Towards Automated Identification of Functional Designations of Components Based on Geometric Analysis of a DMU

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Abstract

With the increasing interest to automatically simplify products' 3D models to cope with varying engineering demands, the identification of functional designation of components has become an insistent need.

In this work, we suggest a method to classify elementary components of a product into a taxonomy of functional designations. This is done based on information present in the product's digital mockup; that is the geometrical properties of different solids in the assembly. We argue that relative interactions between adjacent pieces reveal essential information that guides the identification of functional properties. We refer to such interaction as conventional interfaces.

To allow our reasoning we demonstrate the relationships between geometry and force, and between force and functional properties. These connections establish the link between the mere geometrical representation that we have as input to the desired functional designations of components.

1 Introduction

Digital Mock-Ups (DMUs) are key engineering elements during different stages of product's life cycle. They mainly represent the product as a 3D model comprising geometric properties of components, along with their relative positioning and constraints. DMUs are also collaborative means of information exchange throughout Product Development Processes.

Model's complexity reduction is essential to physics-based simulations, as intensive details present in the design model render resource intensive computation prohibitively expensive. Methods for of simplification already exist [11]. However, in most of those methods, the knowledge about functional properties of components is indispensable.

Despite its importance when adapting a model to specific engineering needs, we can only hope for few poorly standardised annotations about functional denominations of a component in a DMU, usually presented as features. Having such knowledge beforehand facilitates necessary simplifications to scale down DMU's complexity. This is usually done by replacing the geometrically detailed components (such as screws, nuts, etc) by functionally equivalent and geometrically consistent elements (such as line segments), allowing for simulations to take place through simpler tessellations.

The aforementioned motivations actuate bridging the gap between the mere geometric representation of a model and a comprehensive functional classification of its components. Literature has tackled this problem in different ways. Efforts as early as [6] have been paid toform features recognition in solid models. In [6] the geometric model is transformed into a graph representation then graph matching techniques is applied to extract form features, also represented as graphs.

Falcidieno and Giannini in [4] addressed the problem of extraction functional features out of geometrical models, and classified existing solutions back then into human assisted approaches, feature based modelling, and automatic feature recognition and extraction. Their methods fall in the last category and proposes a three stage solution that builds a hierarchical structure of part's shape in accordance to the level of details.

In [1] author advocates an expert system approach to recognise application specific features given the product's solid model as B-Rep.

A survey on recent technique of feature recognition is presented in [2]. Those techniques address a wide range of features, in participation to the Computer Aided Process Planing (CAPP) automation.

In this work we aim at establishing a method to denominate components present in a product's DMU with discriminative functional labels based on the geometric description of the model. The classification is based on the relative positioning of the component with respect to its neighbours and potential interaction between adjacent solids. The reasoning is then done with the help of certain hypotheses and axioms that relate concepts of geometrical configurations, internal forces, objects' mobility, and functional properties together.

This work is an exploratory effort toward a fully-automated identification of components designation, trying to establish the basis for robust algorithms in this direction. A direct application to such approach is structural and thermal analyses and fluid dynamic simulations to assess product's fulfilment to functional requirements. Another application would be the immersive environment simulation for training, testing and other purposes[8, 3, 9].

In the next section, we establish the theoretical background of our research, defining basic concepts, and formulating axiomatic hypotheses.

2 Definitions and Axioms

In this section, concepts that are central to our work and hypothesis essential for the reasoning are defined and highlighted.

2.1 Functional Designation and Taxonomy

In the remaining of this paper, we refer to the identifying denomination of a component that unambiguously describe its functionality and role in an assembly by its *Functional Designation*. Examples of functional designations are cap-screw, tubular rivet, locknut, stud, spur gear... etc. A functional designation can be regarded as a class of components. This is not to be confounded with component's function, as a component belonging to one functional designation class may have more than one function. For instance, a tubular rivet can play both the role of fastening and pivot point at a time. Moreover, one function can be performed by members of different classes of functional designation, an example is cap-screws and solid rivet which both do the job of fastening. However, members of the same functional designation class provide all the same set of functionalities.

Based on this discriminative classification of component, we build a hierarchical taxonomy represented as a tree structure, where leaves are the functional designations, and nodes are their generalisations (e.g. fastening component, screw, rivet, gear... etc).

2.2 Conventional Interfaces

Definition 1. A *component* is a solid bounded by closed surfaces.

According to this definition, our components are completely independents of the construction tree that may group more than one solid in one entity. Moreover, components are three-dimensional manifolds, that is, no non-manifold configuration entry point is considered when analysing components.

This assumption gains its ground from the fact that real components are 3D objects that do have volume. However, simplified object presented as non-manifold or less than three-dimensional objects (e.g. plates represented as surfaces, or strings as curves) are out of the scope of our analysis.

Definition 2. A *conventional interface* between components in a digital mockup is the relative positioning of adjacent surfaces of different components. This can be one of three configurations:

- Clearance;
- Contact; or
- Interference.

Conventional interfaces are the result of the intersection between components' interiors (in the case of interference), components' boundaries (in case of contact) or components' dilation by a specific structuring element (in the case of clearance).

Contacts are very common in assembly models, as they reflect the physical interaction between solids. In a real product components often lie on each others through contact surfaces. Clearances, however, are less common in a DMU, but they still closely reflect reality when components are kept close enough, though not in contact. As its description entails, interferences are non-physical configurations, as solids matters do not intersect in a real functional product. However, the use of interferences is widespread in products' DMUs, as they represent idealisation of highly detailed parts of the real components, such as toothed or threaded connections. They may also represent a deformed object configuration, as for rivets.

Next we formally define aspects such as interference, contact and clearace. To this end, we will apply topological concepts[7] such as solid interior $int(S)$ which is the set or interior points of S in the Euclidean space $\mathbb{R}^3$, and solid closure $cl(S)$ which is the union of the solid interior and its boundaries. We recall that a solid is called an open set if it equals to its interior, and it is called a closed set if it equals to its closure.

We also borrow the morphological concept of dilation[5], where the dilation of a solid S with respect to a structural element A is denoted $S \oplus A$. In our case, the structural element is a closed sphere of radius ρ, and the dilation returns the extension of the solid by ρ.

Definition 3. Two solids C_1 and C_2 are said to be at *interference* if and only if

$$Z_i(C_1, C_2) = cl(int(C_1) \cap int(C_2)) \neq \emptyset.$$

We call $Z_i(C_1, C_2)$ the *interference zone* between solids C_1 and C_2.

The definition states that two solid are at interference if and only if their interiors intersect resulting a non-empty set. In fact the use of closure in the previous definition is unnecessary to define the intersection itself. However, we define the interference zone to be a closed set to enable its reuse in later definitions.

Definition 4. Two solids C_1 and C_2 are said to be at *contact* if and only if

$$Z_c(C_1, C_2) = (cl(C_1) \cap cl(C_2)) - Z_i(C_1, C_2) \neq \emptyset.$$

We call $Z_c(C_1, C_2)$ the *contact zone* between solids C_1 and C_2.

The definition states that two solids are in contact if and only if their boundaries intersection is a non-empty set that is not contained in the boundaries of their possible interference zone. The fact that the interference zone is a closed set allows us to exclude boundaries intersections that are the result of an interference (when boundaries cross each others).

Definition 5. Two solids C_1 and C_2 are said to be at *clearance* with respect to a distance ρ if and only if

$$Z_j(C_1, C_2) = \\ (C_1 \cap (C_2 \oplus A)) - (Z_i(C_1, C_2) \cup Z_c(C_1, C_2)) \\ \neq \emptyset.$$

Where A is closed sphere of radius ρ. We call $Z_j(C_1, C_2)$ the *clearance zone* between solids C_1 and C_2.

The definition states that two solids are at clearance if the ρ-thick shell covering on of the solids intersect with the other resulting a non-empty set.

We refer to the generalisation of interference zone, contact zone, and clearance zone an *interaction zone*.

It is worth mentioning that while interference zones are 3-dimensional (with possible non-manifold configurations) contact zones are either surfaces, curves or points. However, an interferences zones can be of either dimensionality.

For each maximal connected component of each interaction zone, a conventional interface is said to exist joining both components involved in the interaction. The interfaces is then said to be either interference, or contact, or clearance in accordance to the interaction zone type. This can be regarded as a more formal definition of the conventional interfaces.

A conventional interface, thus, has as property a geometric object which is the interaction zone. In its turn the interaction zone has its own properties as well; it can have length in case of curvilinear contact, area in case of surface contact, or volume, either positive in case of interference or said negative in case of clearance.

Hypothesis 1. The digital mockup is consistent.

We are only interested in consistent DMUs, that represents a functional product and contain no contradictory informations. This assumption allows us to derive reasonable conclusions.

Hypothesis 2. Conventional interfaces are time-invariant.

From a kinematic stand point we differentiate between mechanisms and structures when analysing a products model. As mechanisms is supposed to provide a method of transmitting movement between different components of the product, the model is presumed to have at least two different kinematic classes. For instance, a body that is considered stationary, and an axial arm with associated components that possess a rotational movement. Structures however are motionless, that is all components in the model belong to the same kinematic class and thus considered stationary.

Due to the immobility of structures, the whole system is considered time-invariant, including its conventional interfaces. In a mechanism, however, the product model contains relatively mobile parts with respect to each others. That is, the model potentially changes its state over time. We here assume that no matter how the different parts move, the conventional interfaces between those parts, along with their attributes, remain the same. That is the relative movement of parts doesn't add any new interfaces, nor remove old ones, neither does it alter their types (contact, interference, or clearance).

An example would be a four-stroke internal combustion engine, where though the model shows high mobility, components tend to maintain their conventional interfaces unchanged. For instance, the piston stays only in a cylindrical contact with the combustion chamber, despite the translational motion.

This assumption, however, doesn't hold in the general case, one counterexample could be the Maltese cross (Figure 7), where conventional interfaces are added and suppressed while wheels rotate.

The time invariance property of conventional interfaces limits the relative movement of components in the model, allowing us to deduce the existence of internal forces that keep those components together. This hypothesis is realistic, as components in a function product are indeed held together to form certain assembly, and it is only the mechanical stresses exerted between components that

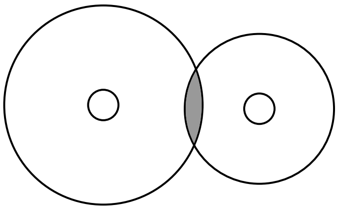

Figure 1: Cross section of idealized toothed connection represented as an interference.

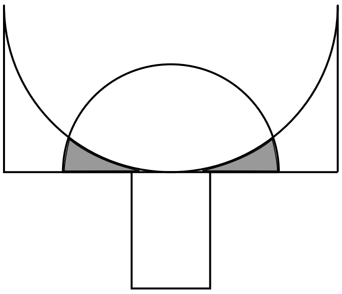

Figure 2: Cross section of an idealised deformed body represented as an interference with non-manifold configuration.

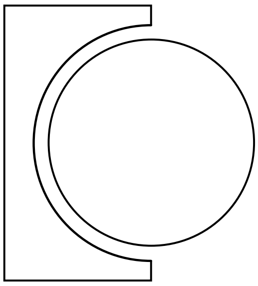

Figure 3: Cross section of a clearance example.

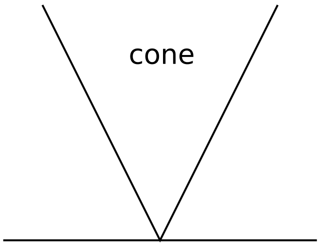

Figure 4: Cross section of punctual contact.

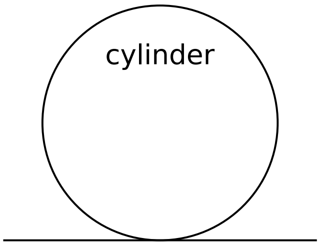

Figure 5: Cross section of linear contact.

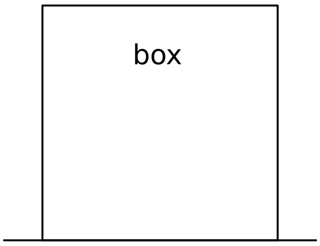

Figure 6: Cross section of surface contact.

keep them assembled.

Hypothesis 3. The product is an isolated system.

This hypothesis is meant to define a reference state in which the product is in mechanical equilibrium. That is:

- the vector sum of all external forces is zero, and
- the sum of the moments of all external forces around any axis is zero [10].

This assumption allows us to exploit lows of conservations to derive more conclusion.

Hypothesis 4. Conventional interfaces are binary relations between components.

We consider one conventional interface to bind exactly two components, having the interaction zone as attribute. Initially, this assumption is not globally valid, as for some cases more than two components can be at the same interference. Nevertheless, such anomalies can be solved by treating those interferences as two or more conventional interfaces, having only two components each.

To have a general perception of how different components in a DMU interact, we represent the above-mentioned relation as an undirected graph.

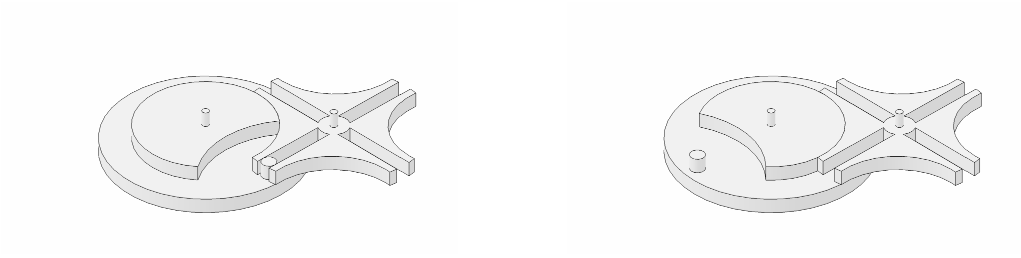

Figure 7: The Maltese Cross at two different stages of its rotation, showing how conventional interfaces change.

Definition 6. The *Conventional Interfaces Graph* of a product's DMU is an undirected graph with components as graph vertices and conventional interfaces as graph edges. Graph edges hold interfaces' attributes.

Further analysis of the graph enables the inference of more information about the functions of components. It also permits making grounded assumptions about the relative mobilities of different parts in the assembly. Such assumptions are based on physical properties, which are in turn deduced from the geometry of the system, and the assumption that our model is consistent.

3 Reasoning Elements

After establishing the theoretical framework, we describe in this section the proposed inference process that leads to the identification of functional designations.

As mentioned before in section 1, the inference is highly dependant on the tight relations between geometry and forces, and between forces and mobility. We refer to these relations as geometry/force and force/mobility dualities, respectively. Duality means that there is a bijective mapping between configuration of the first aspect and those of the other.

3.1 Geometry/Force Duality

Geometric configurations are tightly coupled to internal stresses. This is a result of the assumptions of model consistency and isolation, and conventional interfaces time invariance. An example would be a planar contact between two solids: following the time invariance assumption, the two solids remain in planar contact over time, that is they are held tight together. Since the product is assumed to be an isolated system, only internal forces can be presumed to hold the two solids. Thus, we deduce the exertion of reciprocal stresses between the two solids.

Another, less evident, example would be a cylindrical interference. In this case the sole piece of information about the interface itself is not enough. More geometrical analysis have to propagate to the neighbouring objects in order to deduce the internal stresses. However, either a threaded connection, a tight assembly, or a spline coupling can be hypothesised to exist between the two solids, reducing the number of possibilities to reason about.

3.2 Force/Mobility Duality

Internal forces and stresses determine objects' mobilities to a great extent. For instance, parallel multiple contacts on a solid yield stresses exerted on the same object in opposite directions, thus, we deduce a null mobility along the normal of parallel contacts.

Internal forces normally have a prohibitive effect on mobility. They usually limit objects relative motion. For instance, a cylindrical contact dictates possible translation along the cylinder axis, and possible rotation around it. However, adding contacts involving both bases of the cylinder suppresses any possibility of translation movement, keeping only rotation possible.

In some cases, the absolute lack of mobility indicates deformation that took place to mount the object. As the example of retaining rings, where the only solution to a consistent model (where assembling and disassembling components are feasible) is the existence of elastic transformation. Another example is a rivet, where the null-mobility and non-demountability of objects indicates plastic deformations.

3.3 Inference Locality

The complete Conventional Interfaces Graph CIG has as order the number of solids in its corresponding DMU. This can range from few tens to few thousands, making the reasoning over modestly large graphs prohibitively inefficient. However, the identification of a component's functional designation doesn't require the reasoning over the whole graph, but only over the neighbouring solids to a certain degree (immediate neighbours, neighbours of neighbours...etc). We call $CIG|_C$ the smallest subgraph of CIG that matters to the inference of the functional designation of component C.

$CIG|_C$ is first initiated by component C as one-node graph, it is then iteratively augmented by interfaces that involve at least one component belonging to $CIG|_C$ nodes as graph edges, and their respective components as graph nodes, as long as such interfaces add up to the inference of functional designation of C. The iterative process stops when all candidate interfaces are irrelevant to the identification process.

As all $CIG|_C$ nodes are also nodes of CIG (the set of all solids in the DMU), and all its edges are as well edges of CIG (the set of all conventional interfaces), it logically follows that $CIG|_C$ is a subgraph of CIG. Moreover, and according to its iterative definition, $CIG|_C$ is a connected component of CIG.

The missing piece now is to know how to determine whether an interface participate to the inference process or not. A precise answer to this question will helps pruning the subgraph down to exactly what is needed.

To demonstrate how the construction of $CIG|_C$ is propagated, we consider the example of a cap-screw holding several components together. Obviously the fact that the component is a cap-screw is not available initially, as it is what we are looking for. However, we have the whole CIG of the DMU containing the screw besides other components, along with conventional interfaces between them. We refer to cap-screw as C from now on. Thus, we're aiming to construct $CIG|_C$. First we initiate $CIG|_C$ with C and all its adjacent components as nodes, and the conventional interfaces between those components as graph edges. The addition of immediately adjacent component is justified by their clear participation to the identification process.

The existence of the cylindrical interference between C and B suggests –among other possibilities– the existence of a threaded connection. Following this hypothesis, internal stresses are assumed to exist collinear to the axis of the cylindrical inference α_I, alongside the threaded zone. In the case of fastener components, this forces should propagate creating a loop that ties at least two other components together. However, and since those forces are coaxial to the threaded connection, the propagation can only occur through contact zones that have an average normal that is parallel to the cylindrical axis as well. Examples of such surfaces are:

- Planar surfaces orthogonal to α_I;
- Spherical surfaces with a centre coinci-

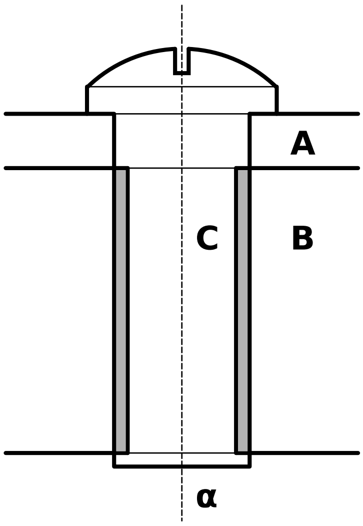

Figure 8: Cross section of an idealised representation of threaded connection in a cap-screw, showing the interference zone in grey.

dent to α_I;

- Conical surfaces with an apex coincident to α_I.

Finally, the force is propagated to the assumed thread through a planar contact in case of cap-screw, that is, the contact between the upper most piece and the head of the screw.

Intermediate contact should not only be parallel (or have parallel global norms), but they also should be non-coplanar. Consider the example shown in figure ????, where two cap-screws assemble three plates. The geometric analysis of the model generates the graph depicted in figure ????. In this example one may mistakenly consider two screw-head/upper-most-piece contacts as part of the same internal stresses loop, as both contacts are parallel to the thread axis. However, this conclusion is faulty, as internal efforts cannot propagate orthogonally to their direction, thus, contacts (parallel to efforts) cannot be coplanar.

This is the result of the consistency of our model. If no such contacts exist (that are globally orthogonal to the axis α), and as long as the model is consistent, the threaded connection theory is invalidated, and another interpretation of the cylindrical interference should be investigated.

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