Visual representation aid in engineering design process: From axiomatic design towards knowledge intelligence

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Abstract. The notion of function has been a key element in most of the design methodologies. Its definition has been controversial within the research community, with issues arising when methodologies rely solely on one universal strict definition. Axiomatic design relies on functional decomposition, which has as a perquisite the correct definition of the main function and subfunctions of a design problem. The inability of design methodologies to be incorporated into CAD and the absence of a systematic way to store precious knowledge occurring during the design process itself becomes a hurdle for true automation and intelligence in design. This paper proposes a visual representation process of the design problem, which verifies itself through relational graph representations and the physical laws governing the structure, where they are given valuable semantics. Knowledge can be inferred, stored and analysed with the scope of making engineering design more intelligent and potentially more automated.

1. Introduction
The conceptual phase of engineering design, is crucial for the quality of the final product. Computer Aided Design (CAD) is the most popular tool to assist designers with the visualization of their model but it is inefficient for true intelligence, because it conveys mostly mere geometrical information, an issue recognised since decades [1], [2]. CAD has developed tools like Knowledge Base Engineering (KBE) in order to become more intelligent, but only managed to automate routine design tasks. KBE Systems are not considered to be alternatives to CAD but rather a sophisticated blend of AI, CAD and object-oriented modelling, which has the potential to capture and efficiently reuse the knowledge [3]. Semantic knowledge in CAD is still poorly handled, and Product Life Management (PLM) systems still fail to capture significant semantic knowledge being generated during the design process.

At the same time academic research tries to fill the absence of semantics in CAD and systemizes design with the development of the field of the “Design Theory and Methodology” [4]. The main objective of the design is the mapping of function to artifacts and products. Erdem et al [5] offers an extensive review of Functional Modelling methodologies and their evolution through years. Among them, Axiomatic Design [6], has been particularly popular in the research community and has also been applied in industrial practice with success, compared to other methodologies.

Vermaas [7] and Dorst [8] believe that the notion of function itself cannot be objective as researchers would like to for a universal application, since it has been used differently among different theories. In AD, according to [9] very often mistakes in the notion of function happen, because there is a presence of physical information in the functional requirements, which prevents the creation of a solution-neutral design environment, it violates the first axiom of AD and trivializes the mapping process between the functional and physical domain. Similarly in other methodologies, ambiguities in the notion of behavior, function and structure appear [10].

The intuitive nature of the design process demands a flexibility of communication between different levels of abstraction in the ill-structured design problems. The standard approach to accumulate and represent abstract knowledge, demanded very hard work and the results were far from
satisfactory. Systematic ways need to be found to induce, represent and manipulate large databases of structured, abstract knowledge, often in causal nature towards the way of robust intelligence [11]. The bottleneck is not the reasoning, but having the right information accessible in the context of real-world inference, which is very often the case of case-specific design methodologies which do not communicate between them through a dynamic flow of information.

In this paper, we propose the incorporation of visual graph elements during the design process, which by default denote functional semantics because of their visuospatial relationships. A strict definition of function is not enough to explore the design space alternatives, but the visual graph elements together with their relationships and the physical laws that govern them, may indicate knowledge and semantics essential to achieve any design intelligence.

2. Capturing the design process in methodologies

In the early design phase according to Kleban [12], designers tend to rely more on ad hoc representations (i.e., sketches) and communicate a lot to exchange information. Systematic methodologies may serve as a tool to capture knowledge in this phase and aid the designer to make decisions through a systematic way, however designers are reluctant to apply them to generate their initial decisions [13]. Most of the methodologies which developed to systematically aid and automate this phase, rely on the notion of function and in particular to functional decomposition, which has its roots in the 70’s [14].

Function, according to Umeda and Tomiyama [15], is the bridge between human intention and physical behavior of artifacts and consider hierarchical decomposition the main task in design. In a conventional application of the methodology the procedure is top-down from abstraction to detail without the important interaction between levels of abstraction which actually occur in the design process [16]. The functions are decomposed into subfunctions until they can be associated with some physical features.

A lot of researchers tried to formalize functions into basic categories so as to automate functional modeling, by treating a device as a black box that transforms energy, information and signals flow [17], [18]. Kitamura et al [19] developed functional ontologies in the SOFAST software with main functions being described by verb and noun descriptions for flow-based modeling in order to provide a universal language between researchers to describe their devices, but difficulties on implementation arose due to the limited freedom these representations offer.

Gero [20] tackles the problem of static representation with dynamic change in the design context, introducing the Function-Behavior-Structure model (FBS) with function being the intermediate between the goal of the human and the behavior of a system and with structure being the means to achieve this function. The model supports functional decomposition by relating sub-functions to structural features and to their physical states in order to achieve the former. Dorst and Vermaas [10] make a critical review about the ambiguities introduced in the FBS model proving it to be unstable in consistent use.

Kannengiesser and Gero [21] recently revisited the design thinking methodology and its link to cognitive science. According to the dual-system theory on Kahneman’s book that the paper revisits, the human cognition is governed by two systems, a fast, intuitive and effortless thinking and a slower analytic thinking which requires greater effort, with the first being the one which governs our daily activities. This finding, questions whether we are able to decide on problem solving in an objective manner. If dual-system theory plays indeed a role in design, then a design tool support for system 1 and system 2 design thinking is likely to differ. Most of the design methodologies and implementations rely heavily on system 2 without proposing anything for system 1.

Axiomatic Design (AD), offers a systematic way of analysing problems by considering high-level Functional Requirements (FRs) mapped with a zig-zag process to the Design Parameters (DPs) by fulfilling the independence and information axiom. The zig-zag process offers the designer a chance to modify the problem and explore the design space, having a significant representation flexibility benefit compared to other methodologies. AD has been proven to be particularly helpful in situations where
designers are trained on how to apply the methodology and possess a great amount of knowledge for the design problem they want to solve. Successful industrial applications of AD have been mentioned, which concern mostly big enterprises [6].

Nakao and Iino [22] completed a survey with engineering students implementing AD. They found out that it is very hard for students to handle abstract concepts and are weak in dealing with FRs without physical substance. The students tend to list FRs chronologically and DPs spatially. FRs cannot be inferred from DPs and the students have to express invisible FRs with only verbal expressions. Some of occurring issues the methodology has, such as the FR being mixed with non-functional requirements have being mentioned in [9].

Little attention has been given to intuitive design and how to capture knowledge in this phase. By default the designer cannot have all the information it is required to solve the problem at the very beginning as proposed in most methodologies, but could benefit from various representation tools with less formal schema, which could provide a more convenient cognitive way for the human brain to extract potential FRs or DPs and explore the design space.

3. Visual Representation and ad-hoc modeling

Peirce with his semeiotic theory [23] who invented the most widely used notations of logic and believed that every mathematical (logic) reasoning is diagrammatic and especially found in graphs. Early Entity-Relationship (ER) graphs with the purpose of automating assembly design were able to represent basic hierarchical relationships, but didn’t offer a way to escape explicit modelling of the graph prior to analysis [24].

Sowa and Majumdar [25] explore analogical reasoning by using conceptual graphs (CGs). Conceptual graphs are linked to relational databases, which represent a model with its entities, attributes and relationships. Sowa also believed that the rules in the CG are fundamentally graphical: they are easier to show than to describe, that’s why he created graph grammar rules. The type of concepts and relations in a CG reflect the choices made by the original programmer, which in turn reflect the options available in the original programming tools. With class hierarchies and strict ontologies, the designer has some weak tools to represent the complex nature of the design process.

Yaner [26] extends the Structure-Behavior-Function model [27] and adds drawings and shapes for representation in the standard functional descriptions. Spatial relations are seen as an intermediate between shapes and behavior, so explicitly link functional knowledge to visuospatial knowledge [27].

Goel believes that the functional knowledge should be grounded to visuospatial knowledge [27].

Liang and Paredis [28] realize the importance of graph representation for a systematic and possibly automated exploration of design alternatives and classifies types of ports according to the FBS system. Ports are interfaces that connect elements of a system and through them energy, material flow and signals flow, a notation originating from the black box theories. In contrast to other methods in this work they don’t consider only input and output flows but also internal flows which give semantics to the components themselves.

Kokotovich [29] explores the design thinking process during the design and the different way novice and expert designers operate. The network structure without class hierarchies, is the richest, assisting the designer in developing an understanding of the problem space and the dynamic interrelationships among the design issues. Hierarchical mind map in design fails to describe via text or graphic images the supporting rationale or complex symbiotic relationships between issues.

Towards this direction Mavrikas et al [30] applied their method of Synaptic Networks on a case study of a Helicopter gearbox by creating a topological graph model consisting of elements, interfaces and contacts in a non-hierarchical manner. By representing the system visually, they were able to trace the functional flow paths and realize solutions which were non obvious before the representation analysis and they access the idea of modularity by re-arranging the graph. Similarly on another implementation of the Idea Algebra and Synaptic Networks Amrin and Spitkas [31] make a topological representation of an automotive drivetrain and trace again possible flow paths regarding force and torque equilibrium by extracting information of the relative position of the components. The model
however requires an explicit definition of its topology in order to perform automated reasoning about its function, which is often not easy to have in a design synthesis phase.

An intelligent model is the one which supplementary to our subjective thinking can include some objective elements that can be inferred not only by the visuospatial representation of components and its mapping to physical behavior (like in Idea Algebra) but also from an intelligent relational model expressing the possible different roles a component or its attributes can have in a system, without the restriction of a strict class hierarchy. The model should be able to support the gradual design thinking process by being dynamically expandable.

A potential tool for the application of this model in computers, could be one which utilizes knowledge graphs KG (intelligent graph databases). Grakn is developed by a startup company named Grakn Labs Ltd, offering an innovative KG tool which relates entities, relationships and attributes. Messina et al [32] give an early introduction to Grakn knowledge graph and its role in handling complex biological research data. It is not a traditional graph database, but a knowledge schema that may include nested relationships and infer non obvious ones. Grakn supports the gradual building of the model and provides automated reasoning while enabling the necessary flexibility to represent complex relationships, being found in a system/device. Grakn can offer an advantageous way to represent components in a system but additional schemas should be developed which support physical laws required for analysis as integral part of engineering design.

In figure 1 the fact of “Marry married Peter on 2/2/2020” can be represented in Grakn as depicted on the right, while compared to a standard entity representation on the left. The person in this Grakn representation plays the role of the spouse in a marriage relationship and attributes are linked to them. The representation is advantageous since now more marriages which happened on the same date can be attached to it and the graph can extend. An analogy can be found also for engineering relationships.

![Grakn Representational Schema](image)

**Figure 1.** Grakn representational schema on the right compared to a standard entity one

### 4. A case study:-Comparisons with AD

The case study comes from an actual design project encountered by one of the authors. The client is an R&D firm in the field of optomechanics and needs assistance in designing some components in their optomechanics set. In particular the client asks for the design of a component which is going to attach a rotating mirror with a motor that provides motion to the mirror while the latter is located within one degree tilt from it. In engineering practice, such abstract descriptions about the design project and its goals are quite usual and designers are accustomed to these. It is widely accepted that the designers themselves with their expertise, have to interpret these into actual engineering requirements. In order to solve this problem with AD the designer would have to define the highest level FRs and then map them to DPs, probably by collecting more information to define this primary function. The scope of the case study is to present an implementation of a visual representation graph-like schema, which aids the design process by providing implicit functional information based on relationships between the components and indicating the physical laws of the problem.

This is achieved through the use of simple shapes which represent components, but spatially position them in 2d space, in a way to cognitively perceive the structure. The human brain is familiar with such a technique, which, by analogy, is similar to designing something in CAD for visual perception in the design synthesis phase, but without the tedious modelling process. By placing the
motor next to the mirror (figure 2) an alignment relationship is implied, as well as rotation around the same axis (Axis 1), which was confirmed that it was indeed the case with the client, since motion can be transferred also when the axes of the components are not perfectly (or at all) aligned (alternative design solution). This is a type of knowledge that this form of visual representation is able to imply (semantics).

It is also required to represent the one-degree tilt requirement, so the client further explains that the mirror should be attached onto something that is in between the motor and the mirror and should be in one degree tilt relationship from the plane of this object, as depicted in figure 3.

![Figure 2. Motor and mirror rotate around Axis 1.](image1)

![Figure 3. Mirror should be at one degree tilt from the plane vertical to the yet undefined ‘something’.](image2)

The level of abstraction in the visual representation is a matter of design choice and the motor could still keep considered the motor as a black box or could be analyzed into basic components (figure 4).

The motor and the mirror are parts of a specific relationship A which indicates transfer of motion. The design becomes more detailed as more specific elements are gradually added according to the client’s description; the whole set should be installed on an optomechanics base component in a mechanical fixation relationship, depicted by B in our representation (figure 5).

![Figure 4. More detailed view of the motor.](image3)

![Figure 5. Relationships A and B defining the relational topology of motor, mirror and optomechanics base component.](image4)

The relationships in this graph like representation, do not comply with the functional basis taxonomies in their description. They also do not comply with the one-way attributions been given in class hierarchies. The system is perceived in its wholeness and the problem as underdetermined as it is, so the components are not limited in a unique relationship. For example, the motor can play the role
of transferring motion in a transfer of motion relationship but could also play a different role in another type of relationship which could be later defined, following the Grakn relational schema, described in Section 2. This description enables a more realistic view on design problems.

The components are seen as members of functional modules, but not in the sense of the black box being mentioned earlier (input-output) but as graph modules being part of a relative topology which consists of a combination of relational and physical phenomena relationships. For example, a module that can potentially satisfy A, could be a standard shaft-coupler-shaft solution (figure 6) with one of the shafts being the component which shares relationships within two modules. The relationship A is a result of the relationships E, C, D, F. A suitability verification for introducing the shaft-coupler-shaft to take the place of A, would have been the crosschecking for satisfaction of physical laws (torque transfer, etc.) together with the satisfaction of relationships and roles. For example, the shaft should play the role of torque transfer medium in a transfer of motion relationship, instead of the shaft playing any role in a relationship which doesn’t concern transfer of motion. If relationships and roles in the graph schema merge and if by laws of physics the solution is appropriate, modules could be inserted to substitute certain relationships of the graph like A.

**Figure 6.** Nested relationships of all components.

In a similar manner, different location possibilities for the optomechanics base component can be explored and evaluated. The client has a standard post holder component as depicted in figure 7 and has to find a way to fix the whole structure on this base component. The optomechanics base component by default receives other components and secures them in place. If the optomechanics base component should be attached to the structure, a component that is geometrically suitable to fit in it should be found, which in this case could be only the shaft (cylinder). However, the optomechanics base has no moving parts so it cannot accept the moving components of the shaft-coupler-shaft module since they all represent a transfer of motion relationship while the optomechanics base component only served fixation relationships. In creative design though, different possibilities can be explored to include moving components on the optomechanics base component or static elements on the shaft-coupler-shaft module so as to satisfy the physics for the continuity of the model.

Since B cannot be attached to moving shaft-coupler-shaft module, the only static component of the structure is the main body of the motor. The relationship B should have an additional component which can satisfy the fixation relationship and the geometric relationship of attachment to the motor, since there is no matching geometry to assemble, already there. The motor has threads on the left side so the optomechanics base component together with the extra component of the B will have to share same positioning requirements since they are in a fixation relationship. This way of analysis is part geometric part spatial, part functional, which provides a more holistic view of the design problem. A fixation relationship can translate into physical spatial characteristics, which means that if the optomechanics base component is fixed with the motor in a way which will cause its rotation like in figure 9, the motor follows its spatial position and vice versa. This reverse relationship is something that could have easily not been taken into consideration as a fact as well in AD. By exploring the different spatial positioning possibilities of the optomechanics base component it intuitively appears...
that these components are placed on the base plate in a fixation relationship G as well. The base plate in this problem appears to be the absolute reference for spatial positioning.

![Figure 8. Standard optomechanics base component](image1)

![Figure 9. Moving optomechanics base component to the static component and exploring position possibilities according to geometric requirements](image2)

It is the first time that the relative position of the base plate to the whole assembly is introduced as a concept. The client has taken this for granted and didn’t initially explain this, since what they tried to reach was a solution to fulfill relationship A. The optomechanics base component is in a positioning relationship (G) with the base plate. In the standard notion of hierarchic relationships, the base plate would give a position to the optomechanics base component and this would give the position to the rest of the assembly since the base plate is the absolute reference frame. Semantic-wise the E, C, D and F relationships, are all required to result in aligned and connected together components, since that is what the laws of physics impose for this type of coupling transfer of motion and if the mirror has to move, the whole block of Motor and Shaft-Coupler-Shaft would have to move together with the optomechanics base component as well, since it is in a fixed relationship with the motor.

After talking with the client, it was found that what appears to be the primary functional requirement which would have been required to be known for AD decomposition, is a lot more complicated and non obvious than what at first the client had explained. As a matter of fact, the first requirement that the client mentioned, is a combination of two potential subfunctions which would follow the independence axiom.

The Base Plate plays a specific role in this model, but can also play other roles in other models (following the Grakn schema). For every optomechanics component that is placed on the base plate in a fixation relationship (which could have a physical mapping to x,y,z coordinates), the base plate will always play that certain role of a “giving position” component in a positioning relationship, additionally to a fixation one. The motor and the mirror now are parts of the whole assembly of the optomechanics set, since the representation can expand, having the base plate as a common sharing semantics component.

The degrees of freedom of the optomechanics base component in relation to the base plate is its rotation around its axis and around a specific center of rotation on the base plate. If the whole current structure rotates around this center, it is possible that the structure will interfere with other components spatially. More information is required from the client whether it is the motor that has to rotate around that point or the mirror and whether they have predicted the spatial interferences.

The client answered that it is the mirror that should have the flexibility to rotate in the set up since it plays the role of collecting a light beam which comes from a laser and the rest of the components of the general assembly are placed spatially in such a way as to capture that. The specification of the one-degree tilt is for converting that beam into a light cone which is the main information for the design problem. Therefore, the client could have defined a more accurate primary functional requirement; the mirror should receive a light beam and convert it into a cone. This description would have been essential for performing AD functional decomposition, but it was not until this point that it was
feasible to address the bigger picture of the problem by the aid of the visual representation of the model. The initial description was already decomposed into two FRs and unable to indicate the main physics problem behind the design.

So as to accurately control the position of the mirror with reference to the Base Plate, the optomechanics base component should be transferred towards the mirror. Since the mirror is rotating, it would be required to be connected with an intermediate component which is stationary, like a frame/base, which was already considered before. In this phase the representation can indicate two solutions:

- There could be a stationary component which contains the rotating mirror and provides a plane with respect to which the mirror can lie at one degree tilt.
- There could be the aforementioned, which also has that type of geometry that the motor can be fixed on (it has been left without fixation since the optomechanics base component moved)

Therefore, this procedure would lead to two (at least) different solutions, which implicitly denote different physical laws and semantics. Accepting that relationship-wise the components are in compatible connections from the relational graphs the second verification comes from the physics. For example, the solution of figure 7 was good enough before it was realized that the optomechanics base component had to move towards the mirror. However, the solution had formed a cantilever. Rotating components which belong in cantilever structures, cause vibration which can lead to the excitation of eigenfrequencies and lead to system failure. The client only later in the design process mentioned that the mirror has to rotate at 2200 rpm, which can lead to significant vibration phenomena which can affect the whole assembly and have a negative effect on the light cone. In that case, the graph model acts in a preventive way, as it alerts the designer for failures.

Eventually more than one acceptable solution can be found which should:

- Comply with matching relationships and roles of the components
- Comply with the laws of physics

The design problem as initially described, proved to be almost misleading for the main design goal that was to be resolved. This is not the fault of the client, neither the designer’s, but it is the nature of ill-structured design problems. Universal vocabulary or strict class hierarchy descriptions may lead to partially right descriptions, however excluding the possibility to dynamically change the model while exploring the design space. One could consider that the information of this design problem did exist since the beginning, but it was not until the design synthesis between the different layers of abstraction, that managed to retrieve the main objective of the problem and on which parts to focus for proposing a design solution.

In this research paper the focus was on a general description of the effect the method can have on the gradual thinking process, but in future work, a relational schema will be developed utilizing Grakn which will be coupled with physical laws. In that way, knowledge about the model and the process of the sequential design decisions will be able to be stored in order to be analyzed to extract valuable insights with the scope of improving design automation and advance in the use of AI in engineering design [33,34].

Conclusion

A visual process for representing design problems and design thinking is proposed, which implies functional semantics. There is no need to explicitly define the primary function as demanded by functional decomposition methodologies, since this is a piece of information which is complementary for the design solution. The nested relationships between the components, the flexibility of the representation schema graph and the observation of the physical laws implicitly denoted by the representation, are all equally important to contribute to a design solution. The research community admits the need of hybrid representations to capture the semantics of models. A need to translate academic research to computer language while benefiting from state-of-the art software tools is necessary for the creation of next generation design software.
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