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ENUMERATING THE COMPONENT SPACE: FIRST STEPS TOWARD A DESIGN NAMING CONVENTION FOR MECHANICAL PARTS

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ABSTRACT

A standard naming convention for mechanical parts is proposed in this paper. We refer to this naming convention as the component basis. The component basis is a first step at classifying an exhaustive list of human-made mechanical transmission artifacts as functional forms, geometric shapes, simple machines, and natural forms. The proposed component basis provides a framework for the development of a suite of computational conceptual design tools. This suite of design tools includes a function-based computational concept generator and a product evolution methodology.

Key words: component basis, design languages, product decomposition, function-component matrix, concept generator.

1. INTRODUCTION

In conceptual design or redesign, the process of abstracting a product is essential to representing a design artifact or its sub-artifacts. At this conceptual level of design, details of the various devices are less important than the ability to represent complex objects using relatively simple messages [1]. This desire to simplify information transfer has spurred improvements in the naming of artifacts since the beginning of human communication.

Names are simply abstractions of physical artifacts. The abstraction conveys from the sender to the receiver some understanding about a physical device through a simple word or collection of words representing the name of the artifact. When product names are more specific, more is inherently understood about the artifact. In the realm of physical devices, the component level is the lowest level that is generally discussed, and is therefore the most important during design. "A component is a mechanism, described in terms of variables and constraints that can interact with other components only through variables associated with explicitly specified terminals [2]."

Components represent the fundamental artifacts from which mechanical systems are constructed. Previous efforts have shown that there are many ways to classify the names given to the components that make up mechanical systems. After reviewing these previous efforts, it is proposed that a basis set of names can be compiled that will allow the enumeration of any mechanical device using <u>only</u> those names found in the basis. Collections of names, referred to as lexicons, nomenclatures, taxonomies, ontologies and dictionaries, are given different labels depending on their intended use. We describe several of these collections in this paper. Our ultimate goal is to develop a lexicon for mechanical components that conveys design knowledge using a commonly understood and fundamental set of abstractions and supports archival, search and reuse of component design knowledge.

1.1 Motivation

Concept Generation: Many researchers have explored automated design tools to improve synthesis activities. Early efforts include catalog design [3-5] and more recent efforts tend to focus on graph grammars that assemble a product from sets of components with defined behaviors [6-8]. One common attribute of these research efforts is that they are typically only applicable at the embodiment phase of design (or the latter part of synthesis) after general types of components have been selected to solve a product's functionality.

Our recent research efforts focus on developing a computational *conceptual design* tool. The core of this computational approach is a concept generator that uses stored design knowledge to map function to component form [9]. It allows designers to generate concept variants after specifying

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a functional representation of the product being designed. Within the concept generator, new concept variants are developed based on the similarity in function between the new design and the components within the knowledge base. When this goal is achieved, the concept variants from the generator are described by the components within them. A design team is then able to base concept selection on quantifiable measures using preliminary mathematical models of component performance formulated for the possible concept variants.

To advance the development of this concept generator, a standard set of component names is needed that allow designers to capture and record design knowledge from specific products. This archiving process requires that a functional model and a bill of materials be developed for each product entered into the knowledge base of the concept generator. The functional model must adequately capture the desired function of the product and the bill of materials must contain every component within the product. Using these two pieces of information, components can be related to the function(s) they solve. As component-function knowledge is recorded for many products, a repository of design knowledge is formed. This repository of design knowledge is modeled after the Design Repository at NIST [10]. The design knowledge repository provides the engine for the computational concept generator. When using the concept generator, a functional model of the product being designed is the only information needed to generate a list of component solutions from the component-function repository. These component solutions can then be synthesized into concept variants.

Communication: Communication of design information gives rise to a number of issues. Often, different methods are employed in categorizing components, and the use of natural language leads to ambiguity in interpretation among different designers. These issues make design communication difficult among different sections of the same organization or even among individuals. This problem of communication ambiguity has led researchers to standardize vocabularies to describe functions and failure modes within engineered products [11, 12], but there has been little effort to construct a standardized component basis. Establishing uniformity and consistency in the representation of components will improve designer communication both within and between organizations.

2. BACKGROUND

2.1 The Lexicon Of Chenhall

Museums are in the business of collecting, cataloging, and classifying the artifacts of humankind. In order to carry out this business in a repeatable manner, a system of classification is needed for those artifacts. One of the tools employed to aid in this classification is a lexicon. According to Chenhall [13], "The lexicon … is based on the assumption that every man-made object was originally created to fulfill some function or purpose and, further, that original function is the only common denominator that is present in all of the artifacts of man, however simple or complex." The known (or assumed) function of an object represents the highest level of organizing principle upon which human-made artifacts can be classified and named. A logical system for naming objects consists of a hierarchical ordering based on three fundamental levels of terminology: (1) a controlled list of major categories; (2) a controlled list of classification terms; and (3) an open ended list of object names. Each of these levels is based on the function of the object:

- Major categories are a very limited set of easily remembered functional classes.
- Classification terms are carefully defined subdivisions of the major categories.
- Object names are the words used to identify individual artifacts.

This approach to the classification is similar to that used in the Linnaean system of classifying species in biology [14]. In the Linnaean system, the two classes are the genus class and the species name; these are equivalent to the classification and object name within the system of Chenhall. In Chenhall's lexicon, the classifications are defined very clearly, while the object names are left open ended. This approach allows those interested in the lexicon to add to the collected knowledge contained therein. When used properly, a classification and an object name from Chenhall's lexicon results in a name that is unique in all of humankind's creations.

2.2 Other Approaches

Active research in the artificial intelligence (AI) field of knowledge capture and representation is closely related to the work reported here. In knowledge capture and representation for mechanical design, the term ontology is used to describe the collection of names. In general, ontology is a philosophical theory about the nature of existence, but AI researchers have adapted the term to describe "a shared and common understanding of some domain that can be communicated between people and application systems" [15]. Neches et al. [16] claim: "An ontology defines the basic terms and relations comprising the vocabulary of a topic area."

One difficulty in developing an ontology for mechanical devices is the naming of a device based on a consistent classification scheme. For example, does a long slender two-force member describe a link, a beam, or a shaft? Stahovich, et al. [17] claim that the fundamental ontology for mechanical devices should be based on object behavior not structure. Paredis et al. [18] suggest that a complete description of a component requires the addition of form to the classification, where form specifies a particular instantiation of a component, e.g., a part number for a motor. Both approaches imply that behavior is a key element in classifying mechanical components. Does this clear up the issue of the *long slender two force member*? The behavior of this component is describable using the mathematical representation of the states of a device [2]. Modeling using

the state representation of the component leads to the input/output relationship. Input/output relationships taken at a more abstract level are, by definition, the function of a component, device, or system. "A function of a product is a statement of a clear, reproducible relationship between the available input and the desired output of a product, independent of any particular form [19]." In the case of the *long slender two force member,* the input/output relationship is to *transmit force*, where *transmit force* is a function taken from the functional basis of Hirtz et al. [11]. Hence, it is proposed that the *function* of a component is the fundamental ontology for mechanical devices.

2.3 Observations

In this work, we find common ground between our goal for a basis set of component names in mechanical design and Chenhall's lexicon for classifying human-made artifacts. Because most components used in mechanical design are indeed human-made artifacts, they must be describable in the lexicon of Chenhall. One difficulty is that the lexicon does not include all possible artifact names, in fact "Artifacts originally created to be a physical part of some other object have, in most cases, been excluded from the lexicon" [1]. In terms of design, "artifacts originally created to be a physical part of some other object…" describe components. Since components cannot be adequately described in Chenhall's lexicon, we propose this expansion in order to sufficiently categorize and name them.

The ontological approach of the AI community takes a similar approach to component classification by using the function and form of a component as fundamental elements in its classification. The inclusion of function is a consistent theme in both the practical approach of Chenhall and the virtual approach of the AI community. The presence of component function in component naming is an important linkage between the theory of knowledge capture and representation and the theory of design. An understanding of function is integral to the design process [19, 20]; hence, a natural relationship between components and function must exist. This concept leads to the approach taken in this work.

3. RESEARCH APPROACH: OUR LEXICAL SCHEMA

This work represents the results of a first attempt to develop a comprehensive set of names for the components used in the design of mechanical devices. The schema used to classify the component names within this work is limited to artifacts that are best categorized as mechanical effort transmissions. This categorization includes those objects primarily concerned with the transmittance of forces and torques. The classifications within this major category are as follows:

Functional Forms
Geometric Shapes
Simple Machines / Mechanical Powers
Nature

Functional Forms: This class contains component names that are based on the function performed by the component. The following examples include the name of a function and an object name derived from that function. The function names derive from the functional basis of Hirtz, et al. [11]. Examples include: guide➔ guide, stop➔ stop, actuate➔actuator and indicate➔indicator.

Geometric Shapes: This class contains component names that are based on the fundamental geometry of the component. Examples include: cylinder, ball, disk, and ring.

Simple Machines: This class contains component names that are based on the fundamental relationship between the component and one of the "simple machines." The simple machines, first called the Mechanical Powers, are taught in elementary school and therefore offer a widely recognized area for component naming. Pappus of Alexandria first defined the mechanical powers in the last volume in a set of eight books written in the first part of the 3rd century [21]. Examples include: lever, wedge, screw, pulley, wheel and axle, and inclined plane.

Nature: The final class of component names offers naming opportunities based on a components' similarity to naturally occurring artifacts. These include biological or anatomical structures such as the limbs and organs of animals or physical phenomenon such as fluids and magnets. These component names are intuitive and common, and do not readily map to the other naming bases. Hence, the names derived from natural artifacts are included in this distinct class of component names. Examples include: arm, heel, and magnet.

4. RESULTS: A COMPONENT BASIS

In this section, a set of names is compiled and is proposed as a basis set of component names for mechanical effort transmitters. As a basis, this compilation represents a complete set of names capable of enumerating any mechanical effort transmitter device using <u>only</u> those names found in the basis. Using each of the naming sources listed above as a filter, four sets of component names can be formulated, each containing the fundamental name of the component, its synonyms, and a brief definition of the component.

The complete set of component names harvested from applicable literature and technical reference publications results in 114 terms. These 114 terms comprise the component basis shown in Table 1. The methodology for gathering the component names is based on a search of various technical reference books [22, 23], design texts [19, 22], museum nomenclature [13], dictionaries [24-26], and general experience with many products and devices. The definitions contained in the tables are a compilation from various sources. The phrasing is as general as possible to allow the name's definition to apply to the primary name and the associated synonyms.

5. APPLICATION

The establishment of a basis set of component names used in conjunction with the functional basis [11] facilitates the construction of a function-component matrix that is used in the computational concept generation tool [9, 27]. The function-component matrix forms a relationship between components and their functions for a product where the components determine the columns of the matrix and the sub-functions, listed from the functional model, determine the number of rows. The matrix elements are filled with a zero if a component is not used to solve a given sub-function, or a positive integer indicating the number of instances that a component is used to solve a given sub-function. Thus, the existence of a component solving a certain function conveys design knowledge to the designer. The numerical value of the function-component matrix element supplies additional statistical information about the component.

After multiple function-component matrices are developed, they can be aggregated into a single matrix. The aggregated matrix is called the *chi matrix* and is represented by **X**. This approach is shown schematically in Figure 1. The component basis is used to combine similar components into a single column of **X**. Before the component basis was developed, it was common for similar components to occupy multiple columns simply because they had different component names. If more than one product has the same component, the matrix element $\square_{ij}$ represents the cumulative number of times component *j* solves sub-function *i*.

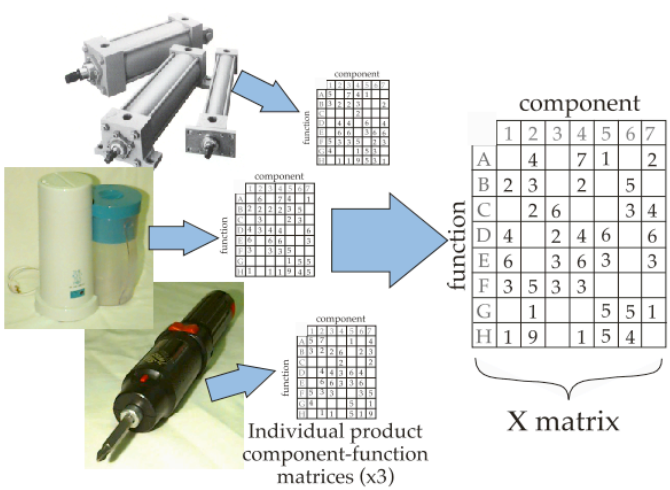

Figure 1: A conceptual representation showing the formation of a function-component matrix.

After design knowledge is captured in the **X** matrix, it can be reused to create new concept variants. This manipulation forms the foundation of the concept generator. The input to the concept generator is a functional model of the product to be designed. The functional model is expressed quantitatively in a filter matrix, **F**. The filter matrix is an *n*x*n* matrix with its rows and columns representing *n* sub-functions. Non-zero entries appear on the diagonal corresponding to sub-functions of the new product's functional model, as shown schematically in Figure 2. Notice that the filter matrix has "zero" off-diagonal elements. Only the diagonal is needed to specify functions for the product.

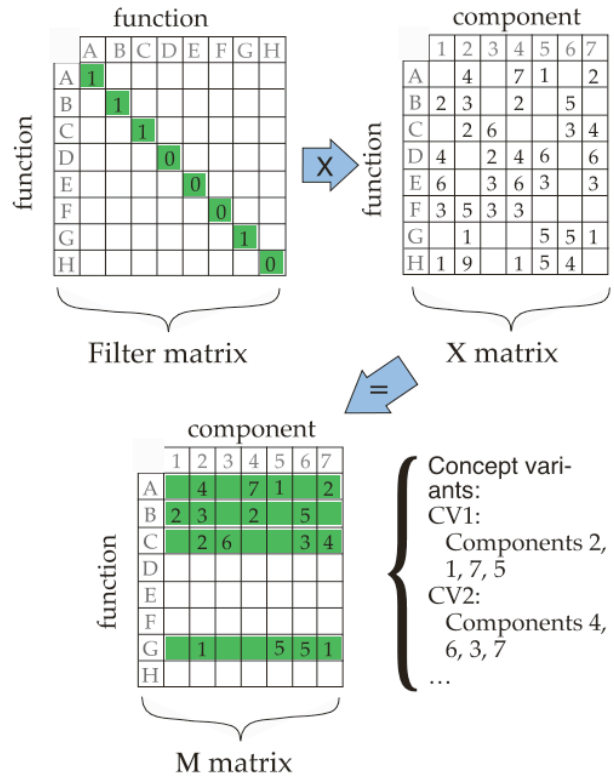

Figure 2: A schematic representation of the concept generator.

To generate concept variants, the *n*x*n* filter matrix pre-multiplies the *n*x*m* **X** matrix (the function-component matrix) to produce a *n*x*m* morphological matrix of alternatives, **M**. This matrix manipulation is shown schematically in Figure 3. Mathematically, the concept generator is formulated as:

$$\mathbf{F}\,\mathbf{X} = \mathbf{M}. \qquad (1)$$

The simplicity of the matrix manipulation understates the power of the concept generator. This one equation yields a computational method to generating a morphological matrix like those used by Pahl and Beitz [20], Ullman [28], Ulrich and Eppinger [29]or Otto and Wood [19]. Preliminary research on the concept generator has produced promising results in the development of a future computational conceptual design tool [27].

Twenty-two consumer household products are investigated to develop two chi matrices in order to verify the component basis seen in Table 1. The comparison of these matrices serves as an initial validation that the component basis is capable of naming a wide range of components. $\mathbf{X_1}$ is

developed using common engineering component names, while $\mathbf{X_2}$ is developed using the component basis. The products used in this comparison range from cordless screwdrivers, internal combustion engines, popcorn poppers and a washing machine. The twenty-two investigated products consist of 577 individual components that solve 118 functions. After aggregation into a single matrix, $\mathbf{X_1}$ contains 150 different component names. In comparison, by using the names from the component basis to enumerate the 577 components, $\mathbf{X_2}$ contains only 54 different component names. Fragments of $\mathbf{X_1}$ and $\mathbf{X_2}$ can be seen in Figures 3 and 4, respectively.

Another application that is currently under investigation is the use of the component-function matrix as a means of knowledge capture in the synthesis of compliant mechanisms. In this context, compliant mechanisms are components that provide a relative motion function by virtue of their ability to deform. This application to compliant mechanisms is integral to a product evolution methodology known as effort flow analysis [30]. Compliant mechanisms present a particularly interesting challenge to component naming, since they tend to be highly function-shared combinations of formerly separate components. In light of this function sharing, compliant features of components such as integral attachments and living hinges are called functional components to highlight the fact that the function provided was once solved by a separate component [30]. A short set of these functional components (compliant) is given in Table 2. The concept generator and the capture of compliant mechanism knowledge are just some applications that represent the motivation for undertaking the establishment of a usable component basis.

6. CONCLUSIONS AND FUTURE WORK

The component basis presented in this work represents an early, yet rigorous, attempt to identify a standardized set of mechanical components categorized as mechanical effort transmissions. The component basis uses the lexical scheme of Chenhall to identify major categories, to define classification terms and to list all mechanical components. Additionally, synonyms, definitions, and relative motion characteristics are listed for each component name within the basis. With the component basis, advanced techniques in concept generation are possible. These techniques seek to reuse existing design knowledge in order to improve the design process and allow designers to use a wealth of information stored within design knowledge bases. Finally, the existence of the component basis can vastly improve design communication.

Initial validation of the components basis shows that all components within a sample of twenty-two consumer products can be enumerated using only those names within the basis. Furthermore, using the component basis to enumerate the components from these products resulted in a more than 60% reduction in component names within the associated chi matrix. During this initial validation exercise, it has become evident that there is a need for heuristic methods for determining the proper component name when a given component meets the definition of more than one basis term.

Future work in this area includes expanding the component basis to include other major categories of devices such as electronic products. This expansion of the component basis will foster further growth of the function-component matrix for the concept generation tool as well. Finally, the component basis needs more extensive validation before being integrated with current design repository systems [10, 31]. Part of this validation effort will consider alternative basis generation methodologies, such as WordNet, MESH, etc.

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	cylindrical trigger sleeve	trigger mechanism	ball ammunition	cable	bar	bearings	bushing	shaft holder	cutting blade	control knob
import solid	0	0	0	0	5	0	0	0	0	0
secure solid	0	0	0	0	8	0	0	0	1	0
couple solid	0	0	0	0	0	0	0	0	0	0
source solid	0	0	0	0	0	0	0	0	0	0
position solid	0	0	0	0	0	0	0	0	1	0
separate solid	0	0	0	0	1	1	0	0	9	0
store solid	0	0	0	0	4	0	0	0	0	0
control solid	0	0	0	0	0	0	0	0	0	0
guide solid	0	0	0	0	4	1	0	0	0	0
transport solid	0	0	0	0	0	0	0	0	0	0
stabilize solid	0	0	0	0	0	0	0	0	0	0
supply solid	0	0	0	0	2	0	0	0	0	0
change solid	0	0	0	0	0	0	0	0	0	0
rotate solid	0	0	0	0	0	1	0	0	0	0
stop solid	0	0	0	0	0	0	0	0	0	0

Figure 3. Fragment of X_1.

Table 1: Basis Set of Mechanical Component Names (alphabetical)

Name	Synonyms	Class	Definition
1. Actuator		Function	Any device that is moved a predetermined distance to initiate, operate or control another mechanical device.
2. Agitator	Mover, stirrer	Function	A mechanical device used to maintain fluidity and plasticity, and to prevent segregation of liquids and solids in liquids, such as concrete and mortar.
3. Arm	Limb, appendage	Nature	Any structure resembling one of a pair of limbs peculiar to humans and other primates.
4. Axle	Stub axle, beam axle, axle shaft	Simple Mach.	A supporting member designed to carry a wheel that may be attached to it, driven by it, or freely mounted on it.
5. Ball	Sphere, orb, globe	Geometry	A round or rounded body or mass.
6. Band	Belt, Strap, Girdle, Band, Restraint, Strip, Leash, Tie, Lash	Geometry	An flexible band made of leather, plastic, fabric, or the like that is used to convey materials or to transmit rotary motion between shafts by running over pulleys with special grooves. A narrow usually flat strip of a flexible material used for securing, holding together, or wrapping
7. Bar	Rod, pole, staff, shaft, rail, stick, dowel, banister	Geometry	Long piece of rigid material that is slender in proportion to its length.
8. Beam	Girder, rafter, joist, plank	Geometry	A large piece of squared material, long in proportion to its breadth and thickness, used to support parts of a structure.
9. Bearing	Journal bearing, thrust bearing	Function	Any part of a machine or device that supports or carries another part that is in motion in or upon it, such as a journal bearing or thrust bearing.
10. Bladder	Membrane, Sac,	Nature	A device resembling any of various sacs found in most animals and made of elastic membrane.
11. Blade	Cutting edge, knife, razor, compressor blade, turbine blade, rotor blade, fan blade	Nature	An item resembling the blade of a leaf, for example, an arm of a screw propeller, electric fan, or steam turbine. The broad flat or concave part of a machine that contacts the material to be moved or cut.
12. Block		Geometry	A compact piece of solid material.
13. Body		Nature	A mass, especially one that is complete and independent.
14. Bulb		Geometry	A rounded dilatation of any cylindrical structure.
15. Burner		Function	The component of a fuel-burning device, such as a furnace, boiler, or jet engine in which the fuel and air are mixed and combustion occurs.
16. Button	Push button, switch, knob	Geometry	Any small rounded body. A knob, globule, disc, etc. that is used as an interface to cause the activation of a device or component especially by closing an electric circuit.
17. Cam	Eccentric, cam plate, camshaft	Simple Mach.	An eccentric curved wheel used to transform rotary motion from a shaft into reciprocating translational motion.
18. Carousel		Simple Mach.	A circular conveyor on which objects are kept in continuous motion.
19. Case	Container, box, shell, holder, casing, crate, crust, chest, skin, armor, housing, skin, sheath, envelope, wrapping, cage, enclosure	Function	A device fitted to contain or enclose other devices or items.
20. Chip	Flake, chunk, integrated circuit, transistor	Geometry	A small, and especially thin, piece of material, separated by hewing, cutting, or breaking; a thin fragment chopped or broken off. A small wafer of semiconductor material that forms the base for an integrated circuit.
21. Choke	Throttle, nozzle	Function	A restriction in a pipe that reduces fluid flow.
22. Chute	Runner, trough, slide	Geometry	A sloping trough with a flat bottom end that is used to transport goods from a high level to a lower level.
23. Claw	Talon	Nature	A mechanical or other contrivance resembling the sharp horny nail with which the feet of birds and some beasts are armed, generally curved with sharpened extremity used for grappling or tearing.
24. Coil	Loop, spiral, helix	Geometry	A series of concentric circles or rings in which a pliant body has been disposed. Such a disposition or form in a body, which is rigid.
25. Collar	Band	Nature	A ring, circle, flange, or perforated disk, surrounding a rod, shaft, pipe, etc., that restrains lateral motion. A short piece of pipe serving as a connection between two pipes.
26. Comb	Rake	Function	A combing tool with curved or straight tines, used for gathering dispersed material.
27. Condenser		Function	Any device or system that condenses a liquid from a gas.
28. Cone	Funnel	Geometry	A solid figure or body, of which the base is a circle, and the summit a point, and every point in the intervening surface is in a straight line between the vertex and the circumference of the base.

29. Counterweight	Ballast, counterbalance	Function	A nonworking weight or load that is attached to one end or side of a machine in order to balance the weight carried on the opposite end or side. A working part that is attached and positioned at least partly in order to improve the balance of a machine.
30. Coupling	Union, compression coupling, clamping coupling	Function	A fitting, usually having internal threads only, used to connect two pieces of pipe or hose. A device used to connect coaxial shafts for power transmission from one to the other.
31. Cover	Covering, cap, top, lid, hood, shield, shroud, guard	Function	That which covers, anything that overspreads an object, with the effect of hiding, defending, sheltering, capping or enclosing it.
32. Cylinder	Container, tube, drum, roll, canister, Barrel, cask, spool, bobbin, tank	Geometry	Any of various practical devices having the shape of a cylinder, such as the chambers of a revolver that hold the cartridges, or a container in which compressed gas is stored for use in pressurized operations. Any of a variety of devices having the cylindrical shape of a drum. A short cylinder revolving on an axis, which turns other smaller wheels connected to it. Any cylindrical part of a machine. A horizontal cylinder or cone (or combination of the two) around which a rope or wire is wound in a hoisting mechanism.
33. Disk	Diskette, hard disk, floppy disk, compact disk, rotor	Geometry	A thin flat circular member.
34. Divider	Diaphragm, partition, panel, wall, barrier, lining, bladder	Function	A device that divides an area into smaller separate spaces.
35. Door	Gate, flap, access panel, entrance	Function	A movable barrier, usually turning on hinges or sliding in a groove, and serving to close or open a passage into a space.
36. Elbow	Ell, fitting	Nature	An angle in a passage for fluids and gasses.
37. Evaporator		Function	Any device in which evaporation occurs, especially one designed to concentrate a solution.
38. Extension		Function	A device allowing the movement by which the two elements of any jointed apparatus are drawn away from each other.
39. Fan	Windmill, Impeller, Propeller	Geometry	A device composed of radiating blades around a revolving hub.
40. Fastener	Fitting, Rivet, Nail, Lock, Clip, Catch, Snap Fit, Catch, Stud, Snap, Clasp, Saddle, Trap, Staple, Straight Pin, Press-Stud, Pop-Rivet	Function	A component used to make an object fast and secure, especially by pinning, tying, or nailing. (Excludes screws and their derivatives)
41. Fiber	Thread, filament, strand, string, cord	Geometry	A tenuous thread-like body.
42. Filter	Strainer, colander, sifter, trap sluice, sieve, screen, clarifier, separator, muffler, silencer	Function	An apparatus used to prevent the passage of undesirable constituents in a flow based on different properties, e.g. specific gravity, phase, electric potential, size, frequency, etc.
43. Fin	Blade, Vane, Airfoil, Rudder, Slat	Nature	A feature or device resembling, in shape or function, the membranous appendage extending from the body of a fish used to propel or guide the body. A projecting flat plate or thin expansion that occurs on the side or edge of a structure.
44. Finger	Tine	Nature	Something that resembles any of the five terminating members of the hand. A projecting piece (as a pawl for a ratchet) brought into contact with an object to affect its motion.
45. Fluid	Liquid, solution	Nature	Having the property of flowing, consisting of particles that move freely among themselves, to give way before the slightest pressure.
46. Flywheel	Inertia wheel, momentum wheel	Simple Mach.	A circular device which spins on a central axis that can store angular momentum.
47. Fork	Split, junction, yoke	Geometry	A component with two or more pronged extensions.
48. Frame	Skeleton, structure, support, spine, backbone, undercarriage, caliper	Function	A structure which serves as an underlying support or skeleton, or of which the parts form an unfilled outline or skeleton.
49. Friction Enhancer		Function	Facing material attached to a device that is used to reduce heat and increase friction.

50. Gas		Nature	One of the three fundamental forms of matter, along with liquids and solids. Unlike a solid (and like a liquid), a gas has no fixed shape and conforms to the space available. Unlike a liquid, a gas has no fixed volume and conforms to the space available. When compared with solids and liquids, gases have widely separated molecules, have low density, and are easily compressed.
51. Gear	Cog wheel, rack, pinion, ring, sun, planet, worm	Simple Mach.	Components working one upon another, by means of teeth, or otherwise, in order to transmit force and motion between rotating shafts or translating devices.
52. Grip	Handle, Hand Hold, Gripper, Manipulator, Graber	Function	A component that allows any action that is thought of as comparable to grasping something or keeping it in place. Something that grips or grasps.
53. Guide	Guide Pin, Guide Rod, Guide Bar, V-Guide, Channel, Pilot, Track, Path, Way, Locating Hole, Pathway, Trace, Rail, Jig Pin	Function	Any device by which another object is led in its proper course.
54. Hammer	Mallet, Impactor, Striker	Function	A tool for transmitting force at a specific location, generally consisting of a solid metal head set transversely on a wooden handle; used for pounding nails, beating metals, and similar impact-related tasks. Any of various tools or machine parts that function in a manner similar to that of the hand tool hammer.
55. Heat Exchanger	Intercooler, Platen, Radiator	Function	A device used for the transference of heat from one medium to another
56. Heel	Heel block	Nature	Any part that resembles a shoe heel in shape, use, or location in relation to other parts
57. Hinge	Pivot, Axis	Function	The movable joint or mechanism that provides for rotation about an axis, such as the revolution of a lid, valve, gate or door, etc., or of two movable parts upon each other.
58. Hook	Catch	Geometry	A length of material, bent back, or fashioned with a sharp angle, often forming a part of something, as a pole, chain, etc., adapted for catching hold, dragging, sustaining suspended objects, or the like.
59. Inclined plane		Simple Mach.	A surface sloped at an angle to the horizontal (or some other reference surface), which provides a mechanical advantage for raising loads.
60. Indicator	Knob, handle, Dial, face, disk, gauge	Function	An external plate or face on which revolutions, pressure, etc. are indicated by an index-finger or otherwise, as in a gas-meter, telegraphic instrument, steam or water-gauge, etc.
61. Inductor	Coil, Transformer	Function	A conductor or device in which an E.M.F. or current is induced.
62. Insert	Grommet Eyelet, Bushing	Function	An object of one material around which another material sets, solidifies, is formed, or which is forced into it after it has set. A removable, soft-material lining (often metal) used to limit the size of an opening. A firm material used to strengthen or protect an opening or to insulate or protect something passed through it.
63. Insulator	Lagging, wadding, padding, filling, Insulation, Vibration damper, vibration suppressor	Function	The material that provides the condition of being isolated by non-conductors to prevent the passage of electricity, heat, sound, or vibration.
64. Jacket	Water jacket	Function	A covering that encloses an intermediate space often used to allow a temperature-controlling fluid to circulate
65. Jaw	Mouth	Nature	A device resembling in function the structure of the bony joint forming the mouth structure in an animal.
66. Key	Half-moon key, cotter key, shear key	Function	A piece of material which is inserted between other pieces; usually, a pin-, bolt- or wedge-like artifact fitting into a hole or space so as to lock the various parts together.
67. Leaf	Sheet, page, flap	Nature	A thin sheet or layer of material produced either by beating out or by splitting. A hinged part or one of a series of parts connected at one side or end by a hinge.
68. Lens		Nature	A piece of glass, or other translucent substance, with two curved surfaces, or one plane and one curved surface, serving to cause regular convergence or divergence of the rays of light passing through it.
69. Lever	Handle, knob, switch, bar, peddle, rocker arm, Lever Arm	Simple Mach.	A rigid structure of any shape (a straight bar being the normal form), fixed at one point called the fulcrum, and acted on at two other points by two forces, each tending to cause it to rotate in opposite directions round the fulcrum.
70. Lining	Inside layer, coating, facing, liner	Function	Any material occurring or placed next beneath the outside one. A covering or coating for an inside surface. Material that lines or that is used to line especially the inner surface of a vessel or passage.
71. Link	Connection, pawl, rod, strut, brace, cross piece, girder	Function	Any connecting part transmitting motive power from one part of a machine to another. A member designed to resist pressure or thrust in a framework.
72. Louver	Shutter, register, vent	Function	One or more slanted fins, fixed or movable, for controlling a flow of air or the radiation of light.

73. Magnet	Lodestone, electromagnet	Nature	A piece of lodestone, or a piece of iron or steel to which the characteristic properties of lodestone have been imparted, either permanently or temporarily, by contact with another magnet, by induction, or by means of an electric current.
74. Manifold	Rail, tee, fitting	Geometry	A high-pressure fitting with multiple ports all at the same potential.
75. Membrane	Casing, covering, crust, film, lining	Nature	A thin pliable sheet-like tissue (usually fibrous), serving to connect other structures or to line a part or organ.
76. Mesh	Net, web, grille, screen	Geometry	An interwoven or interlocked structure. A device through which soft materials may be forced for reduction to finer particles.
77. Needle	Spine, pointer, indicator, stylus	Geometry	A slender, usually pointed, indicator on a dial or other measuring instrument. Any of various slender hollow devices used to introduce matter (as air) into or remove it from an object.
78. Nozzle	Jet, injector, fuel injector	Simple Mach.	A device that exports a continuous stream of concentrated and well-defined incompressible or compressible fluid. A device for converting fluid pressure into fluid velocity usually with minimum loss.
79. Nut	Wing nut, lug nut, female screw	Nature	A perforated block having an internal screw thread, used on a bolt or screw for tightening or holding something.
80. Pad	Filling, cushion, wadding	Function	Something soft, of the nature of a cushion, serving to protect from or diminish jarring, friction, or pressure, or to fill up hollows and to fill out or expand the outlines of the body.
81. Pin	Hold down, jam, post, hinge, axis, pivot, peg, dowel	Geometry	A cylindrical piece used to fasten two parts together or to support one part that is suspended from another, allowing one degree-of-freedom. A short shaft that forms the center and fulcrum on which something balances, oscillates, or turns.
82. Piston	Ram, plunger	Function	The working part of a pump, hydraulic cylinder, or engine that moves back and forth in the cylinder to control the passage of fluid.
83. Plate	Cover, shield, platen	Geometry	A smooth flat piece of material that is thin compared to its length and width.
84. Plug	Stopper, cap, bung,	Function	A piece of solid or firm material driven into or used to stop up a hole or aperture in which it tightly fits.
85. Pulley	Step Pulley	Simple Mach.	A wheel or drum fixed on a shaft and turned by a belt or the like for the application or transmission of power.
86. Quadrant		Geometry	A thing having the form of a quarter-circle. An instrument that changes horizontal reciprocating motion to vertical reciprocating motion.
87. Receptacle	Container, receiver, vessel, holder, port, outlet, tray, dish, repository, socket, cup	Function	That which receives and holds an artifact. A component into which another component or device may be put. A hollow part or piece, usually of a cylindrical form, constructed to receive some part or item fitting into it.
88. Release	Catch, pawl, lock	Function	A device that is designed to hold or free a mechanism as required.
89. Rib	Beam, strut, spoke, spine, spar, ridge, flange	Nature	A raised band or flange, especially one made upon a metal plate in order to stiffen it or facilitate attachment. Something resembling, in shape or function, one of the paired curved bony or partly cartilaginous rods that stiffen the walls of the body of most vertebrates. For example, a transverse member of the frame of a ship that runs from keel to deck, a light fore-and-aft member in an airplane's wing, or one of the stiff strips supporting an umbrella's fabric.
90. Ring	Loop, Hoop, Disk, Washer, Band, Rim, Wheel, Hoop, Flange, Link, Race	Geometry	A circle of material, of any dimension, employed as a means of attachment, suspension, compression, force transmission, etc.
91. Rotor	Disk, wheel, impeller, hub, spindle, nave, indexer, index head	Simple Mach.	Any circular object that undergoes rotational movement such as in an electrical machine, turbine, compressor, blower, wheel, or contactor.
92. Scoop	Ladle, dipper, skimmer, shovel, bucket, scoop, spoon, cup	Function	A concave utensil for bailing out, ladling liquids or removing soft material.
93. Scraper		Function	An instrument used for scraping.
94. Screw	Jackscrew, power screw, drive screw, lead screw, Bolt, fastener, set screw, machine screw, lag bolt	Simple Mach.	The general name for that kind of mechanical appliance of which the operative portion is a helical groove or ridge (or two or more parallel helical grooves or ridges) cut on the exterior surface of a cylinder. A long slender fastener consisting of a head, shank and external threads.
95. Seal	Gasket, O-Ring	Function	Any means of preventing the passage of gas or liquid into or out of something, especially at a place where two surfaces meet.

96. Shaft	Pole, Bar, Rod, Shank, Pipe, Output Shaft, Driveshaft, Input Shaft, Jack Shaft, Half Shaft	Geometry	A commonly cylindrical bar used to support rotating pieces or to transmit power or motion by rotation.
97. Skid	Sled, Shoe, Runner, Rail	Function	A component either under or within a machine used to facilitate sliding of components relative to one another.
98. Spring	Cantilever spring, coil spring, leaf spring, plate spring, torsion spring	Function	An elastic contrivance or mechanical device, usually consisting of a strip or plate suitably shaped or adjusted, which, when compressed, bent, coiled, or otherwise forced out of its normal shape, possesses the property of returning to it.
99. Sprocket		Simple Mach.	A toothed wheel that engages a power chain.
100. Stamp	Die, Punch	Function	A device used to exert pressure on a material, as to compress, shape, or mark it.
101. Stator	Stator Plate	Function	The stationary part of a machine around which a rotor turns.
102. Stop	Bumper, Snubber, Travel Limiter	Function	A device that is automatically activated by a predetermined displacement to limit the operation of a system.
103. Support	Foundation, Buttress, Crutch, Leg, Seat, Slab, Scaffold, Brace, Bed, Stanchion, Reinforcement, Buttress, Base, Pillar, Column, Joist, Bracket, Sole Plate, Anchor, Pedestal, Stand, Foot, Base, Jig, Fixture, Table, Underpinning, Piling, Bench, Crutch, Platen, Saddle, Prop, Structure	Function	Anything that holds up, or sustains the weight of a body. A prop, support, pier or abutment.
104. Tab	Projection, Stub, Tang, Flap, Strip	Geometry	A projection, flap, or short strip attached to an object to facilitate opening, handling, or identification.
105. Tip	Point, head, top, end, apex, point, stylus	Geometry	An apex or extremity of an object, designed to be a contacting point, end, cap, or cutting edge.
106. Tire		Simple Mach.	A continuous ring of rubber or other material, usually filled with air, that encircles the rim of a wheel that serves to support weight, absorb shock, provide traction, and so on.
107. Toggle	Switch, Flip-Flop	Function	A bi-stable device.
108. Tooth	Cog	Nature	A projection resembling or suggesting the tooth of an animal in shape, arrangement, or action Any of the regular projections on the circumference or sometimes the face of a wheel that engage with corresponding projections on another wheel especially to transmit force.
109. Tube	Pipe, cylinder, hose, duct, pipe, conduit, channel, duct, nipple, sleeve	Geometry	A hollow body, usually cylindrical, and long in proportion to its diameter, used to convey or contain a liquid or fluid, or for other purposes.
110. Valve	Regulator, tap, flap valve, rotary valve	Function	Any of numerous mechanical devices by which the flow of liquid, gas, or loose material in bulk may be started, stopped, or regulated by a movable part that opens, shuts, or partially obstructs one or more ports or passageways. The movable part of such a device
111. Wedge	Block, sliver, slice	Simple Mach.	A piece of hard material, thick at one end and tapering to a thin edge at the other.
112. Wheel	Rim, disk	Geometry	Any of various machines, devices, or the like characterized by a revolving circular frame or disk.
113. Wing	Airfoil	Nature	Each of the limbs or structures by which an animal or manmade craft is able to generate a lifting force.
114. Wire	Cable, lead, chain	Geometry	Metal wrought into the form of a slender rod or thread by the operation of wire-drawing.

Table 2: Functional components (compliant)

Name	Synonyms	Class	Definition
1. Compliant Q-Joint	Quadrilateral joint	Combined	A compliant mechanism joint formed by connecting the ends of the members of a 4-bar mechanism using short-length compliant joints (living hinges) [32].
2. Compliant Coupling		Combined	A coupling containing a resilient member such as a metal spring or rubber disk; used to connect two rigid shafts that cannot be aligned.
3. Compliant Hinge	Living Hinge	Combined	A coupling containing a resilient member such as a metal spring or rubber disk; used to provide a DOF between connected components.
4. Integral Attachment	Snap Fit	Combined	A feature formed into a part that provides attachment between parts and establishes part location, alignment, and orientation [33].
5. Compliant Shaft	Flexible shaft	Combined	Any shaft that is made of flexible material.

	actuator	ball	band	bar	bearing	blade	button	cam	case	chip
import solid	0	0	0	5	0	0	0	0	2	0
secure solid	0	0	0	8	0	1	0	0	1	0
couple solid	0	0	0	0	0	0	0	0	0	0
source solid	0	0	0	0	0	0	0	0	0	0
position solid	0	0	0	0	0	1	0	0	0	0
separate solid	0	0	0	1	1	9	0	0	2	0
store solid	0	0	0	4	0	0	0	0	2	0
control solid	0	0	0	0	0	0	0	0	0	0
guide solid	0	0	0	4	1	0	0	0	0	0
transport solid	0	0	0	0	0	0	0	0	0	0
stabilize solid	0	0	0	0	0	0	0	0	0	0
supply solid	0	0	0	2	0	0	0	0	0	0
change solid	0	0	0	0	0	0	0	0	0	0
rotate solid	0	0	0	0	1	0	0	0	0	0
stop solid	0	0	0	0	0	0	0	0	0	0

Figure 4. Fragment of X_2.

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