevant manifestation of a physical effect. It adds more specific attributes for geometry, geometric relations and material. The physical effect of friction can be created between two cylindrical surfaces, one rotating and the other stationary, for the purpose of "absorbing rotational energy" (Figure 3). The rotating part may be metallic and the stationary part polymeric to reduce wear, increase μ and maximize heat dissipation through the metallic part. The cylinders need to be nominally coaxial and of the same radius. Thus, working principles are derived from physical effects by specializing their geometry, material, and attribute relationships (conditions). New physical variables may also be introduced. The same physical effect may be exploited in different ways to produce different working principles. There is a *1:n* mapping from physical effects to working principles.

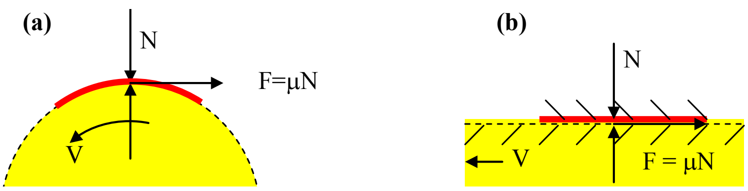


Figure 3. Two working principles derived from the same physical effect

5.3 Modeling Working Structure

A single working principle may correspond to a single mechanical function, which in turn, may correspond to a single design function, but this would be a rather simple device and a special case. Typically, several working principles may be combined to provide a mechanical function. Combinations of working principles are referred to as working structures. Design functions usually translate to multiple mechanical functions and sub-functions, each of which may be satisfied by use of some particular working principle or combination. Hence working principles need to be combined into working structures, and those may be combined with other working structures. Therefore, we need to examine how to model combinations of working principles into compatible structures, and structures with other structures. First, we examine how a Working Principle combines with another Working Principle. There are two Working Principles combined in the hand brake (Figure 4, working structure 1) obtained from two Physical Effects: friction and static force equilibrium. The first Physical Effect is embodied in the brake shoe as the following working principle:

Use friction from a matching cylindrical surface to stop a rotating cylinder

(corresponds to *<ABSORB><Rotational_Energy>*).

The second Physical Effect (equilibrium) is embodied in the working principle of a second class lever for the sub-function *<Multiply><Force>*.

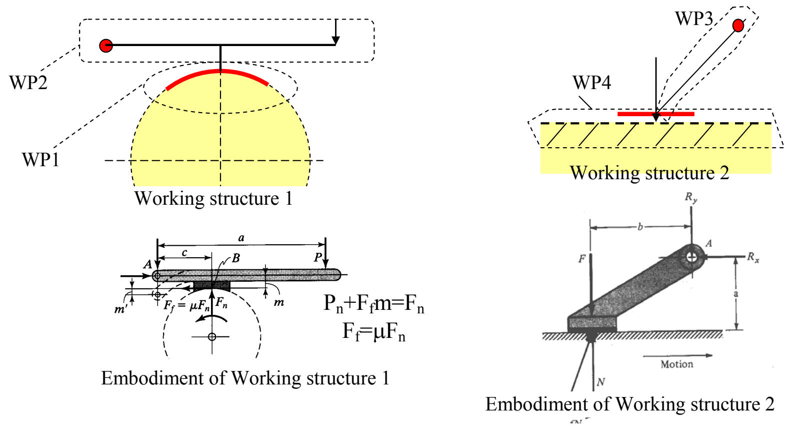


Figure 4. Hand Brakes Working Structures

Physical variables, geometry, material attributes, physical laws, and constraints from both working principles are combined to describe the behavior of this component working structure. These equations combine to describe the behavior corresponding to this working structure.

We see first that there is a physical connector between the elements of two Working Principles. Secondly, there is a physical variable connection (Normal force F_n). In some cases, there may also be sharing of geometric entities. Thus, the requirements boil down to the following:

Coupling of physical variables
Coupling of geometric elements (assembly relations)
Sharing of geometric elements (common faces…)
Intermediate connectors (physical or functional)

Figure 4 also shows another embodiment of a brake. The geometry pair and the brake are both different. This would produce a different working structure. Working structures that satisfy the same mechanical function are deemed isomorphic. Isomorphic working structures should have the same behavior model. There are both geometric and non-geometric couplings between WPs that could result in emergent behavior that is not encapsulated in either WP. Therefore, at least two types of interfacing elements are needed (Figure 5): Geometric (GI) and Non-geometric (NGI). Bond graphs work well in physical effect space but not geometric space. The use of a standard set of constraints (logical, algebraic, geometric, differential) is used in our model.

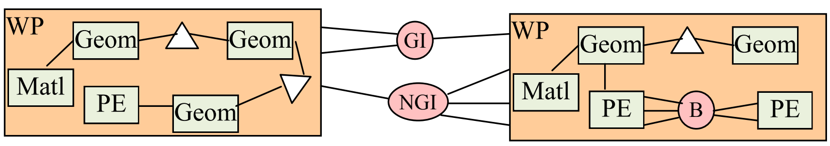


Figure 5. Hierarchical Information Model and its Abstractions

<u>Modeling geometric interfaces</u>: Some Working Principles and Working Structures involve encoding of assembly relations. Almost all mechanical and electro-mechanical devices are assemblies of multiple parts. Thus, we can say that assembly design is the very crux of engineering design. A simplistic assembly model is the connectivity or liaison graph in which the nodes represent parts and the arcs represent contact. This simplistic view is incapable of representing multiple contact pairs between the same two parts. A review of assembly models literature shows that most of the work is directed at

assembly sequence planning or assemblability analysis when detailed design has been completed. We need to go beyond assembly features by capturing functional definition of generalizable part-part interfaces in the form of knowledge structures termed Assembly Functional Interfaces (AFI). Each part may have many AFIs where it interacts with other parts; they combine to produce desired functions. AFIs, like assembly features, encode mutual constraints on mating features' shape, dimensions, position, and orientation, but more importantly, AFIs are carriers of functional information.

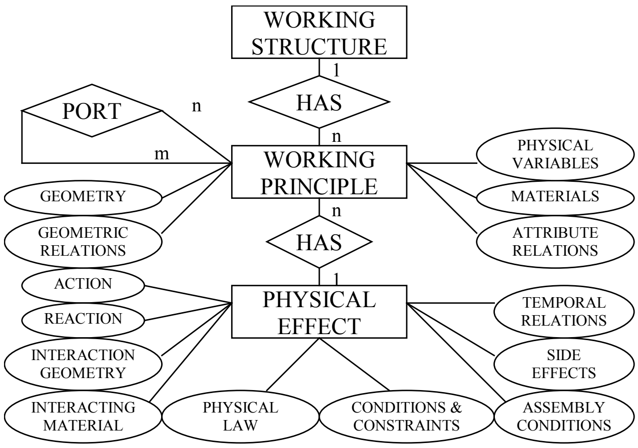


Figure 6. Working Structure Entity-Relationship-Attribute Diagram

We have previously developed a canonical definition of assembly features based on the NIST Open Assembly Model (Murshed 09) and screw theory (Whitney 04). Screw matrices are key in the definition of AFIs; screws can be pre-defined or extracted by mathematical procedures. We also observe that common joints typically involve simple geometric surfaces (planes, cylinders, spheres). Each mating surface pair can be represented by screws. The net DoFs and load transmission directions can be found from the intersection of all screws representing the mating pairs for a AFI. The operations Rcp, $\cup$, $\cap$ are mathematically well defined and we have implemented computational procedures to apply them with any set of assembly features (Dixon 10). AFIs can capture stereotypical properties of different types of interfaces that deliver mechanical functions. We still need to investigate the set of attributes sufficient for conceptual design, the generic set of AFIs needed, and how to extend this representation to more complex AFIs.

5.4 Component Models

Every machine element or device consists of one or more working structures. Therefore, components can be modeled as networked working structures. Figure 7 shows an excerpt of a machine element DNA library (the database is too large to illustrate within the page limits). One may take particular note of the semantic structuring and richness of this information compared to function-artifact catalogs.

6 DISCUSSION

A pilot implementation using the machine genome model is under way strictly for proof of concept. The Testbed has several types of open, extensible libraries for defining elements of the Machine Genome. Working Structure instances will be created with the Structure Builder Module with direct access to the Working Principle Catalog. The Working Principle Catalog is defined through a Module that is linked to libraries of Physical Effects, Constraints, Assembly Features, Geometric Features, and Engineering Variables. Similarly, through the Port Definition Module, Ports can be defined using general purpose constraint relations. A Working Structure Instance (i.e. a design) can be stored through an Instance Versioning System to keep control of the design's evolution. The underlying implementation language for physical effects and working principles must incorporate physical variables (temperature, voltage, force, stress, etc.). Fortunately, there are ISO standards (ISO 31-1992) that specify the name, variable type and units for physical variables used in engineering. We should note that our model should not be confused with Genetic Algorithms, a computational method for optimization. Also, SAPPHIRE and KIEF do not focus on following stricty genomic principles.

Models are fundamental to science, which creates them for simplification and generalization in order to gain an understanding of physical or biological phenomenon. A repository of machine genes, chromosomes and proteins for different artifact categories need to be defined, archiving years of design expertise. These databases will aid future designers with different types of conceptual design, from first principles (using specific genes), variant (tracing back the DNA of an existing machine and modifying it), selection (by defining the required DNA or chromosone and matching it with known genes), and parametric (modifying certain genes of an existing design). A multi-level physics based function model (Machine Genome) goes beyond Pahl & Beitz where there is no connection between the different levels (PE, WP, WS), and no behavior or geometric model used. This model goes beyond Bond Graphs which are typically component based and cannot work when multiple geometric interactions deliver a function. The Machine Genome also models a device in terms of several inter-related models: PE, WP, WS, Behavior and Component/assembly. The Machine Genome has the potential to become the common underlying model for engineering CAD tools for conceptual design.
Like other genome modelling projects, machine genome development will require international collaboration at a massive scale. Perhaps The Design Society could drive such an initiative?

	Machine Element	Physical Effects	Material
Shafts	Shaft	Force on a rigid body cuases motion	Solid - Metal
Couplings	Plain Coupling	Form Closure - two bodies fixed relative to each other by fixing them with a third body, all of them rotating about the same axis of rotation.	Solid - Metal
	Toothed Coupling	Form Closure - two bodies , one male and one female are fixed with each other by form closure	Solid - Metal
	Flange Coupling	Form Closure - two bodies are fixed with each other at more than two points allowing no relative motion.	Solid - Metal
	Bostflex Coupling	Form Closure - two slightly misaligned bodies made to rotate with each other by fixing them through an elastomer	Solid - Elastomer
	Jaw Coupling	Form Closure - two bodies , one male and one female are fixed with each other by form closure	Solid - Metal, Rubber
	Universal Coupling	Form Closure - two shafts with non collinear central axis fixed with each other by universal joint	Solid - Metal
	Oldham Coupling	Form Closure - two parallel coplanar shafts are fixes with each other by a couple of 2 sliding surfaces arrangement	Solid - Metal
	Fluid Coupling	Fluid Friction | Viscosity	Liquid - Viscous Fluid
	Magnetic Coupling	Electromagnetism	Solid - Metal with electromagnetic properties
	Gear Coupling	Form Closure - two bodies fixed relative to each other by fixing them with a third body, all of them rotating about the same axis of rotation.	Solid - Metal
	Chain Coupling	Form Closure - two bodies fixed relative to each other by fixing them with a third body, all of them rotating about the same axis of rotation.	Solid - Metal
	Steel Grid Coupling	Form Closure - two bodies fixed relative to each other by fixing them with a third body, all of them rotating about the same axis of rotation.	Solid - Metal

Geometry	Motion
A circular cylindrical object	Rotational motion about the central axis of cylinder
A hollow cylidrical object to hold two circular shafts	Rotational motion about the central axis of coupling
Two hollow cylinders fixed to rotating shafts, one with male geometry and the other one with female geometry	Rotational motion about the central axis of any shaft.
Two rotating objects are fixed with each other at more than two points	Rotational motion about the central axis of any one shaft.
Two rotating but slightly misaligned shafts (misalignment around 1 degree)	Rotational motion of two slightly misaligned shafts about their respective central axis.
Two hollow cylinders fixed to rotating shafts, one with male geometry and the other one with female geometry	Rotational motion about the central axis of any shaft.
Shafts rotating about non collinear axes	Rotational motion of two shafts about two non collinear axes.
Shafts rotating about parallel coplanar axes, two planar surfaces sliding over each other	Rotational motion of two parallel coplanar shafts with respect to each other
Two shafts rotating about same axis of rotation, a fluid volume rotating in circular motion about the same axis of rotation	Rotational motion of two shafts and certain fluid volume about the same axis of ratation
Two nested electromagnets with the same axis of rotation	Rotaional motion of two shafts connected to two electromoagnets about the same axis of rotation
Two rotating shafts with gear teeth structure on outer side and one hollow coupling with gear teeth structure on inner, nested	Rotational motion of shafts and coupling nested with each other about the same axis of roatation
Two rotating shafts with sprocket structure on outer side, and a circular chain connected to both of them	Rotational motion of two shafts and the chain they are connected to about the same axis of rotation
Two rotating shafts with spline structure on outer side, and a steel grid connected to both of them	Rotational motion of two shafts and the steel grid they are connected to about the same axis of rotation

Working Principle
A long rigid object rotating about a fixed axis and fixed at both ends to rotating artifacts transfers power and motion over a distance.
A rotating shaft is fixed with a stationary one at the end by fixing both of them to a third connecting hollow coupling transfer its motion and power through form closure over a distance.
Rotating shafts are fixed with a two hollow couplings, one male and another female one, which are attached with each other at male - female end transfer motion and power through form closure over a distance.
A rotating shaft fixed with a stationary one at the end at more than two points transfer its motion and power through form closure over a distance.
A rotating shaft fixed with a slightly misaligned one with an elastomer transfer its motion and power through form closure over a distance.
Rotating shafts fixed withhollow couplings, male and female attached with each other alongwith rubber inserts
A rotating shaft fixed with a stationary one at the with a universal joint arrangement to transfer its motion and power through form closure over a distance.
Two parallal coplanar rotating shafts rotating with a central disc with toungue and groove arrangement on both sides; transfer motion, power through form closure by sliding surface arrangement
A rotating turbine produces a circular flow of a fluid which due to friction produces a rotary motion of another turbine.
A rotating electromagnet kept close to another stationary one transfer its motion due to magnetic property of both electromagnets.
Two rotating shafts with a gear teeth on outer side nested with a hollow coupling with a gear teeth on inner side nested in a mechanical arrangemen;t transfer motion, power through form closure
Two rotating shafts with sprocket structure on outer side are connected to a single circular chain in a mechanical arrangement to transfer motion and power through form closure over a distance.
Two rotating shafts with spline structure on outer side are connected to a single steel grid in a mechanical arrangement to transfer motion and power through form closure over a distance.

Figure 7. Excerpts from machine elements DNA library

ACKNOWLEDGEMENTS

This work was supported in part by US National Science Foundation Grant#1150271. The opinios expressed are not endorsed by NSF.

REFERENCES

Antonsson, E. K., Cagan, J., 2001, Formal Engineering Design Synthesis, Cambridge University Press.

Blundell, A., 1982, Bond Graphs for Modelling Engineering Systems, Ed. 1, John Wiley & Sons, England.

Bogatyreva, O., Pahl, A-K, Bowyer, A., and Vincent, J., 2003, "Data Gathering for Putting Biology in TRIZ", TRIZcon 2003, 18-1 – 18-7.

Wolfram Research, Scienceworld, http://scienceworld.wolfram.com/physics/topics/Effects.html
Chakrabarti A, Srinivasan V, Ranjan and Lindemann U, A case for multiple views of function in design based on a common definition, AIEDAM V27, August 2013, pp 271 279.
Chakrabarti A, srinivasan v, SAPPHIRE – an approach to analysis and synthesis, international conference on engineering design, iced'09, August 2009, Stanford, USA.
Dixon A, Shah J, "Intelligent feature tutor and recognition algorithms for assembly features," CAD & Applications conf, Dubai, June 2010. (also published as journal paper in CAD & A, V7(3), pp 319-333.
Dorst K, Vermaas PE (2005) John Gero's Function-Behavior-Structure model of designing: a critical analysis. Research in Engineering Design 16(1-2):17-26.
Finger, S. and Rinderle, J., 1989, "Transformational Approach to Mechanical Design Using a Bond Graph Grammar", 1st Intl. Conference on Design Theory and Methodology, ASME DE-17, pp. 107-116.
Fritzson P, Principles of Object-Oriented Modeling and Simulation with Modelica 3.3: A Cyber-Physical Approach, Wiley, 2014
Gero JS, Kannengiesser U (2007) A function–behavior–structure ontology of processes. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 21(04):379-391
Goel AK, Rugaber S, Vattam S (2009) Structure , Behavior and Function of Complex Systems: The Structure, Behavior, and Function Modeling Language. AIEDAM, 23(1):23-35
Haggis, G. H., 1974, Introduction to Molecular Biology, 2nd ed., Wiley, New York.
HGP, 2005, Human Genome Project, National Human Genome Research Institute, National Institutes of health, http://www.genome.gov/
Illies, H. T. and Shapiro, V., 2004, "Equivalence Classes for Shape Synthesis of Moving Mechanical Parts", Journal of Computing and Information Science in Engineering, Vol. 4, pp. 20-27.
JCISE, 2004, Special Issue on Computer Aided Conceptual Design (CACD), Horvath, I. and Rosen D. (Guest Editors), Journal of Computing and Information Science in Engineering, V4(1)..
Karnopp, D. C., Margolis, D. L. and Rosemberg, R. C., 2000, System Dynamics, Modeling and Simulation of Mechanical Systems, Ed. 3, John Wiley & Sons, New York.
Kirschman, C. F. and Fadel, G. M., 1998, ''Classifying Functions for Mechanical Design,'' Journal of Mechanical Design, V. 120, pp. 475-482.
Lacroix & Critchlow, Bioinformatics, Morgan Kaufman, 2003.
Murshed M, Dixon A, Shah J, "Neutral Definition and Recognition of Assembly Features For Legacy Systems Reverse Engineering", ASME Design Tech Conferences, DETC2009-86739, San Diego, Sep 2009.
NIST: The Materials Genome Initiative at NIST, June 2013.
NRC, The National Plant Genome Initiative. National Research Council , National Academies of Science, 2002.
OSMC: http://www.modelon.com/products/
OSTP, Materials Genome Initiative, US National Science & Tech Council, June 2011.
Pahl, G. and Beitz, W., 1996, Engineering Design - A Systematic Approach, Springer Verlag, London.
Paynter, H., 1961, Analysis and Design of Engineering Systems, MIT Press, Cambridge, MA.
Rinderle, J., 1991, "Attribute grammars as a Formal Approach to Melding Configuration and Parametric Design," Research in Engineering Design, Vol. 2, No. 3, 1991, pp. 137-146.
Schmidt, L. C., and Cagan, J., 1997, "GGREADA: A Graph Grammar-Based Machine Design Algorithm", Research in Engineering Design, vol. 9, pp. 195-213.
Schmidt, L. C., Shi, H., and Kerkar, S., 1999. "The 'Generation Gap': A CSP Approach Linking Function to Form Grammar Generation". Proceedings of 1999 ASME DETC, Las Vegas, NV.
Schmidt, L., Shetty, H., Chase, S., 2000, "A Graph Grammar Approach for Structure Synthesis of Mechanisms", Journal of Mechanical Design, vol. 122, no. 4, pp. 371-6.
Stone, R. B., Wood, K. L., and Crawford, R. H., 2000, "Using Quantitative Functional Models to Develop Product Architectures", Design Studies, 21(3), pp. 239-260.
Szykman S., Racz, J. W., and Sriram, R., 1999, "The Representation of Function in Computer-Based Design", Proceedings of 1999 ASME DETC, Las Vegas, NV.
Thoma, J. U., 1975, Introduction to Bond Graphs and their Applications, Ed. 1, Pergamon Press, London.
Umeda Y, Ishii M, Yoshioka M, Tomiyama T. Supporting conceptual design based on the function-behavior-state modeler. Artif Intell Eng Des, Anal Manufact (AIEDAM) 1996;10(4):275–88.
VDI2221, 1987, VDI- Design Handbook 2221: Systematic Approach to the Design of Technical Systems and Products (transl. By K. Wallace), VDI-Verlag.
Voegl, S., 1988, Life's Devices: The Physical World of Animals and Plants, Princeton University Press, NJ.
Whitney, D. E. , 2004, Mechanical assemblies : their design, manufacture, and role in product development, Oxford University Press, New York.
Yoshiokaa M, Umeda, Takedac, Shimomurad, Nomaguchie, Tomiyama, Physical concept ontology for the knowledge intensive engineering framework, Advanced Engineering Informatics 18 (2004) 95–113