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Physical Quantity Vocabulary for Functional Representation

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Abstract

The importance of functional representation cannot be overstated. In current practice, especially in the very early design stages, functional requirements are often randomly proposed and loosely represented, largely by means of human language. This paper presents a new function representation method, which aims to improve the consistence and accuracy of functional representation. The core component of the method is a functional vocabulary, which is composed of a set of carefully selected physical quantities. Traditionally, physical quantity is often used to measure the property of a physical object. Relatively few efforts have been devoted to employing physical quantity to represent functional requirement. Furthermore, we prescribe the designer to follow the IDEF0 modeling method to organize a pair of two physical quantities in the format of "input (design range) → output (design range)". Lastly, we propose to leverage the new method to support Axiomatic Design's zigzagging process, the decomposition operation in particular. Multiple practical examples and a case study are presented in order to showcase how to use the proposed new method to solve real-world design problems.

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Keywords: Functional representation, physical quantity, design method

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1. Introduction

Design is a function-driven decision making process. The important role that function plays in driving the early-stage design, conceptual design in particular, cannot be overstated. According to Axiomatic Design [1-3], functional requirement plays a critical role of bridging customer needs in the customer domain to design parameters in the physical domain. The important research questions concerning function include how to generate new function, represent generated function, analyze existing function, decompose a function into sub-functions, and map functional requirement to design parameter. For each research question, there exist a number of previous studies, such as Pahl and Beitz[4], Hubka[5], Ulrich and Eppinger[6], Ullman[7], Brown [8-9], etc.

The focus of this paper hinges on the functional representation. In the very early design stages when everything remains highly intangible, the designer often use their spoken language to randomly propose and loosely describe functional requirements. For example, it is often observed that the novice designer confuse functional requirements with design parameter, constraint, and performance requirement [teaching axiomatic design]. A key challenge of functional representation is how to reduce the ambiguity of language and to improve the consistency of description. In practice, it is often observed that different designers use diverse expressions to describe the same concepts, and even the same functional description may actually represent different meanings. As a result, given the same product, different designers often arrive at completely different, if not mutually conflicting, functional representation.

In the past, many efforts in the design community have been devoted to improving the accuracy and consistence of functional representation. For example, Szykman proposed a standardized representation of functions, which includes a schematics (information models) of functional representation and its associated flows, as well as some initial attempts to develop the taxonomy of functions and flows [10]. Szykman described a core representation of product development information based on the NIST Design Repository Project [11]. Little [12] summarized a common vocabulary for

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product functions and flows which is developed based on function analysis. Stone & Hirtz [13-14] integrated two independent research efforts towards a more established functional basis, resulting in a unique design language called functional basis, where product function is characterized via a verb-object (i.e., function-flow) format. Thompson introduces a method to structure the process of how functional requirements are proposed and integrated into the Axiomatic Design process [15].

This paper presents a new functional vocabulary that is developed based on a careful selection of 25 physical quantities. By definition, physical quantity refers to the physical property of a phenomenon, body, or substance, which can be quantified by measurement. Furthermore, we follow the IDEF0 functional modeling to organize a pair of two physical quantities, in the format of "input (design range) output (design range)", as a way to represent the functional requirement. Last but not least, we incorporate the proposed functional representation approach into Axiomatic Design's zigzagging process, in particular, to support the zagging operation (i.e., the decomposition of a FR into its sub-FRs while considering the constraint from the FR's corresponding DP)

2. Physical-quantity Function Basis

2.1 What is Physical Quantity?

Physical quantity refers to the quantifiable physical property of a phenomenon, body, or substance. Generally speaking, physical quantity includes base quantity and general derived quantity. Base quantity means those fundamental quantities, based on which, other quantities can be further defined. Seven base quantities have been defined by the International System of Quantities (ISQ), as summarized in Table 1 [16]. In contrast, the general derived quantity means those quantities whose definitions are determined based on the base quantities. In the context of engineering design, density, flux, flow, current are all commonly used derived quantities, which are associated with many other physical quantities. Sometimes different terms such as current density and flux density, rate, frequency and current, are used interchangeably in the same context, sometimes they are used uniquely.

There are two types of physical quantity: intensive quantity and extensive quantity. Extensive quantity means that the quantity of a system is equivalent to the sum of quantities of all the system's components. For example, the weight of a system is contributed by the weights of all its components, the energy of a system must count all kinds of energies of its sub-systems, etc. The examples of extensive quantity include energy, length, mass, momentum, volume, electrical charge, weight, etc. In contrast, an intensive quantity means that the system's value of quantity is independent of the combination of quantities of its components. For example, different components of a car have different temperatures of their own, and the car's temperature is not equivalent to the sum of temperatures of all its components. The examples of intensive quantity include temperature, hardness, pressure, density, etc.

Table 1. Base physical quantity name.

Quantity name	SI unit name	SI unit symbol
Length, width, height, depth	meter	m
Time	second	s
Mass	kilogram	kg
Temperature	kelvin	K
Amount of substance,	mole	mol
Electric current	ampere	A
Luminous intensity	candela	cd
Plane angle	radian	rad
Solid angle	steradian	sr

2.2 Physical Quantity Vocabulary for Function Representation

We propose to develop a basic physical quantity vocabulary, which is a group of domain-independent keywords with reasonable definitions in order to describe functional requirements, to meet emerging needs based on existing solutions, and to guide the decomposition process and further design improvement. We relied on relevant studies of mechanical engineering in order to scirelect the keywords for the physical quantity vocabulary. For example, we employed the notion of "thermodynamic system" to choose the key physical quantities concerning "energy". All mechanical systems need certain energy to power the system. The typical energy source include kinetic energy, potential energy, thermodynamic energy, etc. Heat can be defined as a form of energy due to the temperature difference between the system and its external environment. The notion of thermodynamic system suggests that there exist exchange of both mass and energy (in the form of heat and work) between a system and its surrounding. Since energy is an intensive physical quantity, the total energy of a system is equivalent to an addition of energies of all the system's components. Sometimes, external forces (e.g., magnetic field or electric field) also has impacts on the system's energy. In that case, the impacts must be quantified and added to the calculation of the system's total energy. The energy transfer made possible by temperature difference between a system and its surrounding is called "heat", and any other energy transfer except "heat" is called "work".

Based on the fundamentals of thermodynamics, energy exchange, and mass exchange, we selected three basic categories each with its key physical quantities, with a total of 25 keywords, as shown in Table 2, 3, and 4. It should be noted that, diverse product domains may require different, if not unique, physical quantity vocabulary. In that regard, the vocabulary we proposed in this paper is tailored to the design of mechanical systems, in particular.

Table 2. Base vocabulary of energy.

Energy	Physical quantity	Symbol	SI Units
Mechanical energy	Momentum	P_i	kg·m/s
	Velocity	V	m/s
	Angular Momentum	L	kg·m^2/s
	Angular velocity	ω	rad/s
Chemical energy	Amount of substance	n	mol
Pneumatic, Hydraulic energy	Flow	u	m^3/s
Electrical energy	Electric current	I	A
	Electric flux	Φ_e	Wb
	Electric field strength	E	N/C
Magnetic energy	Magnetic flux	Φ_m	Wb
	Magnetic induction	B	T，N/(A·m)
Radioactive energy	Luminous intensity	C	cd

Table 3. Base vocabulary of work.

Work	Physical quantity	Symbol	SI Units
Mechanical work	Force	F	N
	Displacement	s	m
	Moment	M	N·m
	Angular displacement	θ	rad
Expansion work	Pressure	P_d	Pa，N/m2
	Volume	V	m3
Electric work	Electric Voltage	U	V
	Quantity of electricity	Q	C
Surface work	Surface Tension	σ	N/m
	Area	A	m^2

Table 4. Base vocabulary of heat.

	Physical quantity	Symbol	SI Units
Heat	Temperature	T	K
	Heat flux	Φ_h	J/(s·m2)
	Quantity of information	S	bit，J/K

Considering the practical feasibility, we only included the macro-level energy, for instance, mechanical energy (e.g., kinetic, elastic potential, and gravitational potential energy), chemical energy, pneumatic energy, hydraulic energy, magnetic energy, and radioactive energy. And we purposefully excluded those micro-level energy (e.g., molecular kinetic energy, potential energy, etc.), which can hardly be applied to majority of today's product development tasks. Furthermore, in the real-world applications, it is extremely difficult, if not impossible, to clearly differentiate and uncouple one form of energy from another. For example, the electronic energy can be generated from electromagnetic energy, radioactive energy, magnetic energy, acoustic energy and mechanical energy.

According to Axiomatic Design, three criteria determine the quality of functional requirements: complete, minimal, and independent. Since physical quantity is used to represent functional requirements in our approach, we also followed the above three criteria to develop and to examine the proposed vocabulary. That being said, the vocabulary summarizes a complete list of key physical quantities, with no redundancy, which can independently represent ay functional requirement of a mechanical system.

The proposed physical quantity vocabulary is expected to enhance early stage design in the following ways. First, it allows the designer to reflect, duplicate the design process in a more precise and accurate manner. Next, it improves the novice designer's capability to propose and to represent functional requirements. Thirdly, it can facilitate designers to identify physically invisible similarities between artifacts of different categories, therefore opening new possibilities for design by analogy. Next, a physical quantity is always associated with a particular physical object, therefore, it may be used to facilitate the zigzagging process prescribed by the Axiomatic Design. Furthermore, Last but not least, the predefined physical quantity may be more easily understood by computers, leading to possibility of further advancement of design automation.

2.3 Use Physical Quantity to Frame Functional Requirement

Based on the physical quantity vocabulary provided above, we propose to use the IDEF0 modeling method [17] to frame or reframe functional requirement as a particular kind of relationship between an input and an output. And both input and output of a function must be one of the 25 keywords included in the above physical quantity vocabulary.

A bearing is a mechanical device used to fulfill the primary functional requirement to constrain relative motion towards the desired motion. This functional requirement can be decomposed into more detailed and specific sub-FRs. Take the air bearing for example, first the input of air flow is transformed to the output of pressure (FR_1), next the input of pressure is further transformed into the output of displacement (FR_2). Together, FR_1 and FR_2 achieve to realize the desired transformation from flow to displacement. Table 5 shows functional representations of different kinds of bearings.

Table 5. Functional representation of different kinds of bearings.

Design Parameter	Functioanl Requriement	Design Parameter
Sliding Bearing	FR: Flow (u) → Displacement (s)	DP: Sliding Bearing
	• FR_1: Flow (u) → Pressure(Pd)	• DP_1: Wedge clearance
	• FR_2: Pressure → Displacement(s)	• DP_2: Lubricant
Magnetic Bearing	FR: Electric current(I) → Displacement(s)	DP: Sliding Bearing
	• FR_1: Electric current (I) → Magnetic induction(B)	• DP_1: coil
	• FR_2: Magnetic induction (B) → Displacement(s)	• DP_2: Electromagnetic force
Air bearing	FR: Flow(u) → Displacement(s)	DP: Air bearing
	• FR_1: Flow(u) → Pressure(Pd)	• DP_1: Air nozzle
	• FR_2: Pressure (Pd) → Displacement(s)	• DP_2: Air

Table 6. Functional representation of different kinds of springs

Springs	Representation of FR using spoken language	Representation of FR using physical quantity
Coil springs	FR$_1$: to store kinetic energy	FR$_1$: Force(F)→displacement(s)
	FR$_2$: to release kinetic energy	FR$_2$: displacement(s)→Force(F)
Leaf springs	FR$_1$: to store kinetic energy	FR$_1$: Force(F)→displacement(s)
	FR$_2$: to release kinetic energy	FR$_2$: displacement(s)→Force(F)
Torsion bar springs	FR$_1$: to store angular momentum energy	FR$_1$: Moment(M)→Angular displacement(θ)
	FR$_2$: to release kinetic energy	FR$_2$: Angular displacement(θ)→Moment(M)
Air springs	FR$_1$: to store flow energy	FR$_1$: Volume (V)→displacement(s)
	FR$_2$: to release kinetic energy	FR$_2$: displacement(s)→Volume (V)

Spring is an elastic object often used to satisfy two functional requirements: FR$_1$ (to restore energy) and FR$_2$ (to release energy). However, without further specifying which kind to energy to store/release and the specific transformation mechanism, it is very difficult to explicitly distinguish different kinds of springs such as coil spring, leaf spring, torsion spring, and air spring. Table 6 compares the representation of FR using spoken language and using our proposed approach. Take the vehicle suspension system for example, its main functional requirement is to control the absorption and release of energy under different conditions. There exist multiple alternatives of springs (e.g., coil springs, leaf springs, torsion bar springs and air springs) that all can satisfy the above functional requirement. And the designer can refer to the Information Axiom, prescribed by Axiomatic Design, to select the best spring that has the least information content or the highest probability of success.

2.4 Use Physical Quantity to Support Zigzagging

We propose to use the new method to facility the zigzagging concept generation process prescribed by Axiomatic Design. A typical zigzagging process consists of three steps:

1. Zig operation: map a given functional requirement (FR) in the functional domain to its corresponding design parameter (DP) in the physical domain.
2. Zag operation: decompose the main FR into more specific and detailed sub-FRs, while considering the constraints from the previously chosen DP in the upper layer and downstream domain.
3. Zig operation: map the decomposed sub-FRs in the functional domain into sub-DPs in the physical domain.

In the context of Axiomatic Design's zigzagging process, the physical quantity vocabulary is most useful in the step (2), when there is already a physical DP determined as boundary condition. Note that, as its name suggests, the specific value of any physical quantity can only be determined when there is a physical object (i.e., DP in design) available to be measured. That being said, in practice, it is extremely difficulty to directly propose a general functional requirement using the physical quantity out of scratch. Below is an enhanced zigzagging process based on the

(a) Based on a certain customer need, propose a general functional requirement using spoken language or other functional representation technique.
(b) Map the proposed FR to design parameter (DP)
(c) Decompose the general FR into multiple sub-FRs according to the principles of "complete", "minimal", and "independent". The sub-FRs are described using one of the 25 key words within the physical quantity vocabulary, based on the format of "input (design rage) → output (design range)". Note that, the specific design range of both input and output of any sub-FR must be within the capability of the DP chosen in last step.
(d) Map the sub-FRs in the functional domain into sub-DPs in the physical domain.

3. Illustrative Example

This section presents two illustrative examples of how to use the proposed method to solve real-world design problems. The first example is regarding the product of CPU radiator, which functions to prevent CPU from overheating. Figure 1 illustrates a typical CPU radiator. And Table 7 presents its functional representation. Generally speaking, heat can transfer through three ways: conduction, convection, and radiation. The radiator cools a CPU through two steps. First, the heat generated by the CPU is exchanged to the surface of heat sink by means of conduction. Next, the cooling fan functions to dissipate the heat by means of air convection.

The second example is concerning the product of manager chair, as illustrated in Figure 2. Table 8 presents its functional representation that is framed using both spoken language and physical quantities.

Table 7. Functional representation of CPU Radiator

Representation using spoken language	Representation using physical quantity
FR$_1$: transfer heat from CPU to radiator	FR$_1$: Heat flux(Φ_h) → Temperature(T)
FR$_2$: dissipate heat to surrounding environment	FR$_2$: Flow(u) → Temperature(T)
• FR$_{21}$: transform electrical energy to kinetic energy	• FR$_{21}$: Electric Voltage (U) → Moment (M)
• FR$_{22}$: transfer kinetic energy to the fan	• FR$_{22}$: Electric Moment (M) → Angular velocity (ω)
• FR$_{23}$: limit shaft displacement in the axial and radial direction	• FR$_{23}$: Force (F) → Displacement(s)
• FR$_{24}$: diffuse heat by convection	• FR$_{24}$: Flow(u) → Temperature(T)

Table 8. Functional representation of manager chair

Representation using spoken language	Representation using physical quantity
FR$_{1}$: to provide user with support	FR$_{1}$: force → displacement
• FR$_{11}$: to support arm weight	• FR$_{11}$: force → displacement along vertical direction
• FR$_{12}$: to support body weight	• FR$_{12}$: force → small displacement along vertical direction
• FR$_{13}$: to support back weight	• FR$_{13}$: force → angular displacement in 360
FR$_{2}$: to provide the most comfortable position	FR$_{2}$: force → displacement
• FR$_{21}$: to adjust height of the side handle	• FR$_{21}$: force → displacement along vertical direction
• FR$_{22}$: to lock height of the side handle	• FR$_{22}$: force → zero displacement along vertical direction
FR$_{3}$: to move from one position to another	FR$_{3}$: force → displacement
• FR$_{31}$: to spin around	• FR$_{31}$: force → angular displacement in 360 degree
• FR$_{32}$: to move forward or backward	• FR$_{32}$: force → displacement along horizontal direction

Fig. 1. A typical CPU radiator design

Fig. 2. A typical manager chair design

4. Conclusion and Future Works

This preliminary study aims to initialize some long-term efforts of developing a domain-independent and common functional vocabulary, from which designers can select a limited number of functional keywords to frame their functional requirements. By doing so, the purpose is to reduce the ambiguity of functional representation especially at high abstraction levels and in very early phases. This paper presents a new functional representation method, the core component of which is a functional vocabulary that is composed of a set of carefully selected physical quantities. Furthermore, we prescribe the designer to follow the IDEF0 functional modeling to frame a functional requirement as a pair of two physical qualities, in the format of "input (design range) → output (design range)". Last but not least, because no physical quantity can be measured without a physical subject in place, we adopt the new functional representation method to support the decomposition operation within Axiomatic Design's zigzagging process.

The future works of this study will be approached from multiple directions. First, we will carry on the theoretical investigation in order to strengthen the foundation of the new method. There remains a few interesting research questions to be addressed. For example, does inclusion of the intensive quantity violate the Independence Axiom, how to organize the functional requirements that are represented as a transformation of physical qualities into a structured hierarchy, how to adopt the Information Axiom to evaluate possible alternatives of DP based on the design range of both input and output physical quantities. Next, we plan to conduct another case study on a more complex mechanical system, such as, a vehicle engine. The purpose is to explore and to validate the proposed method's effectiveness of reducing undesired complexity. In that regard, Suh's Complexity Theory could be a very useful framework [18], upon which, the new study may be carried on. Last but not least, we also plan to conduct a controlled design experiment in order to compare the proposed method with the traditional functional representation approach, in terms of their impacts on the designer's conceptual design performance.

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