5-2012

Qualified Affordance-based Design

Jun Hu
Clemson University, junh@clemson.edu

QUALIFIED AFFORDANCE-BASED DESIGN

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

---

by
Jun Hu
May 2012

Accepted by:
Dr. Georges M. Fadel, Committee Chair
Dr. Joshua D. Summers
Dr. Gregory M. Mocko
Dr. Jonathan R.A. Maier

ABSTRACT

Function-based approaches are taught by the engineering design community and implemented in practice. The most significant advantage of these approaches is that they can guide the designers to abstract the essential problems from the design requirements, build the function-based models, and consequently provide the direction of the solution. However, due to the lack of a consistent scientific definition on the meaning of the function, these approaches may be contradictory when representing human-centered aspects, features, and non-physical purposes. To address this issue, design researchers have pursued two general directions: (1) broadening the meaning of function and (2) introducing an alternative scientific concept such as “affordance” or “wirk” to compensate for the weaknesses of the functional descriptions. Research on affordance is the focus in this thesis. Although the term affordance has been introduced in design methodology, some significant details like representation, categorization, and application into mechanical design still need to be further studied.

Therefore, this thesis starts by analyzing the ambiguity of function in design to support the necessity of involving affordances, and then reviews and compares the usages of affordance in Human-Computer Interaction (HCI), Artificial Intelligence (AI), design, psychology, and philosophy. The research opportunities are identified from the review and the comparison of the various approaches. One of the opportunities is to qualify the affordance-based design. Therefore, a new categorization of affordances applicable for product design is proposed, including doing and happening Artifact-Artifact Affordances

(dAAA and hAAA), doing and happening Artifact-Environment Affordances (dAEA and hAEA), and doing and happening Artifact-User Affordances (dAUA and hAUA).

DEDICATION

To my parents

ACKNOWLEDGMENTS

First, I don’t know what words can express my gratitude to Dr. Georges Fadel for his wise guidance and continuous patience during my study and research over the past two years. He is always willing to help when my research encounters a bottleneck. It has been a pleasure to work with him and I believe that I have learned a lot from him. I also take this opportunity to thank Dr. Jonathan Maier and Dr. Paolo Guarneri for sharing their ideas in the early stage of my research and later on helping identify the problems in my proposal ahead of this thesis. I would also like to thank Dr. Joshua Summers and Dr. Gregory Mocko for supporting me throughout this research.

I would also say thank you to all the student members of the Clemson Engineering Design Application and Research (CEDAR) group. I always obtained bright sparks from the teamwork in the group. I especially cherish the time cooperating with Manh Tien Nguyen visiting CEDAR from the Technical University of Munich. We worked in the same area for half a year and discussed a lot on the research.

In addition, I am grateful to Dr. Jiquan Yang from Nanjing Normal University and Dr. Sabrish Babu and his group from the School of Computing at Clemson University for their significant and unselfish help during the building of the VR treadmill. I want to also thank Ms. Barbara Ramirez from the Department of English at Clemson University for correcting my English writing in this thesis.

Last but not least, I dedicate this thesis with love and gratitude to my parents for their unwavering support in the past twenty five years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

CHAPTER 1: INTRODUCTION

1.1 Motivation

The modern design theories and methodologies, a result of the rapid technological advance over the past half century, have been systematically developed and supported by designers' experience. Efficient and effective, they have aided engineers in designing both classical machines and modern devices.

One of the concepts in those design theories and methodologies is function. Important because function aids in creating product's conceptual models, which helps designers realize how a device works, connecting various subsystems of the internal system. As a result, function has become the foundation of many design theories and methods like German systematic design approach (Pahl *et al.*, 2007) and Axiomatic design (Suh, 2001), and by using these function-based theories and methods, designers can describe a product functionally in its early stage of development.

However, although function has been applied in design for years, this concept does not have a precise, clear, universally acceptable scientific definition. Therefore, designers apply the concept of function in their work, defining it according to their practical needs (Vermaas, 2011). In addition, some design methodologists like Vermaas (2011) tried to define it as a universal concept applicable to many aspects of a product; however, others like Pahl *et al.* (2007) tended to limit its range to how a product works, especially to design of transforming processes, specifically as they apply to the flows of energy, signal, or material, while not indicating aspects such as protective and supporting parts like shells and frames or user interfaces.

As a result of these issues, design methodologists continue to clarify the definition of function; for example, Erden *et al.* (2008) derived a common definition from practical cases, while others like Maier and Fadel (2000) believed that since there is no underlying theory supporting the consideration of function, the most fundamental aspect of engineering design, perhaps an alternative shall be considered to address the current limitations of function; thus, they first introduced affordance, a concept found in perceptual psychology (Gibson, 1979), developed a relational theory explaining its role in a designer-artifact-user (DAU) system (Maier and Fadel, 2005, 2006, 2009), and extended it further to prescriptive methods such as affordance-structure matrix (ASM) (Maier and Fadel, 2007, 2009). Based on the previous work on affordance and affordance-based design, this thesis reviews the concept of affordance in the literature, discusses its categorization, and applies it to the design example of a Virtual-Reality (VR) treadmill.

1.2 Thesis overview

This research work primarily aims to help designers understand the roles of affordances in the design process. This is accomplished through the case study of designing a VR treadmill. In this case study, different types of affordances are used to improve the different parts of the initial prototype generated through function-based design. To be specific, CHAPTER 2: reviews the previous research on function, affordance, and their respective design approaches from the communities of not only engineering design, but also philosophy, psychology, HCI, and AI. CHAPTER 3: briefly discusses the research opportunities when introducing affordances into design and provides the research foci of this thesis. Then, based on the use of affordances in the literature, a new categorization and its corresponding interaction models of affordances are proposed in CHAPTER 4: . Finally, CHAPTER 5: elaborates the conclusions drawn from this research and projects the prospects of affordance-based approaches in the future. The general research overview of this thesis is illustrated in Figure 1.1.

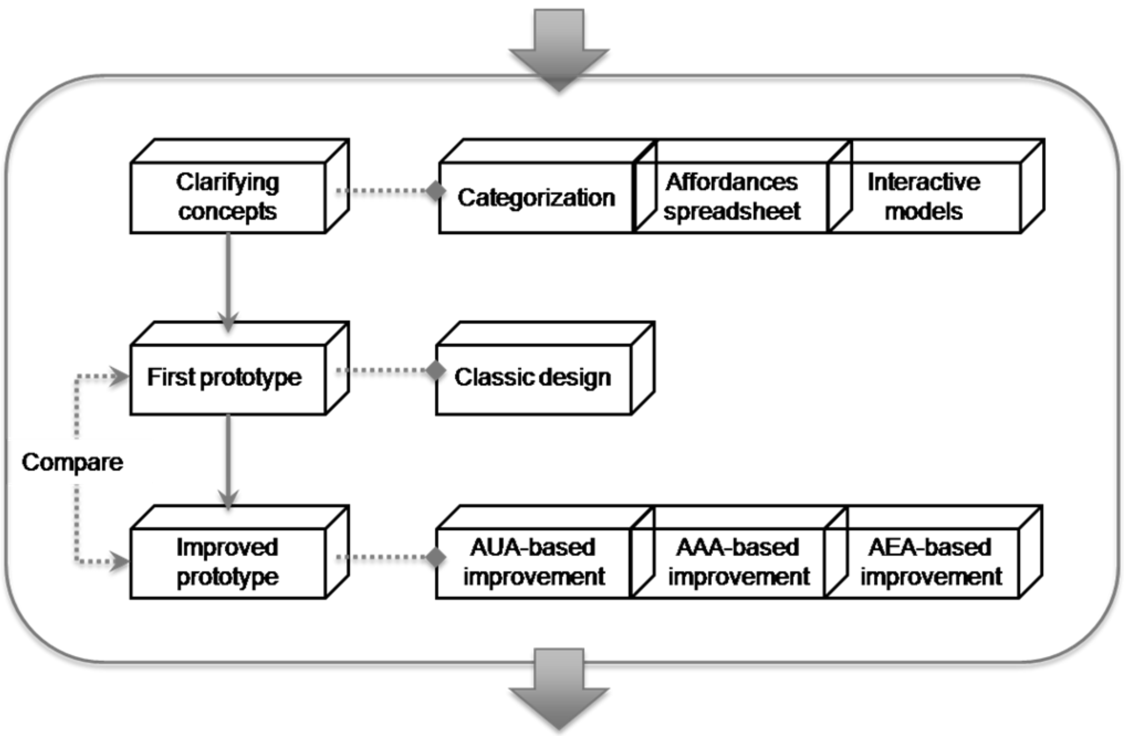


Figure 1.1: Research Overview

CHAPTER 2: CONCEPTS REVIEW

2.1 Function

According to Akiyama (1991), the concept of function was initially used in engineering by L. D. Miles, who introduced function analysis as part of his value analysis (VA) method in 1940s; later on, analyzing products functionally was developed by C. W. Bytheway, A. E. Mudge and M. Tamai in the 1960s. Then in the 1970s and 1980s, as Akiyama (1991) reviewed, Rodenacker, Richter, Koller and Roth successively proposed and developed function structures and function-oriented design methodologies. Following them, in 1984 Pahl *et al.* published the first edition of *Systematic Engineering Design* (Pahl *et al.*, 2007), a milestone that enhanced the fundamentals of function analysis, function structures, and energy-material-signal flows in what became later function-based design methodologies. An illustration of their function-based structure and three flows is shown in Figure 2.1 below.

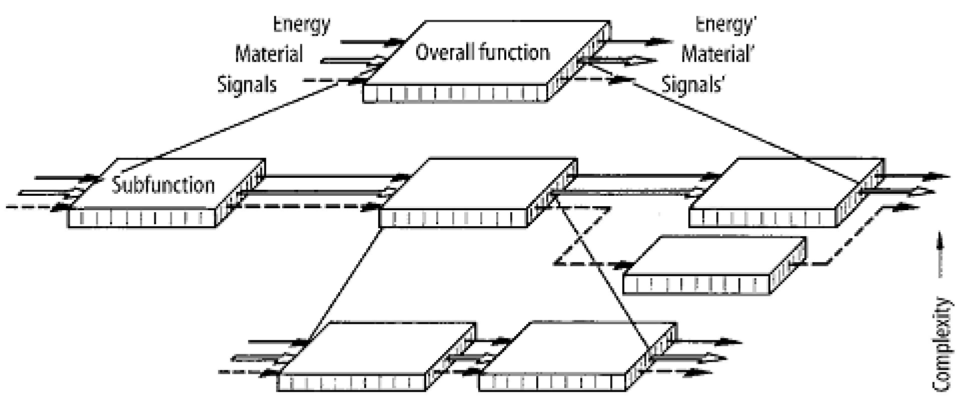


Figure 2.1: A typical function structure (Pahl *et al.*, 1996)

Pahl *et al.* believed that "Functions are usually defined by statements consisting of a verb and a noun, for example 'increase pressure,' 'transfer torque' and 'reduce speed.'" In this format, the noun can be identified based on the objects that are acted upon, while the verb cannot be apparently identified because one action can be represented by multiple synonymous verbs of abstract or specific meanings. Therefore, to help designers identify the verbs in functions, Pahl *et al.* abstracted five generally valid verbs (change, vary, connect, channel, and store) from various verbs that can be used in the function structure. Later on, Kirschman and Fadel (1998) suggested four basic groups of verbs (motion, control, power/matter, and enclose) to represent mechanical functions. Hirtz *et al.* (2002) proposed a more comprehensive vocabulary (six classes of materials, thirteen classes of energy, two classes of control, and eight classes of functions) for all the energy-signal-material flows and functions. Then Caldwell *et al.* (2009) investigated the frequency of using the verbs in the Hirtz's vocabulary based on the function structures of about 110 products and picked the top-eight frequently used (occurrence > 3%) verbs (transfer, import, convert, export, guide, change, actuate, store) to build a pruned edition of function vocabulary. Furthermore, Pailhès *et al.* (2010) proposed to view the subsystems in products only from the energy-based perspective, translated the subsystems into five characteristic energy forms, including converter, converter/source/sink, transmitter, link to the reference, and control/command as seen in Figure 2.2, and modeled material flows to eight types of energy flows as seen in Table 2.1.

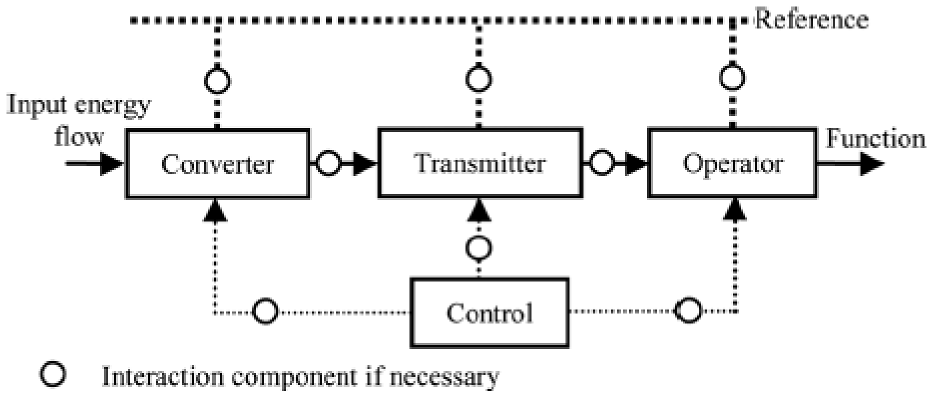


Figure 2.2: The energy-based functional model (Paihès *et al.*, 2010)

Table 2.1: Example of relevant conjugate variables (Paihès *et al.*, 2010)

Type of energy	*Relevant conjugate variables*		*Energy flow (power)*
	Temporal Variables	*State Variables*	
Mechanical (translation)	Speed (v)	Force (F)	v, F
Mechanical (rotation)	Rotation speed (w)	Couple (C)	w, C
Hydraulic/pneumatic	Volume flow rate (q_v)	Pressure (p)	q_v, p
Thermal (sensitive)	Capacity flow rate (q, C_p)	Temperature (T)	q, C_p, T
Thermal (storage)	Flow rate (q)	Internal Calorific Value (PCI)	q, PCI
Electrical	Current (I)	Electrical potential (U)	I, U
Static mechanical (translational)	Virtual speed (v*)	Force (F)	0
Static mechanical (rotation)	Virtual rotation speed (w*)	Couple (C)	0

Another influential design method, Axiomatic design (Suh, 2001), does not directly use functions but stipulates a set referred to as functional requirement (FR) that characterizes the functional needs of the product in the functional domain. The FRs are not listed in a specific format, but, based on the statements in the examples, they can be represented in the verb-noun format, providing a more flexible approach than that of Pahl *et al.* when representing functions. The basic premise of Axiomatic design is the zigzag mapping between four domains (customer, functional, physical, and process) as shown in Figure 2.3, with the key step of mapping Functional Requirements to Design Parameters ($\{FRs\} \rightarrow \{DPs\}$).

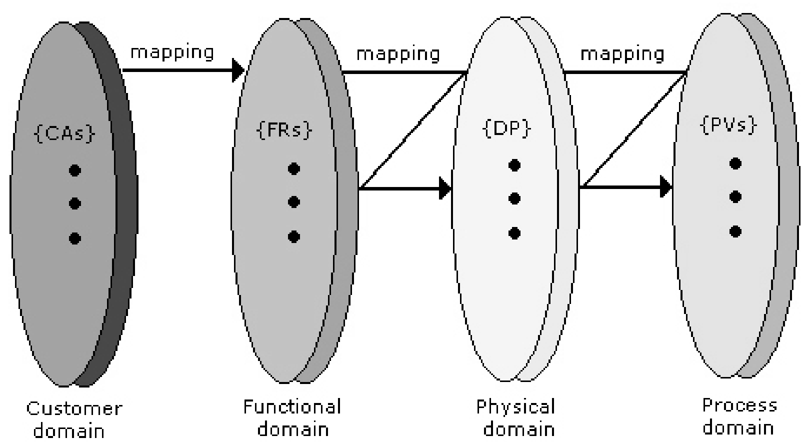


Figure 2.3: The fundamental concept of Axiomatic design (Suh, 2001)

In a separate development, Altshuller (1984, 1994, and 2000) from the former Soviet Union proposed a series of problem-solving theories named TRIZ (Theory of Inventive Problem Solving) in which functions are also used but with different meanings and properties compared to the use in the western world. For example, in the theory of Ideal Final Result (IFR), functions of a product are considered either helpful or harmful and the ratio of the helpful to the harmful represents the degree of ideality of the product (Fey and Rivin, 2005). While in another tool, named function-effect chart, thirty functions are listed and mapped to 100 scientific effects. Based on this chart, designers can select and identify the essential working principle of the design.

2.1.1 Ambiguous definitions in engineering

Although function has been the focus of much discussion and research, no canonical definition in engineering has emerged. Researchers, for example Erden *et al.* (2008), attempted to derive a universal meaning based on statistics using eighteen engineering models. However, their sample is not large enough to be representative of all the function meanings. Even they admit that their research is still "not yet on a level to develop an encompassing functional modeling paradigm." In 2010, Houkes and Vermaas published *Technical Functions*, a milestone in that it comprehensively reviews most mainstream definitions of function in natural science, engineering, and philosophy, proposing a series of approaches classifying them. However, given the background of these researchers, their explanations are primarily rooted in philosophy, with no corresponding engineering models being proposed. They suggest engineers accept the ambiguity of the concept and apply an appropriate meaning based on the task at hand, without providing a translation method for ensuring universal understanding of how the term is being used in a specific situation. Their suggestion is particularly problematic when a project is divided into subtasks, each completed by different engineers, before being synthesized.

While there is much ambiguity in the definition of function, essentially two types are used in the design phase. Some use it to mean the output from a system, while others consider function as a transformative relationship between input and output. For example, Akiyama (1991) asserted that functions referred to "dynamic, independent, and process-oriented actions or workings," while Chandrasekaran and Josephson (2000) and Ullman (2002) proposed they were the desired or intended outputs from a system, including its behaviors and properties. Altshuller (1989) believed the outputs of a product are functions in his Ideal Final Result (IFR) theory and identified positive or negative types based on judging them beneficial or harmful. Brown and Blessing (2005) provided an indirect definition, saying that "function is provided by behavior," a result that could be referred to as output action with its role being specified by either users or designers. In contrast, Pahl *et al.* (2007) and Otto and Wood (2001) indicated that function represented a general input/output transformative relationship of the product.

As the review above suggests, the primary difference between these two types of meanings focuses on which phase of the workflow from the input to the output should be defined as function. Actually, both perceptions can be valid, depending on the design problem to which they are being applied. For example, in analogy-based design, defining function as desired output allows designers to identify similarities and then find analogous examples (McAdams and Wood, 2002). On the other hand, in some cases, especially those involving apparent energy/material/signal transformations, considering function as an input/output (I/O) transformative relationship is more applicable. Pahl and Beitz's systematic approach is a representative example.

However, the two definitions have both distinct and common problems. Regarding the distinct ones, for the function defined as transformative relationship, it cannot represent the non-transformative relationships. For example, Maier and Fadel

(2009) argued that the function of a motor's enclosure is hard to identify; even if it is a common sense that the enclosure is used to prevent liquid contamination and, thus, protect the motor. The actions "protect" and "prevent" do not refer to any transformative processes. So do other non-transformative actions like retaining, guiding and supporting listed by Crilly (2010). As for the function defined as desired output, it can represent the non-transformative actions mentioned above but cannot specify the input. In addition, this definition is difficult to differentiate with other concepts also representing the desires like purposes, intents, and goals.

The two definitions also have two problems in common. The first is they cannot explain some significant aspects of a product, including (1) the human-centered aspects, such as controlling and operating, (2) the features, including color, shape, layout, or texture, and (3) the non-physical purposes, like entertainment and aesthetics (Crilly, 2010). These aspects, however, have been shown to be the crucial determinants in product evolution (Gaffney *et al.*, 2007 and Ericsson, 1999). In contrast, as shown in the same case studies, the functional aspects did not actually change much with the evolution.

The second problem is that the two definitions are neither translatable to each other nor explainable by a unique theory. Vermaas (2011) suggested the engineers continue to select the proper meaning of function based on their specific need; however, he admitted that no specific selecting or translating rules between the definitions could be found. He thereby believed that this problem creates ambiguity, which results in the difficulty when subsystems modeled based on different function meanings need to be synthesized into a system. For example, non-transformative actions like protecting, preventing, supporting can be represented as functions according to the definition as output actions but not by the one as transformative relationship, and, thus, they cannot be synthesized into Pahl *et al.*'s (2007) function structure and researched systematically with the transformative functions.

2.1.2 Prospects of clarifying the ambiguity

In order to address these problems on function, researchers have taken on two directions. On the one hand, some research continues to focus on improving the definition of function. For example, Vermaas (2010) proposed intentional-causal-evolutionary (ICE) functions, arguing that for users and engineers, the functions were different: engineers could design intentional functions and improve causal ones, while users could not only perceive the intentional and causal functions but also derive the evolutionary ones based on their experience and knowledge level. His research innovatively categorizes functions based on different social perceptions; however, his proposal is merely based on philosophical reasoning and literature review and it could be an opportunity in the future to implement this proposal into engineering examples. In addition, to represent more functional aspects of a product, researchers, like Pailhès *et al.* (2010), propose involving the concept of virtual work as seen in Table 2.1, allowing static conditions to be viewed as dynamic. For example, the function of a hair dryer enclosure is identified as "house assemblies" (Leung *et al.*, 2005); here "house" is a virtual dynamic action, restricting the virtual displacement of the assemblies it encloses. This proposed concept converts static conditions to dynamic ones, thus ascribing the geometric features of a product to a category that can be explained through functional meanings. However, other essential characteristics, color, texture, and luster, are still difficult to describe functionally, and cannot be attributed to virtual work. So furthermore, Crilly (2010) suggested the non-physical (e.g. aesthetic, ideological, social, status) functions to represent them. However, his proposal matches neither of the two definitions of function and, thus, still need to be supported by practical engineering cases.

On the other hand, since no underlying theory found in science supports why function must be the foundation of design methodologies, Fadel and Maier (2001) suggested involving “affordance” from perceptual psychology as an alternative.

2.2 Affordance

The term *affordance* was coined by the psychologist J. J. Gibson (1979) in the 1970s, and refocused for Human-Computer Interaction (HCI) by Norman (1988) in the 1980s. Since then, this concept has received much research attention in HCI, ergonomics, ecology, psychology, philosophy, and artificial intelligence (AI) over the past thirty years. According to Gibson (1979), the affordances are “what the environment offers the animal, what it provides or furnishes, either for good or ill.” However, the differences in focus between Norman and Gibson have resulted in two different use as summarized by McGrenere and Ho (2000) in their review of nineteen papers from the HCI community, with eight supporting Gibson’s, six Norman’s, and five citing both. Their comparison of the two meanings is seen in Table 2.2 below:

Table 2.2: Comparison of affordance as defined by Gibson and Norman (McGrenere and Ho, 2000)

Gibson's Affordance	*Norman's Affordance*
• Offerings or action possibilities in the environment in relation to the action capabilities of an actor • Independent of the actor's experience, knowledge, culture, or ability to perceive • Binary existence: an affordance exists or it does not	• Perceived properties that may or may not actually exist • Suggestions or clues as to how to use these properties • Dependent on the experience, knowledge, or culture of the actor • Can make an action difficult or easy

As can be seen in this table, the fundamental difference between the two is that for Gibson "an affordance is the action possibility itself," independent of the actor's ability to perceive it, whereas according to Norman affordances are used to "provide strong clues to the operations of things" (1988), dependent on the actor's ability and background, and thus "affordances are of little use if they are not visible to the actors" (1999). This difference is due to different research purposes: Gibson uses this concept in ecology to specify the relationships between an organism (people or animal) and the environment (various objects), while Norman uses it to help HCI designers optimize a product's interface layout to guide the actors to operate the product easily and properly. For example, both the ecologists and HCI designers focus on the affordance "sit-ability" of a chair in a visible environment. However, if this chair is moved to a room so dark that a person entering it cannot perceive the existence of the chair, for ecologists the affordance "sit-ability" is still useful as long as it exists (it can support the weight of the person without any change with the environment); while according to Norman, in this situation the actor cannot perceive the "sitting on the chair," and hence "sit-ability" is useless for HCI designers unless the person accidentally touches the chair or turns on the light and perceives the chair. Note here that an ambiguity occurs since Norman does not directly discuss the existence of the unperceivable affordance “sit-ability,” he instead neglects it as it is “of little use.” To further explain this difference, ecologist Gaver (1991) classified affordances into four types based on perceptual information as seen in Figure 2.4

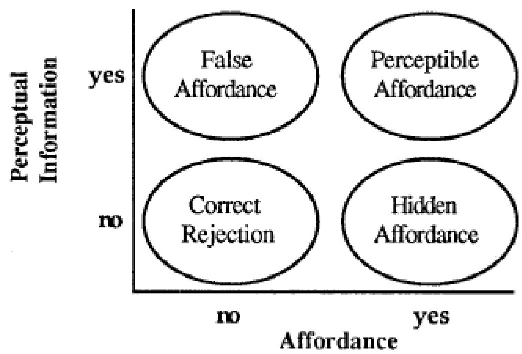


Figure 2.4: Separating affordances from the information that specifies affordances (Gaver, 1991).

The four quadrants of this matrix range from no affordance to affordance on the *x* axis and no perceptual information to perceptual information on the *y* axis. In this classification, the most important issue is that the affordance *per se* may be independent of perceptual information, which is similar to Gibson’s view. However, Gaver agrees with Norman that the actor’s culture, social setting, experience, and intentions can determine whether the affordances can be perceived, emphasizing that only perceptible affordances are useful in the specific application he considers interface design. McGrenere and Ho (2000) evolved Gaver’s four quadrants to a continuum as shown in Figure 2.5, claiming that “maximizing both dimensions can result in the improvements in the design.”

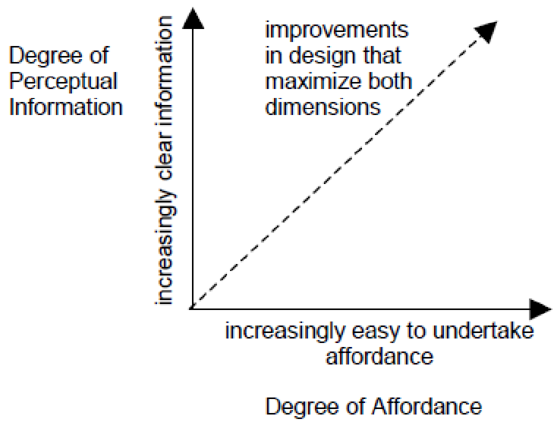


Figure 2.5: Representing the affordance and the information that specifies the affordance on a continuum (McGrenere and Ho, 2000)

2.2.1 Representation and format

Besides the arguments in the definition, issues also remain in representing affordances. Researchers attempted to represent an affordance similar to Pahl and Beitz's function format "verb + noun," in which the verb indicates a transformative behavior from input to output of the system. For example, Gibson (1979) proposed affordance can be represented as "verb + ability" or "afford verb (doing)," for example, a chair has sit-ability or affords sitting; but he did not clearly specify if the verb indicates an input operation from the environment to the object or an output behavior from the object to the environment. However, his analysis in his research works suggests that affordances can either be operations or behaviors, as he included not only the operation-type affordances like sit-ability, climb-ability, catch-ability, and eat-ability but also the behavior-type ones such as bump-into-ability, get-burnt-by-ability, and fall-off-ability. This view is supported and summarized by Scarantino (2002), the first researcher who distinguishes between the two types of affordances: goal affordances that manifest doings and happening affordances that manifest occurrences. Not quite so comprehensive, Norman equated "afford" with "is for," preferring the format of "afford + doing." Although he also does not specify whether the verb represents an input or an output action, his examples such as "chairs afford sitting" and "plates afford pushing," suggest he tends to consider the verb as an input operation.

In contrast, Maier and Fadel (2009) asserted that "affordances determine how the system can potentially behave" and improved on Gibson's format, rendering it more flexible as shown in Table 2.3:

Table 2.3: Affordance representations in Maier and Fadel's case studies (2009) of a vacuum cleaner and an automotive window switch

	Affordances	*Representation*
Vacuum cleaner	Translational move-ability	v. + ability (+ direction)
	Transport-ability	v. + ability
	Store-ability	v. + ability
	Stability	v. + ability
	Annoying user with noise	v. + n. (+ way)
	Cutting user	v. + n.
	Pinching user	v. + n.
	Electric shock-ability	n. + v. + ability
	Dirt remove-ability	n. + v. + ability
	Dirt contain-ability	n. + v. + ability
	Floor clean-ability	n. + v. + ability
	Furniture clean-ability	n. + v. + ability
	Drapes clean-ability	n. + v. + ability

	Loss of clean-ability by blocked air flow path	v. + n. (+ way)
	Blowing dirt in front of machine	v. + n. (+ position)
	Overheating	v.
Automotive window switch	Accessibility of all windows to passenger	v. + n. + ability
	Pleasing user with aesthetics of flushed surfaces	v. + n. (+ way)
	Usability of the same hand for shifting, radio controls, and window controls	v. + n. + ability (+ way)
	Frustrating user by unnatural mapping to window locations	v. + n. (+ way)
	Frustrating user by unnatural mapping of up/down operation	v. + n. (+ way)
	Ability to accidentally activation window up operation	v. + n. + ability (+ possibility)
	Reduces weight	v. + n.
	Reduces electronic redundancy	v. + n.
	Collecting dirt (loose crumbs)	v. + n. (+ reason)
	Becomes stuck (due to spillage)	v. + n. (+ reason)

Regardless of the verbs used, three formats are used to represent the affordances, including v. + ability, v. + n. (or n. + v.) + ability, and v. t. + n. (or v. i.) (v. t. stands for transitive verbs and v. i. strands for intransitive verbs). In addition, the additional part behind the phrases of verbs and nouns is the detailed information such as direction, way, position, possibility, reason or those more specific verbs. Such flexible usage extends the scope that affordances can represent; however, on the other hand, it results in three problems. First, there are no rules for selecting which of the three formats to use from the three formats to represent different affordances. Second, it is not clear if the additional detailed information is part of the affordance format. Third, since the additional information can be directions, ways, reasons or any supplements for either the verbs or the nouns, although adding them can specify the affordances, it meanwhile can greatly increase the variety of affordances and make similar affordances difficult to be differentiated. For example, a vacuum cleaner has turn-ability; if added with directions, then turn-left-ability, turn-right-ability, turn-20-degree-ability, and etc. are generated accordingly. If these are all counted in as affordances, then the number of affordances can become infinite, which is not indicated if affordances are organized and analyzed in the design process.

The crux of the differences in these representations is a result of how the researchers use this concept. For instance, Gibson, a psychologist and Scarantino, a philosopher, attempted to represent affordance as comprehensively as possible to clarify the relationship between the human and the environment; while Norman, who used affordances in the design of effective user interfaces, focused on representing affordances based on the input operations. Maier and Fadel preferred the happening-style format because they emphasized the polarity of affordance, allowing them to use their Affordance Structure Matrix (ASM) (2007, 2009) to evaluate the components of a product or to choose the best candidate from the proposed design plans.

Of these perceptions, Gibson's format "verb + ability" is widely accepted by most researchers from different fields, for example Gaver (1991) and Wells (2002) in ecology, Scarantino (2002) in philosophy, Raubal and Moratz (2006) in AI, and Galvao in HCI (2010). The reason for its acceptance is that compared to Norman's or Maier and Fadel's representations, Gibson's involves both the input and output actions, offering researchers enough freedom to combine affordance theory with their professional knowledge. However, this duality leads to a couple of problems. On the one hand, when trying to differentiate between the doing and happening affordances (Scarantino, 2002) based on whether the corresponding verb is an input or output action, researchers encounter problems with verbs representing a series of actions or processes, which are difficult to be distinguished as operations or behaviors. For example, a typewriter has type-ability; while the verb “type” indicates a combination of both input and output actions including the press-ability and select-ability of the keys, the power-transform-ability of the inner components, and the print-ability and see-ability of the paper.

On the other hand, if the two types are analyzed together rather than separately, researchers will encounter difficulty judging the polarity of affordance. It is easy to judge clearly whether a happening affordance is positive or negative based on the consequence resulting from its corresponding behavior. For example, a car can hit and injure a pedestrian, and this injure-ability is clearly a negative affordance. However, it is difficult to categorize a doing affordance as positive or negative. For example, a button has press-ability based on its design goal. If this affordance and all similar doing ones are considered positive because they contribute to the realization of the design goal, the side effects of the product such as noise and pollution triggered by pressing the button will conflict with the categorization. One possibility for resolving these issues is to decompose the process-meaning verbs into different lower-level ones and then classifying them. The key to this solution is an effective affordance hierarchy and classification theory.

2.2.2 Hierarchy and categorization

Currently most theories of affordance categorization and hierarchy are based on studies of human actions. For instance, Gaver (1991) classifies sequential and nested affordances based on grouping the input operations over time or space respectively. For example, a door has open-ability consisting of its handle's sequential affordances occurring from grasp-ability to turn-ability until the door's pull-ability is realized. While a coke can has open-ability, which requires the cooperation of two hands, i.e. one holding the can, and the other pulling the ring off, and the corresponding affordances grasp-ability and pull-off-ability exist simultaneously in space. Such researchers as Scarantino (2002) believed that "the category of human actions includes mental actions (e.g., dividing a number by two) and physical actions." Based on this perception, AI researchers Raubal *et al.* (2006) suggested three types of affordances, physical, social-institutional, and mental, to help program robots bionic cognitive ability. In addition, based on using three psychological reasoning to simulate the cognitive processes, Kannengiesser and Gero (2010) proposed three classes of affordances, including reflexive, reactive, and reflective affordances, which respectively represents the potential actions based on, derived from, and beyond users' perception. Furthermore, extending Norman's distinctions of affordances based on perceptible information, Hartson (2003) proposed cognitive, physical, sensory, and functional affordances as shown in Table 2.4 and Figure 2.6:

Table 2.4: Affordances types (Hartson, 2003)

Affordance Type	***Description***	***Example***
Cognitive affordance	Design feature that helps users in knowing something	A button label that helps users know what will happen if they click on it
Physical affordance	Design feature that helps users in doing a physical action in the interface	A button that is large enough so that users can click on it accurately
Sensory affordance	Design feature that helps users sense something (especially cognitive affordances and physical affordances)	A label font size large enough to read easily
Functional affordance	Design feature that helps users accomplish work (i.e., the usefulness of a system function)	The internal system ability to sort a series of numbers (invoked by users clicking on the Sort button)

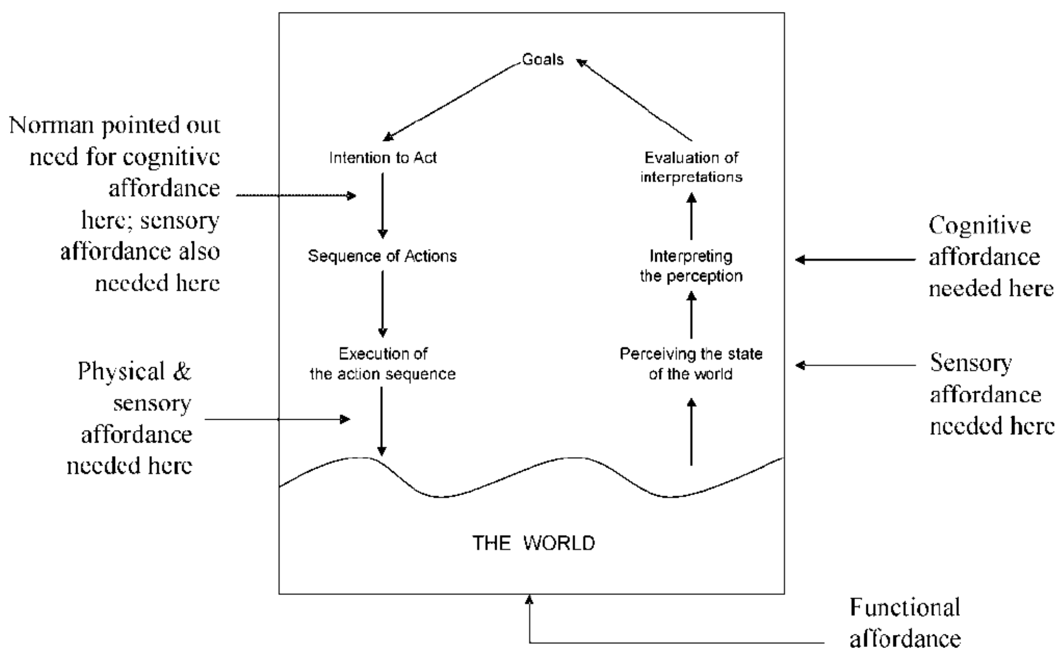


Figure 2.6: An illustration showing on which stage the four types of affordances may act (Hartson, 2003)

However, the descriptions of cognitive affordance and sensory affordance in Table 2.4 disagree with Norman's perception that "features such as shapes, fonts, and symbols determine culture constraints referred to as conventions, rather than affordances" (1999). Currently this difference still remains open to discussion.

Another affordance hierarchy and classification scheme based on human actions is from Albrechtsen *et al.* (2001), who adapted Rasmussen and Vicente's means-ends model from action theory, dividing affordance into five levels, ranging from physical properties to high level goals and intentions as seen in Table 2.5:

Table 2.5: Affordances structured with the means-end hierarchy (Albrechtsen *et al.*, 2001)

1. Value Properties: Purpose, Goal			
Survival	Pleasure	Altruism	
2. Priorities: Abstract Function			
Reward Cooperation Comfort	Danger Nurturing Pain	Nutrition Copulation	Manufacture Privacy
3. Context: General Function			
Communicating Washing Fighting Locomotion	Warmth Bathing Shelter	Drinking Injury Aiding	Eating Support Punishment
4. Movement: Physical Process			
Sit-on Climb-on Stand-on Breathing Throwing	Bump-into Sink-into Grasp-able Pouring Piercing	Fall-off Swim-over Barrier-cutting Carrying	Get-underneath Walk-on Obstacle-lifting
5. Objects and Background: Physical Form			
Layouts	Objects	Surfaces	Substances

Similar to Albrechtsen *et al.*'s scheme, Pols *et al.* (2011) categorized affordances to opportunities for manipulation, effect, use, and activity, which respectively represent the basic actions, actions described in terms of its effects, plans, and social actions. Both of Albrechtsen *et al.*'s (2001) and Pols *et al.*'s (2011) categorization schemes are based on classifying the corresponding actions gradually from specific movements to abstract effects.

One classification scheme not based on human action theories is Maier and Fadel's (2009) Artifact-Artifact Affordances (AAA) and Artifact-User Affordances (AUA) seen in Figure 2.7:

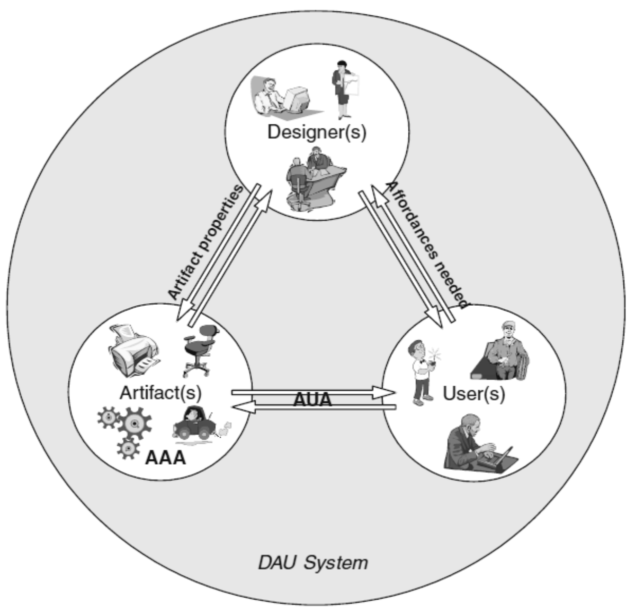


Figure 2.7: Affordance related interactions within a designer-artifact-user system (Maier and Fadel, 2009)

Maier and Fadel claimed that this classification extended the concept of affordance beyond the relationship between the human and the artifact, recognizing the affordances existing between the non-organism subsystems as AAAs, which made the affordance theory applicable in mechanical design. However, actually AAAs cannot represent the affordances between artifacts and the non-organism natural entities such as air, water, and stone; the categorization therefore needs further exploration.

2.2.3 Elements of affordance

Gibson (1977, 1979) initially defines affordances as “offerings or action possibilities in the environment in relation to the action capabilities of an actor,” suggesting affordances represent the interactive relationship between an actor and the environment. Slightly different from Gibson’s definition, Norman (1990, 1999) tended to specify the artifact entity within the general environment, focusing only on interface design. However, McGrenere and Ho (2000) still considered Norman’s work in the area of interaction research between an actor and the environment like Gibson’s. In addition, Shaw and Turvey (1981, 1992) considered affordance as disposition and propose an affordance schema, $(X, Z, O \mid X = Z) = Y$, reading as “*X* affords *Y* for *Z* on occasion *O* if and only if there exists a duality relation between *X* and *Z*.” Scarantino (2002) agreed, proposing a new schema as “*X* has affordance property *A* (at time *t* relative to an organism *O* in circumstances *C*).” Both schemas specify the artifact within the circumstances/environment, indicating the three vital elements in the disposition of an affordance as artifact, actor and environment. No matter if the artifact is specified or not, the user/actor/organism is the center, and all the actions and affordances encircle it. This user-centered perception is widely accepted in HCI, ecology and AI fields.

In contrast, Gero and Kennengiesser (1990, 2002, 2009, and 2010) proposed the function-behavior-structure (FBS) model shown in Figure 2.8, simulating the view of designers:

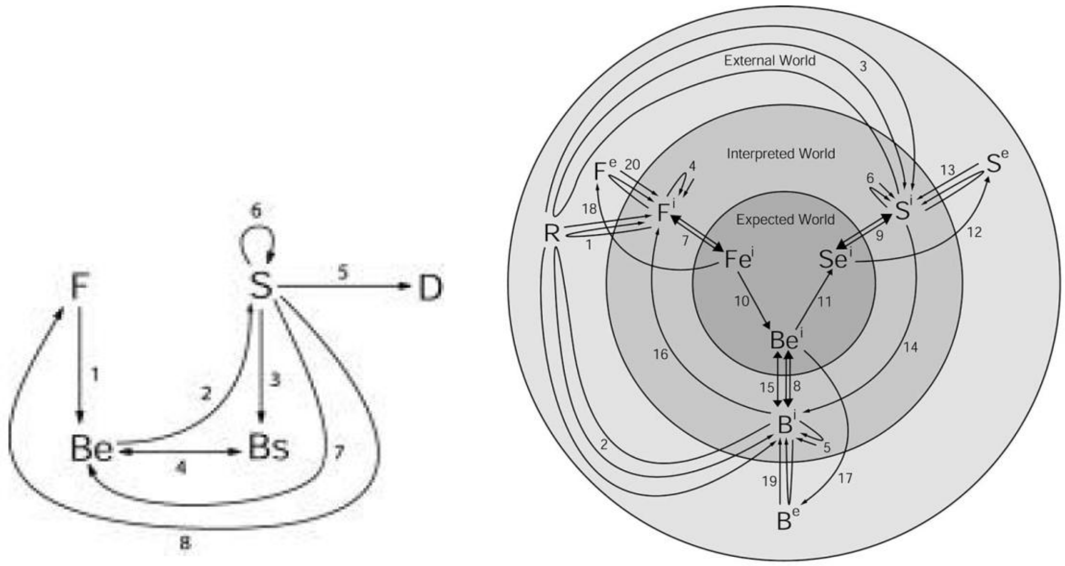


Figure 2.8: Gero's function-behavior-structure (FBS) framework (Gero and Kannengiesser, the left is the 8-step version published in 1990, and the right is the 20-step version published in 2002); *Xe* means the expected *X* (*X=F, B* or *S*)

This model integrates the cognition of users, their perceptions and the environment into the three levels of the world moving from the specific to the universal, suggesting that "affordances are generated in the process of Behavior→Structure" (Gero and Kennengiesser, 2010). More specifically, this FBS model illustrates the steps in designing a product as continuous processes, comparing the designer's expectations with the practical operations of users and the behaviors and functions of the structure. Different from Gibson's and Norman's, in this model a new determinant, the designer, is involved together with the user, the environment and the structure. Based on the FBS model's 8-step version, Cascini *et al.* (2010) emphasized how designers act in the processes, focusing on the bias between the their expectation and the product's practical use, resulting in the misuse, alternative use and failed use. In their framework shown in Figure 2.9, the different entities are separated from the concentric circles of the FBS, and, thus, the processes appear clearer than Gero and Kennengiesser's:

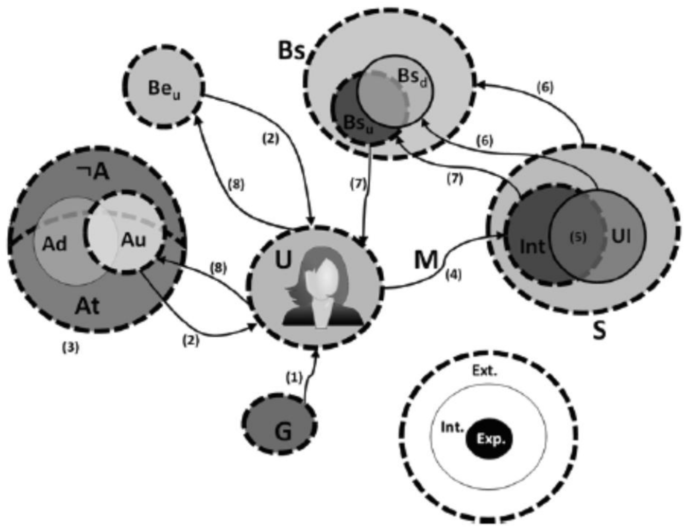


Figure 2.9: Schematic representations of links between the entities of the proposed extension of the FBS framework and relations with the situated model (Cascini *et al.*, 2010)

However, a common problem in both the FBS framework and Cascini's model is that they fail to represent the relationship between affordance and the other entities. Gero and Kannengiesser (2010) suggested that affordances are generated in the process of the users using the product, i.e. Behavior→Structure; however, the verb "generate" does not express clearly how these affordances are determined. Although Cascini's model includes the entity of affordance, in it the concept affordance is not linked with such elements as the environment and the structure.

Comparatively, the designer-artifact-user (DAU) system proposed by Maier and Fadel (2005, 2009) seen in Figure 2.7 and Figure 2.10 is more comprehensive than the

FBS framework and Cascini's model on three aspects: first, it illustrates affordances as potential interactions; second, it specifies both the natural and social factors into the environment; third, it involves the new concept artifact-artifact affordance (AAA), representing the interactions among artifacts. However, this model does not specify the interactions among the different entities in the three worlds as the FBS framework and Cascini's model do.

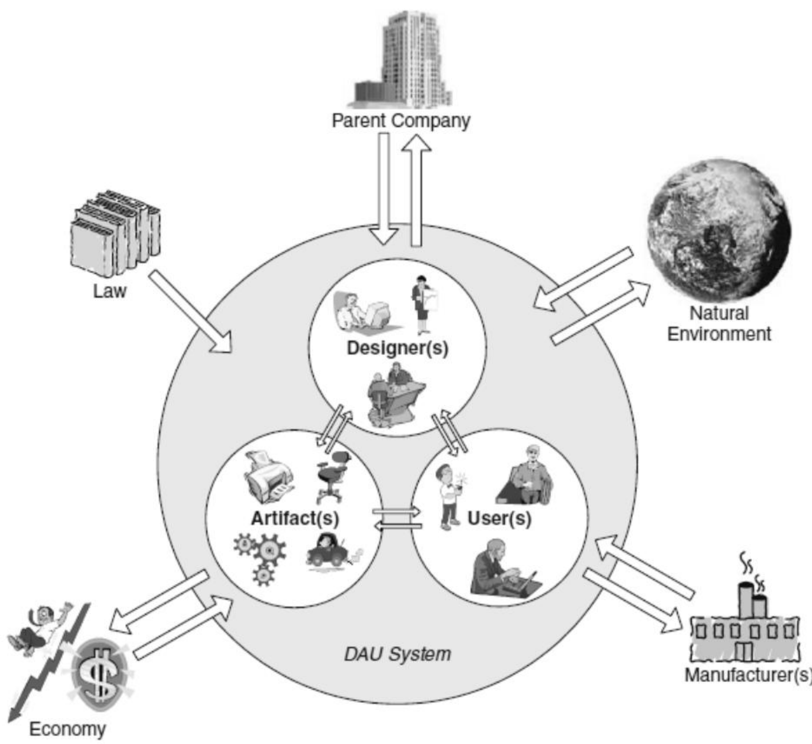


Figure 2.10: Generic situated designer-artifact-user (DAU) system (Maier and Fadel, 2009)

2.2.4 Effectivity and affordance

Although the seven viewpoints concern different elements of affordance, all emphasize the importance of the actor, suggesting that no matter if an organism or not, the actor's ability contributes to the actor's operations, which acted on the artifact leads to corresponding happenings. The terms *capability* (Gibson, 1977, 1979), *ability* (Greeno, 1994) and *effectivity* (Shaw and Turvey, 1981, 1992) are all used to represent the contributions of the actor to the interaction, corresponding to affordance representing the contributions of the artifact to the interaction. In this paper, the term *effectivity* is preferred because of two reasons. First, according to semantics, effectivity can represent not only the ability or capability of an organism but also the effect of an artifact, allowing for comparing the corresponding artifact-artifact affordances. Second, according to philosophical theories, "both affordance and effectivity can be disposition; while capability and ability are not" (Turvey, 1992). Different actors have different effectivities. If the actor is an artifact, its inherent properties determine its effectivities. If the actor is an organism, in particular a person, his/her effectivities are determined by the background such as physical condition, experience, knowledge and culture. Therefore, only when the effectivities match the affordances, then the artifact can be operated as designed and offer the expected results to the operator. For example, a typewriter is designed to have type-ability only available for the users who recognize words. Also, the "slam door" seen in Figure 2.11 has open-ability only for the local people in Britain or those who have learnt how to open it (Turner, 2005):

Figure 2.11: A British "slam-door": an inside user has to first open the window, reach outside, and then turn the exterior handle. Without guideline, this door frustrated many foreigners. (Turner, 2005)

In addition, in the book *Emotional Design* Norman (2005) asserts that the environment can affect the emotions of human actors, subsequently affecting their effectivities. Negative environmental factors such as noise, hot or cold temperature and emergencies can upset human actors and sometimes interfere in their normal perceptions and behaviors. For example, if a cinema door can only be opened inwards, anxiety and panic may impede the effectivities of the crowd in opening the door (Norman, 2005). In contrast, positive environmental factors can help human actors behave normally or even better. For example, Google provides comfortable office surroundings to improve the efficiency of its employees. From the aspect of affordance theory, negative factors have similar negative happening affordances such as upset-ability (or other synonyms), while the positive ones have similar positive ones like comfort-ability (or other synonyms). Reconfiguring the environment to suppress negative affordances and improve positive ones is the task of designers.

It is necessary to emphasize that the effectivities of the actor and the affordances of the artifact do not determine each other; rather, they are parallel on each side of the actor-artifact interaction. Shaw and Turvey (1981) proposed the effectivity schema as the reverse transformation of the affordance schema; for example, *(X, Z, O | X = Z)* represents an affordance and *(Z, X, O | Z = X)* represents the corresponding effectivity. Wells (2002) applied the Turing machine theory to represent affordance and effectivity as a pair, referring to this kind of pairs as configurations. Thus, as Wells stipulated, "affordance *A = (q, a)* represents a situation in which an actor in functional state *q* perceives an entity *a*; while *E = (b, p, k)* represents a situation in which the actor carries out behavior *b*, changes its functional state to *p* and moves in direction *k*. Thus *(A, E) = ((q, a), (b, p, k))* represents an actor perceiving the affordance *A* and effecting the behaviors in *E*." This configuration can be calculated using a Turing machine algorithm, with the result listing all the possible configurations of affordances and the corresponding effectivities. While this attempt of using a computational method extends affordance theory, its practical implementation needs further investigation.

2.2.5 Affordances in design

Since Gibson proposed and Norman improved the concept of affordance in the 1970s and 1980s, various researchers applied this concept to design. According to Norman (1999), "the art of the designer is to ensure that the desired, relevant actions are readily perceivable." Supporting him, Larsen *et al.* (2007) constructed an experiment on a PDA having the new function of voice control instead of the traditional stylus control. To guide the users, they enlarged the horn symbol on the screen as a way of enhancing the perceivable information of affording sound, and decreased the available range of the stylus on the screen as a way of rearranging the affordance priority. Similarly, Murakami *et al.* (2009) attempted to confirm what affordance information affordances the various geometric features such as the shape and size of buttons can provide to users. They demonstrated “the possibility of formulating the affordance features of ‘tilt,’ ‘turn’ and ‘push’ both qualitatively and quantitatively” (Murakami, 2009), but are still working on a specific formulating method.

However, McGrenere and Ho (2000) suggested that the common limitation of these HCI researches is largely focusing on designing the information that specifies the affordance rather than the affordance itself, i.e. mainly on designing the usability of an object but not necessarily its usefulness. The usability represents the capability of the artifact of being used, while the usefulness means the magnitude of having some utility. Their relationship can be seen in Figure 2.12:

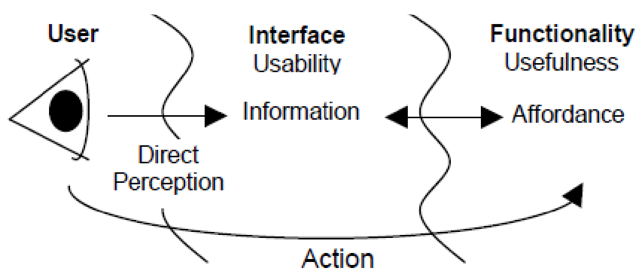


Figure 2.12: Usefulness and Usability. (McGrenere & Ho, 2000)

McGrenere and Ho propose that the affordances should be applied to design not only the interface but also the functionality of the artifact. Actually, when Warren (1984, 1985) first proposed the concept “Affordance Design,” he considered affordances as the design criteria and involved human body-scaling and energy consumption to calculate the optimal dimensions of stairs and apertures. Furthermore, he improved this method to construct an eco-niche based on affordances, claiming that this method “encompasses both the geometric dimensions and dynamic properties such as object mass, rigidity and elasticity of the artifacts" (Warren, 1985). His method is the first that focuses on designing properties of the artifacts based on affordances and thus is widely adopted in the experimental psychology community. However, the application of this method is only limited to designing the simple artifacts with several properties and obvious affordances like stairs' climb-ability and apertures' pass-through-ability; it has not been verified by designing a more complex system such as a machine consisting of subsystems and components. In addition, in Warren's examples, usually one single affordance is selected as the main design criterion, but the multi-affordances cases have seldom been discussed. Furthermore, it is difficult to directly introduce Warren's method to product design because Warren's usage of affordances confuse with that of requirements in design methodology. According to other design methodologies like Suh's Axiomatic design and Pahl and Beitz's function-based design, requirements are usually used as the design criteria.

In contrast to Warren's method, Maier and Fadel (2001, 2002, 2005, 2006, 2008, and 2009) proposed a series of affordance-based design theories trying to apply affordances to the systematic product design. They believe that the affordances can be applied as criteria to select among design plans and evaluate the contribution of the components to the entire system. Usually a completed design process is divided into three phrases as seen in Figure 2.13; thus, according to the scheme they propose as shown in Figure 2.14 and Figure 2.15, their affordance-based methods are mainly used in conceptual and preliminary design:

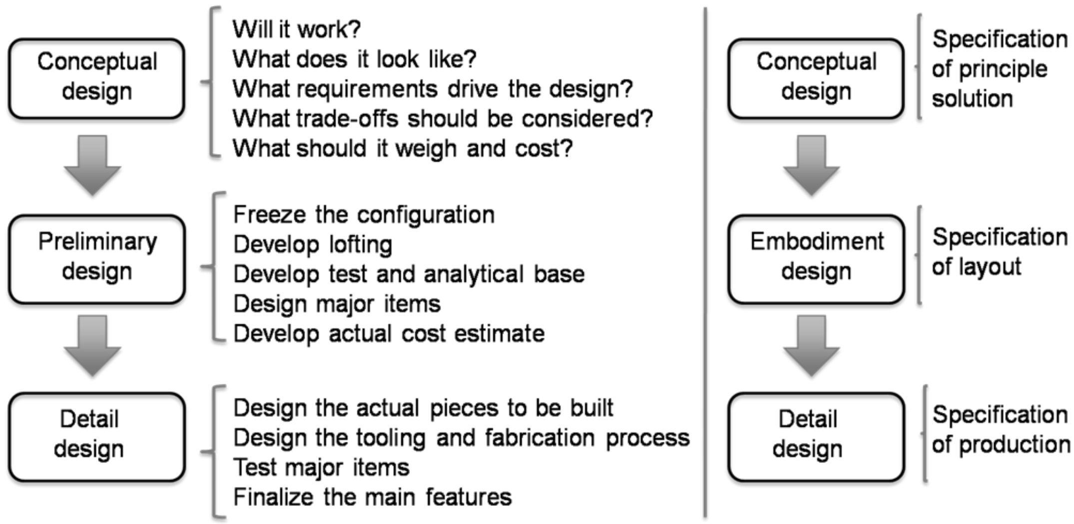


Figure 2.13: Three phases of design and the corresponding tasks in each phase divided by Raymer (on the left, 1992) and Pahl *et al.* (on the right, 2007).

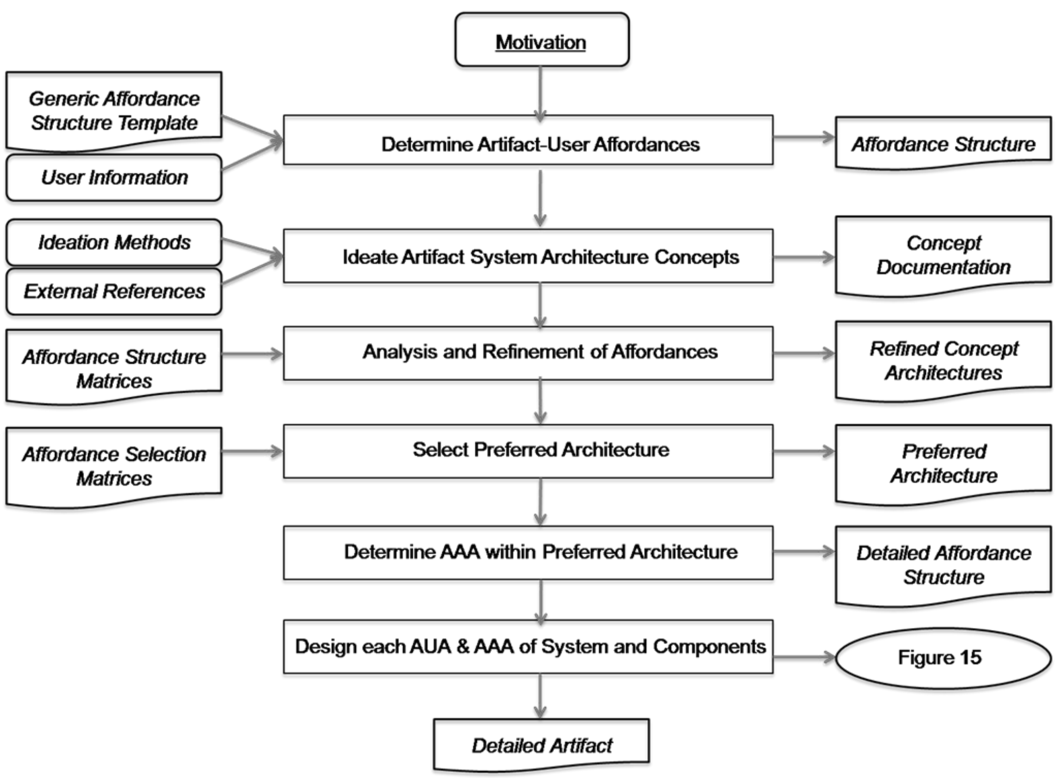


Figure 2.14: Overview of the affordance-based design process (Maier and Fadel, 2009)

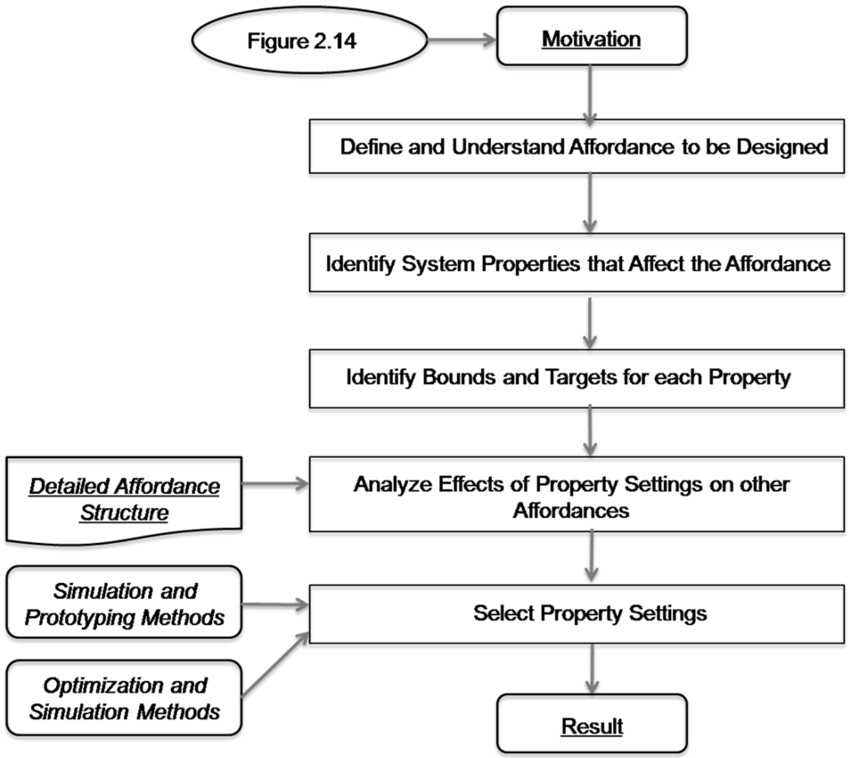


Figure 2.15: Procedure for designing individual affordances

The problem is that the affordances are form-dependent (Maier and Fadel, 2009), meaning that they can only be identified after the structure of artifact is built. However, design is a process of transforming from the divergent and ideal requirements to the convergent and practical artifacts, and hence the affordance-based design must be a process using affordances to realize such a transformation. Based on this perspective, Brown and Blessing (2005) suggested that Maier and Fadel's method is more likely to be an evaluating tool for those already manufactured products instead of designing innovatively, and questioned the applicability of affordance in design. This is still an open research question.

CHAPTER 3: QUESTIONS AND HYPOTHESES

Potential problems when using affordances in the design process were identified in the previous chapter. These potential problems include the ambiguity inherent in articulating, representing, categorizing and organizing (hierarchically) affordances. The research opportunities can therefore be explored in the four following areas:

1. Categorizing affordances that are applicable for product design;
2. Clarifying the roles of the different types of affordances in design and their relationships with other concepts such as requirements, functions and user tasks;
3. Representing affordances in an articulate format supported by a consistent and comprehensive vocabulary;
4. Building the affordance hierarchy and implementing it into the design process;

This thesis is a start of the series of affordance-oriented research and mainly focuses on the first area and parts of the second area described above. A question is proposed with the corresponding research hypotheses:

RQ: Are the current categorization schemes of affordances applicable for product design to represent the potential interactions between an artifact and users, other artifacts, and natural environmental entities?

In this research, first, nine current categorization schemes are evaluated to determine if a new categorization is needed. The evaluation reveals that all of these schemes have some limitations to categorize the affordances collected from literature of various research communities. Then, a new categorization scheme is proposed, with its justification explained in a workflow and applicability evaluated by the collected affordances. Lastly, the associated models of the new categorization are built to illustrate the differences among the categories.

RH1: The current categorizations of affordances are sufficient for product design.

Nine categorization schemes have been proposed by Gaver (1991), Norman (2000), Raubal *et al.* (2006), Hartson (2003), Scarantino (2002), Galvao (2009), Maier and Fadel (2009), Kannengiesser and Gero (2010), and Pols (2011), each based on different research communities. However, some of them have been simply proposed by a few sentences and none of them has been evaluated by the affordances collected from literature of different communities.

RH2: A new categorization can improve the applicability of affordances in product design.

If the applicability of current categorizations still needs to be improved, a new categorization is proposed based on the information generated from the comparison.

To sum up, the research questions, hypotheses and the corresponding tasks are shown in Table 3.1.

Table 3.1: Research questions, hypotheses and tasks

Research Questions	*Research Hypotheses*	*Tasks*
RQ: Are the current categorization schemes of affordances applicable enough for product design to represent the potential interactions between an artifact and organism users, other artifacts, and natural environmental entities?	**RH1:** The current categorizations of affordances are sufficient for product design.	Build a spreadsheet summarizing the use of affordances in literature to evaluate the applicability of the current categorizations and discuss a potential new scheme to address the problem.
	RH2: A new categorization can improve the applicability of affordances in product design.	

CHAPTER 4: CATEGORIZING AFFORDANCES FOR DESIGN

In this chapter, first of all, a spreadsheet of summarizing affordances in literature is built to show how researchers use affordances to represent potential interactions between various entities. Then the applicability of the current nine categorization schemes of affordances from different communities is respectively evaluated in this spreadsheet. Based on the evaluation, a new categorization scheme applicable for product design is proposed and then validated in the spreadsheet.

4.1 Building the spreadsheet of affordances

The spreadsheet of affordances is built as shown in the APPENDIX A: SPREADSHEET OF SUMMARIZING AFFORDANCES USED IN LITERATURE, which summarizes the use of affordances from 55 publications of different research communities, including seventeen from psychology (Albrechtsen *et al.*, 2001; Bærentsen and Trettvik, 2002; Cesari, 2005; Chemero, 2003; Gaver, 1991; Gibson J., 1979; Gibson E., 2000; Greeno, 1994; Konczak *et al.*, 1992; Mark, 1987; Michaels, 1988; Oudejans *et al.*, 1996; Turvey, 1992; Warren, 1985; Warren, 1984; van Leeuwen et al., 1994; Wells, 2002), thirteen from HCI (Amant, 1999; Chen *et al.*, 2009; Galvao, 2007; Hartson, 2003; Larsen *et al.*, 2007; McGrenere, 2000; Murakami, 2009; Norman, 1999; Norman, 2003; Norman, 1990; Oshlyansky *et al.*, 2004; Torenvilet, 2003; Turner, 2005), fourteen from design (Brown and Blessing, 2005; Cascini *et al.*, 2010; Gaffney *et al.*, 2007; Maier and Fadel, 2001; Maier and Fadel, 2009a; Maier and Fadel, 2002; Maier *et al.*, 2009; Maier and Fadel, 2005; Maier *et al.*, 2009; Maier and Fadel, 2009b; Maier and Fadel, 2009c;

Maier *et al.*, 2007; Maier and Fadel, 2006; You and Chen, 2006), four from philosophy (Kannengiesser and Gero, 2010; Scarantino, 2002; Stoffregen, 2000; Pols, 2011), and seven from AI (Raubal et al., 2006; Ugur *et al.*, 2009; Montesano *et al.*, 2007a; Sweeney and Grupen, 2005; Montesano *et al.*, 2007b; Uyanik; Castellini *et al.*, 2011).

In the process of building the spreadsheet, only the affordances represented by the same interactive entities and actions are considered redundant and thereby filtered out. For example, "stair riser affords the user to climb" or "stair riser has climb-ability for the user" appear in almost each affordance-oriented publication from ecological psychology, but the "stair riser affords climb-ability for the user" is collected into the spreadsheet only once. However, if some affordances are similar but their elements are slightly different, they all enter the spreadsheet. For instance, "vacuum cleaner affords hurting the user" is considered different from "vacuum cleaner affords pinching the user," and "vacuum cleaner affords annoying users" is different from "vacuum cleaner affords generating noise" and "the generated noise affords annoying users." This differentiation is based on the action theory (Bærentsen *et al.*, 2006; Pols, 2011), which stipulates that the action "hurting" is more abstract than "pinching" and "vacuum cleaner annoys users" is more general than "vacuum cleaner generates noise" and "the generated noise annoys users," and therefore these actions are considered different. Similarly, "a ball affords users throwing" is considered different from "an object with the suitable size affords users throwing," since the "object" is more general than the "ball" and they are considered as two different entities.

Finally, 283 affordances are collected in the spreadsheet. In addition, for each affordance in the spreadsheet, the interactive entities are listed and specified as actors and acted ones to facilitate the justification when the categorization schemes are evaluated.

4.2 Evaluating the current schemes

As introduced in the literature review, the nine categorization schemes of affordances from different research communities are shown in Table 4.1:

Table 4.1: The categorizations of affordances in literature

Reference	*Categorizations of affordances*	*Community*
Gaver (1991)	Sequential and nested	Ecology
Norman (1999)	Perceptible and hidden	HCI
Raubal *et al.* (2006)	Physical, social-institutional, and mental	AI
Scarantino (2002)	Goal and happening	Philosophy
Hartson (2003)	Cognitive, physical, sensory, and functional	HCI
Maier and Fadel (2005)	AAA and AUA	Design
Galvao (2007)	Functional and operational	HCI
Kannengiesser and Gero (2010)	Reflexive, reactive, and reflective	AI
Pols (2011)	Manipulation, effect, use, and activity	Philosophy

The evaluation in this research is via analyzing the results of applying these nine schemes respectively to categorize the affordances collected in the spreadsheet. The APPENDIX B: CATEGORIZING THE SUMMARIZED AFFORDANCES BASED ON THE NINE

CATEGORIZATION SCHEMES and the subsequent subsections are the details of evaluating each scheme.

4.2.1 Sequential and nested affordances

Gaver (1991) defined that “sequential affordances explain how affordances can be revealed over time; nested affordances describe affordances that are grouped in space.” For example, to open a door, a user needs to behave a sequence of actions, including grasping the door knob, turning it, and then pulling/pushing the door; thus, the knob’s grasp-ability, turn-ability and the door’s pull/push-ability are sequential affordances. In addition, to open a coke can, a user needs to grasp the can and at the same time pull the ring off; here the grasp-ability and the pull-off-ability group in space as nested affordances. The problem of this scheme is that one single affordance cannot be justified as sequential or nested, since in different situations it can combine with other affordances to group sequential or nested affordances. Therefore, since the information in the spreadsheet is not enough to justify the categorization, most of the affordances cannot be precisely categorized, marked as sequential/nested as seen in APPENDIX B: CATEGORIZING THE SUMMARIZED AFFORDANCES BASED ON THE NINE CATEGORIZATION SCHEMES and Figure 4.1. Not viewed as affordances, ten exceptions listed in Table 4.2: Ten collected items are not viewed as affordances are marked with questions marks because they do not clearly represent any interactions. The pie chart in Figure 4.1 illustrates the result of the evaluation.

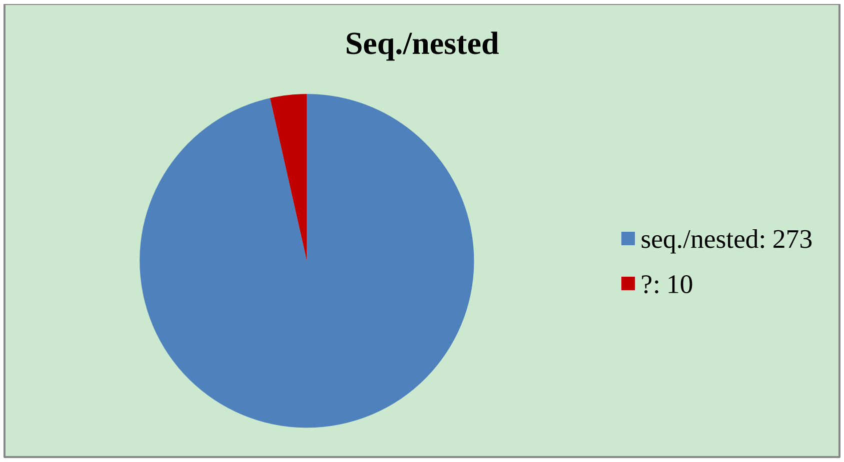


Figure 4.1: the result of evaluating Gaver's scheme

Table 4.2: Ten collected items are not viewed as affordances

No.	*Items*
46	Weight
58	Loss of suction over time
145	Afford life
173	Rusting
177	No additional weight onto the laptop computer
178	No interference to the portable computer and docking station beneath it
181	Product degradation
199	Stability
218	Reduces weight
219	Reduces electronic redundancy

4.2.2 Perceptible and hidden affordances

Norman (1999) believed that for HCI designers only the affordances that can be perceived by users are useful and therefore he categorized perceptible and hidden affordances. Similar to Gaver's scheme, without the detailed information of users and situations, isolated affordances cannot be clearly justified to be perceptible or hidden. Therefore, in the spreadsheet the affordances (except the ten items in Table 4.2) are categorized as perceptible/hidden as shown in Figure 4.2.

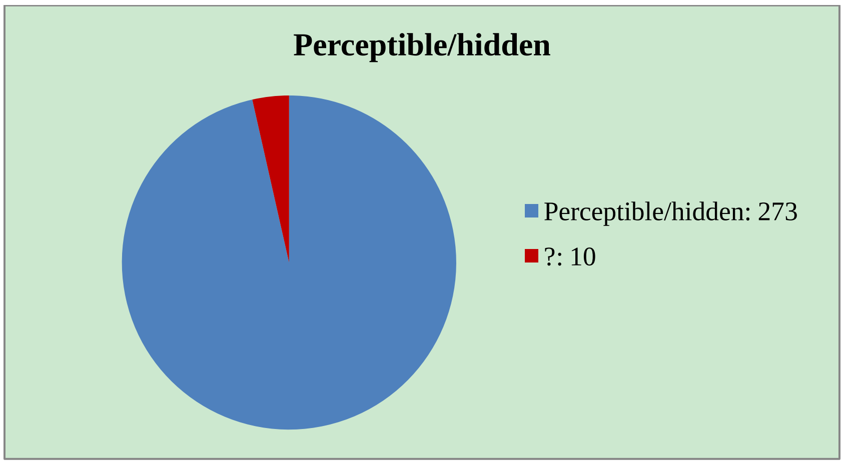


Figure 4.2: the result of evaluating Norman's scheme

4.2.3 Physical, social-institutional, and mental affordances

Raubal *et al.* (2006) categorized affordances based on the action theory (Bærentsen *et al.*, 2006) that actions can be classified from specific to abstract. Accordingly, Raubal *et al.* (2006) defined that "physical affordances require bundles of physical substance properties that match the agent's capabilities and properties; social-institutional affordances indicate the social interaction between agents; mental affordances represent the internal operation of the agents, such as 'decide.'" However, Raubal *et al.* (2006) only gave an example of the mental affordances, but did not illustrate the physical and social-institutional affordances. Therefore, based on the original definitions, the justification protocol for this scheme in the spreadsheet can be derived as:

- The direct interactions between users and objects are categorized as physical affordances. For example, the affordance No. 1 "buttons afford press-ability for users" is a physical affordance.
- The general and abstract social interactions between users and objects are categorized as social-institutional affordances. For example, the affordance No. 227 "the vacuum cleaner affords costing the user with power consumption" is a social-institutional affordance.
- The internal operations (e.g., deciding, calculating, and thinking) of users are categorized as mental affordances. For example, the affordance No. 249 "the path affords the user remembering and selecting" is a mental affordance.

The pie chart in Figure 4.3 shows the result of evaluating Raubal *et al.*'s scheme.

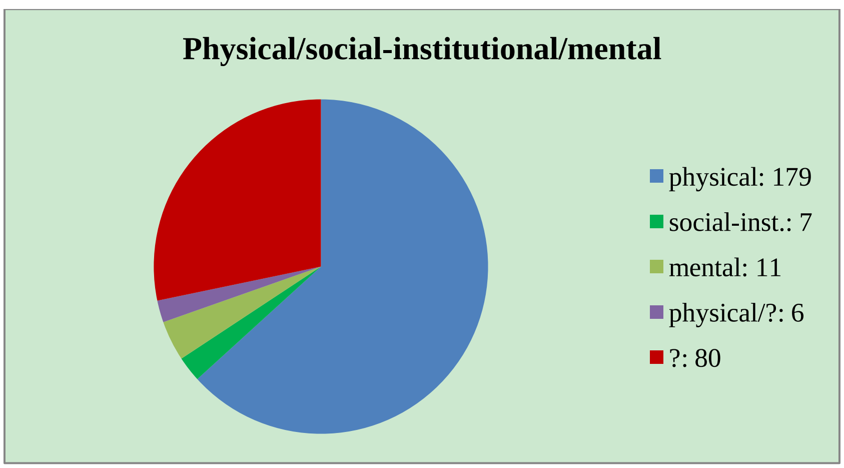


Figure 4.3: the result of evaluating Raubal *et al.*'s scheme

4.2.4 Goal and happening affordances

Scarantino (2002) distinguished between two classes of affordances, namely, goal affordances (their manifestation is a doing, representing events that organisms do, such as climbing, catching, getting under, eating, mailing a letter in Gibson's (1979) examples of affordances) and happening affordances (their manifestation is a happening, representing events that happen to organisms, such as bumping into, getting burned by, falling off, being eaten by in Gibson's (1979) examples of affordances). Therefore, when this scheme is evaluated in the spreadsheet, the justification can refer to the information following the corresponding affordances, including the specified interactive entities and the direction of actions. For example, in APPENDIX B: CATEGORIZING THE SUMMARIZED AFFORDANCES BASED ON THE NINE CATEGORIZATION SCHEMES along with the affordance No. 1 "buttons afford press-ability for users," the interactive entities and the direction of the action "press" are given as "user→button," which means that the two interactive entities are "user" and "button" and the action is from "user" to "button;" hence the press-ability is a goal affordance. Similarly, the affordance No. 71 "cut-ability" is specified as "blade→user," representing the action is from "blade" to "user," and therefore it is a happening affordance.

Note that in this scheme Scarantino (2002) emphasized organisms should be either the actors or the acted entities; therefore, the affordances between non-organism entities collected in the spreadsheet (e.g., the affordance No. 41 "vacuum cleaner affords dirt removal" represents the interaction between vacuum cleaner and dirt) cannot be categorized using this scheme and they are marked with question marks. However, the acted entities can be not only artifacts but also natural objects, substance, organisms, or medium.

There are also some affordances cannot be clearly categorized. These affordances are not represented with detailed interactive entities and direction of actions and the verbs in the representation can stand for the actions either from the users to the target entities or from the target entities to the users. For example, the affordance No. 12 “balls are for bouncing” can mean either “the users bounce the balls” or “the balls bounce on the ground.” For the first meaning, the bounce-ability is a goal affordance; whereas for the second meaning, since the interactive entities are the balls and the ground, the bounce-ability cannot be categorized in this scheme. Therefore, finally this affordance is marked as “goal/?” in the evaluation. Similarly, the affordance No. 48 “vacuum cleaner requires user interaction” is quite a general concept representing various actions between the user and the vacuum cleaner; therefore, this affordance is marked as “goal/happening.”

The pie chart in Figure 4.4 illustrates the result of evaluating Scarantino’s scheme.

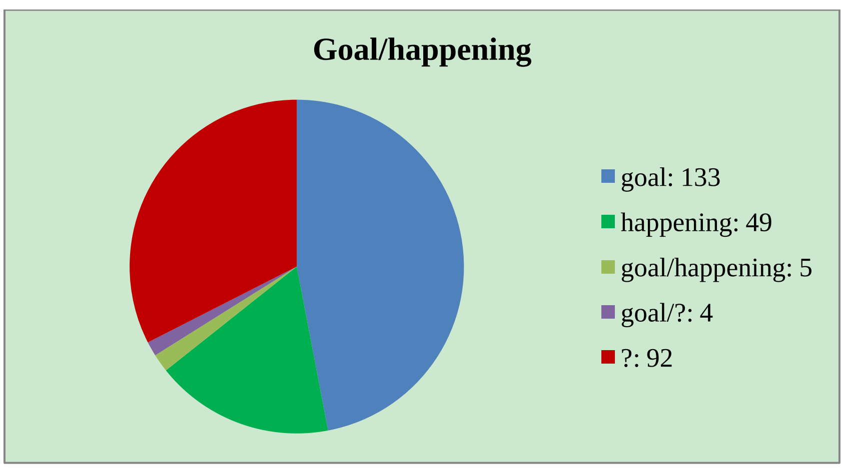


Figure 4.4: the result of evaluating Scarantino’s scheme

4.2.5 Cognitive, physical, functional, and sensory affordances

Hartson (2003) categorized four types of affordances with their descriptions and examples as shown in Table 2.4 based on their different use in the eight stages of the user-entity interaction as shown in Figure 2.6. In the evaluation, some affordances can be clearly justified based on the definitions and examples given in Table 2.4. For example, the affordance No. 1 “buttons afford press-ability for users” describes the physical action that the users behave on the buttons and, thus, the press-ability is a physical affordance. The affordance No. 40 “vacuum cleaner allows use of carpet” describes a functional use of the vacuum cleaner and hence this affordance is a functional affordance. However, the boundary between sensory and cognitive affordances is not clear and actually the sensory and cognitive actions usually go along together. For example, the affordance No. 118 “text affords legibility for users” represents both the cognitive and sensory use of the text and, therefore, the legibility is marked as a cognitive/sensory affordance. The affordance No. 223 “vacuum cleaner affords pleasing the user with aesthetics” is also categorized as a cognitive/sensory affordance.

Note that this scheme can be used to represent some non-organism interactions. The functional affordances can represent the interactions between artifacts because these interactions can help users accomplish work, which match the definition of functional affordance. However, some interactions between natural entities cannot be clearly identified to help users work and, thus, they cannot be categorized in this scheme. For example, the affordance No. 94 “air affords unimpeded locomotion on the ground” does not belong to any categories in this scheme; therefore, it is marked with a question mark.

The pie chart in Figure 4.5 illustrates the result of evaluating Hartson's scheme.

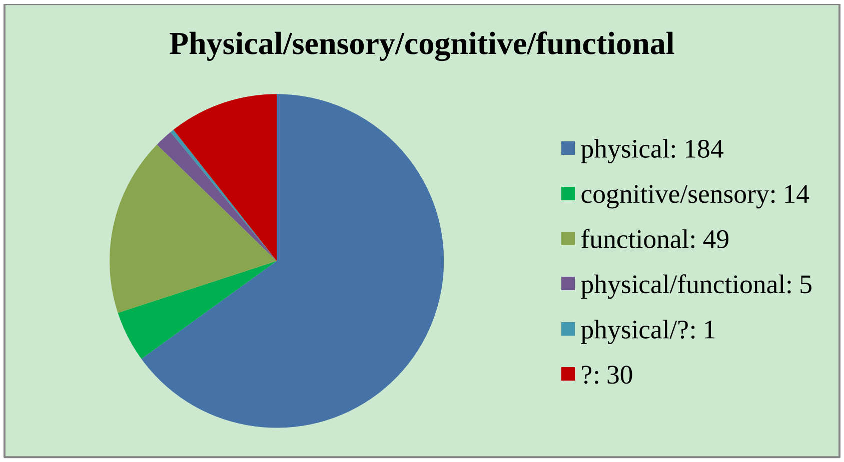


Figure 4.5: the result of evaluating Scarantino's scheme

4.2.6 Functional and operational affordances

Galvao (2007) defined functional affordances to represent the user-artifact relationships "at a higher degree of abstraction" and described these affordances as "do-abilities," such as "pocket-ability" for a cellular phone. In addition, he used operational affordances to represent the user-artifact relationships "at the lower degree of abstraction that point to precise structural and informational attributes that products carry;" however, he did not provide any examples for this category. Therefore, except the ten items in Table 4.2, other affordances in the spreadsheet are classified to functional affordances as seen in Figure 4.6.

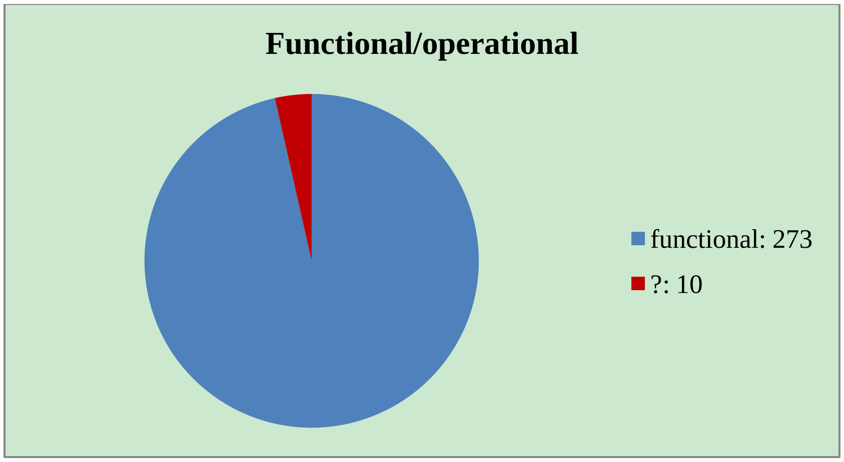


Figure 4.6: the result of evaluating Galvao's scheme

4.2.7 Artifact-user affordances and Artifact-artifact affordances

As Maier and Fadel (2003, 2009) defined, AUA is to "describe the potential interaction between users and artifacts" and AAA is to "describe the potential interaction between two artifact subsystems." In the evaluation, the categorization can refer to these definitions of AUA and AAA. However, Maier and Fadel do not clarify the users to be just human users or any organism users and do not consider the entities that are neither users nor artifacts. For example, as shown in the spreadsheet, (No. 94) air (a type of medium) affords unimpeded locomotion on the ground (environment); (No. 255) a rock (a type of substance) affords throwing; (No. 43) a vacuum cleaner affords making noise (a type of vibration) and (No. 41, 42) sucking dirt (a type of substance); (No. 86) a cat door affords passing through for a cat (a non-human organism). In these examples, apparently none of air, rock, noise, dirt and cat can be categorized to human users or artifacts, and neither can the corresponding affordances be categorized to AUAs or AAAs.

Therefore, these affordances are marked with questions marks. The pie chart in Figure 4.7 illustrates the result of the evaluation.

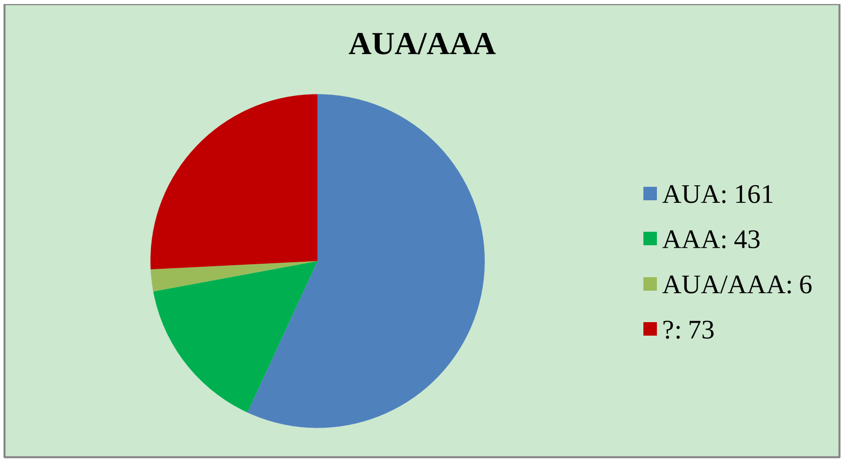


Figure 4.7: the result of evaluating Maier and Fadel's scheme

4.2.8 Reflexive, reactive, and reflective affordances

Kannengiesser and Gero (2010) categorized affordances based on three different types of psychological reasoning: reflexive, reactive, and reflective. The original definitions of these categories are:

- "… The notion of reflexive affordance is a direct form of perception that is often interpreted as not involving any significant amount of internal processing or decision making… A reactive affordance is an action possibility that is selected from a set of action possibilities… Reactive affordances can be seen as the outcomes of a search process, analogous to search in routine or parametric designing. Reflective affordances involve changes in the user's expectations generated by different situations; 'hidden affordances,' i.e. ones without obvious perceptual cues provided by the artifact, can be viewed as instances of reflective affordances…" (Kannengiesser and Gero, 2010).

The problem of this scheme is the same with Norman's scheme (1999), i.e., since the categorization is mainly based on the perception of users, without detailed information about the users and situations, the affordances in the spreadsheet cannot be clearly categorized in this scheme. Therefore, except the ten items listed in Table 4.2, other affordances are all marked as reflexive/reactive/reflective as seen in Figure 4.8.

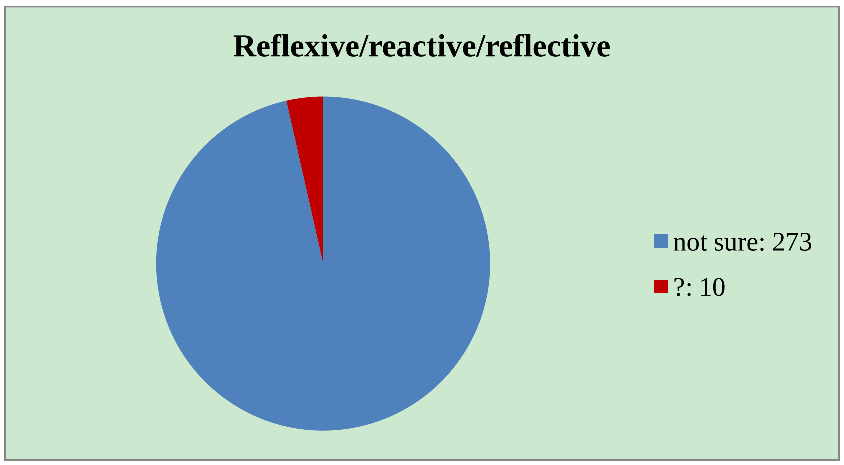


Figure 4.8: the result of evaluating Kannengiesser and Gero's scheme

4.2.9 Manipulation-type, effect-type, use-type, and activity-type affordances

Pols (2011) categorized affordances based on action theory. From specific to general, he classified manipulation-type, effect-type, use type, and activity-type affordances, and listed the corresponding concepts in action theory and the examples for the four categories as seen in Table 4.3.

Table 4.3: Pols' four categories of affordances and the corresponding examples (Pols, 2011)

Affordance	*Corresponding concept action theory*	*Examples of actions afforded*
Opportunity for manipulation	Basic action	Pulling a trigger, hitting a glass pane, pressing a button…
Opportunity for effect	Action described in terms of its effects	Firing a gun, breaking a glass pane, typing an 'a'…
Opportunity for use	Plan	Shooting a person, obtaining an emergency hammer, writing a paper…
Opportunity for activity	Social action	Murdering an enemy, escaping a crashed vehicle, working out a psychological theory…

In the evaluation, justifying the categories is based on the examples given in Table. However, for some affordances that are not clearly represented, it is still difficult to categorize them in this scheme. For example, the affordance No. 106 "a person affords human behaviors for another person" can be any type of the four categories, depending on what the human behaviors refer to. The pie chart in Figure 4.9 illustrates the result of the evaluation.

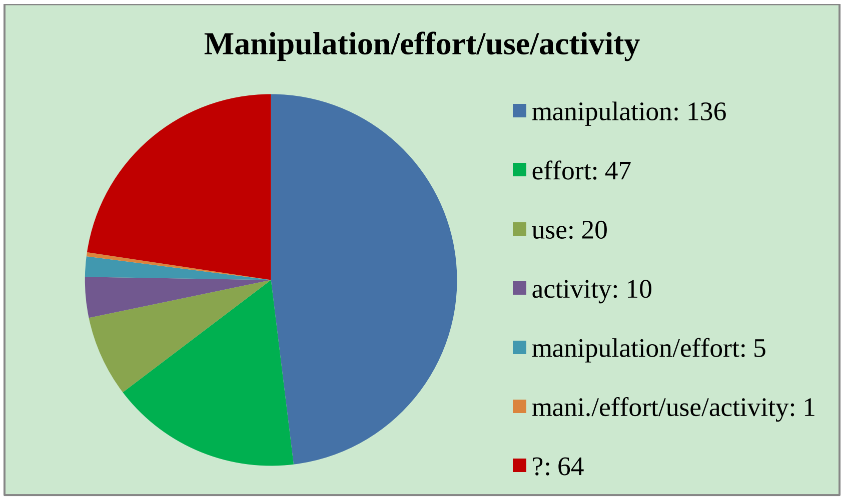


Figure 4.9: the result of evaluating Pols' scheme

4.2.10 Summary

To sum up, the nine schemes have various limitations:

1. Gaver's scheme (sequential and nested affordances) (1991), Norman's scheme (perceptible and hidden affordances) (2000), Galvao's scheme (operational and functional affordances) (2007), and Kannengiesser and Gero's scheme (reflexive, reactive, and reflective affordances) (2010) need the detailed information of the situations and users' background; otherwise, the boundaries among the categories are not clear and the categorization cannot be proceeded. The problem of Hartson's scheme (cognitive, physical, functional, and sensory affordances) (2003) is that the boundaries among cognitive, sensory, and physical are not clear.
2. Scarantino's scheme (goal and happening affordances) (2002) is the only one that classifies affordances based on the actions that organisms act on artifacts or receive feedback from artifacts. However, the scope of this scheme is only limited to organism-entity affordances and the justifying protocol is not detailed.
3. Hartson's scheme (cognitive, physical, functional, and sensory) (2003) does not provide a clear boundary between the cognitive and sensory affordances. And actually they usually appear together. In addition, the functional affordances are defined to represent the positive interactions between non-organisms and other entities; however, they cannot represent those non-helpful interactions as discussed in 4.2.5 Cognitive, physical, functional, and sensory affordances. Pols' categorization scheme (manipulation-type, effect-type, use-type, and activity-type

affordances) (2011) has the similar problems with Hartson's, i.e. the boundaries among the categories of effect-type, use-type, and activity-type are not clear.

4. Maier and Fadel's artifact-artifact affordance (AAA) is the first use of affordances to represent the interactions between artifacts, allowing the application of the affordance-based approaches to solve the inner problems (or design) of artifacts. However, AAAs and AUAs cannot be used to represent the affordances between environmental entities and the target affordances;

Based on the evaluation results of these schemes, a new scheme is proposed in the subsequent section to not only breakthrough the limitations of the current nine schemes but also have the applicability for product design.

4.3 Proposing a new scheme for product design

Design is a process of realizing ideal requirements to practical artifacts; therefore, the expected categorization scheme applicable in design needs to satisfy two basic requirements:

1. As the ultimate outcome of the design process, the artifact (how requirements are satisfied) should be the center of the categorization;
2. The categorization should allow the existence of affordances between non-organism entities, especially between artifacts, so that the applicable scope of affordance-based approaches can be enlarged to the design of the internal subsystems of artifacts as well as the user interface.

4.3.1 The new categorization scheme

Based on these two requirements and the limitations of the nine schemes, in this research the new categorization scheme is proposed based on improving the Maier and Fadel's and Scarantino's schemes. As discussed in 4.2.7 Artifact-user affordances and Artifact-artifact affordances, Maier and Fadel do not clarify the users to be just human users or any organism users and do not consider the entities that are neither users nor artifacts. To address this problem, first of all, the category of AUA can be retained but the meaning of U (user) in AUAs needs to be extended. Based on the examples in the spreadsheet, the users can refer to not only the human beings but also the non-human organisms that can intentionally interact with the artifact. For example, a pet door affords passing through for cats and here the cats are actually the users. In addition, the category of AAA can be retained because the new categorization is proposed dedicatedly to be applicable for product design and in this community it is significant to clarify the interactions among the artifacts. Furthermore, a new category called Artifact-Environment Affordances (AEA) is proposed in this research to contain those affordances representing the interactions between artifacts and those environmental entities that are neither organisms nor artifacts such as substance, medium, and natural objects. As for those affordances between non-artifacts, they are beyond the boundary of product design and therefore are not considered in this research.

As for Scarantino's categorization, the evaluation result in Figure 4.4: the result of evaluating Scarantino's schemeshows that 92 affordances cannot be classified into goal and happening categories. In these unidentified affordances, ten of them are those that cannot be considered as affordances as listed in Table 4.2. For example, “weight” (No. 46) and “reduce weight” (No. 218) of the vacuum cleaner do not clearly represent any potential interactions; “stability” (No. 199) of a car can represent an aspect of quality but not an affordance. The other 82 unidentified affordances are those that do not represent the interactions between organisms and other entities, such as the affordance No. 40 “the vacuum cleaner allows use of carpet,” No. 41 “the vacuum cleaner affords dirt removal,” and No. 42 “the vacuum cleaner affords dirt disposal.”

To improve this categorization, first of all, the concept of goal and happening affordances needs to be re-defined and extended from merely representing the interactions between organisms and other entities to representing the interactions between entities of any types, including organisms, natural objects, substance, and medium. In addition, “doing affordance” is preferred to replace “goal affordance” because the manifestation of “goal affordance” is doing but “goal” contains the meaning of mental process of organism users (Scarantino, 2002).

To distinguish between doing and happening categories, the affordances should be represented in a complete format that clarifies the interactive entities and actions. Actually either the formats “afford doing” or “has do-ability” can be applicable to clearly represent affordances as long as the elements are clarified. For example, it is difficult to categorize doing and happening affordances if one just says “a steering wheel affords turning” or “a steering wheel has turn-ability” because “turn” is a verb that can represent either the user’s operation or the steering wheel’s behavior; however, it is easy to distinguish them if we say “a steering wheel affords the user to turn” (a doing affordance) or “a steering wheel affords turn-ability to the car” (a happening affordance). Therefore, in this research, the affordances are represented with the specific information of the two interactive entities.

As for distinguishing between the doing and happening categories in AAAs, the energy-based approach is introduced. First it is necessary to clarify the directions of the energy flows converted and transmitted between the two interactive entities. For example, suppose in a gearbox the energy flow is transmitted from gear A to B then to C; thus, if B is considered as the target entity, the doing affordance is turn-ability from A to B, while the happening affordance is turn-ability from B to C. In this condition, the doing and happening affordances of B have the same representation but indicate interactions between different gears.

Note that the two selected categorization schemes are orthogonal to each other, i.e., AUAs, AEAs, and AAAs can be categorized into doing and happening classes, written as dAUAs, hAUAs, dAEAs, hAEAs, dAAAs, and hAAAs. To sum up, considering an artifact as the standpoint, the dAAAs and hAAAs represent the potential interactions inside the artifact among various subsystems (assemblies and components). The dAUAs, hAUAs, dAEAs, and hAEAs represent the possible interactions between the artifact with the users (any organisms that can act operations) and environmental entities (including substance, objects, medium and other artifacts). Therefore, the entire new categorization of affordances is illustrated in Figure 4.10.

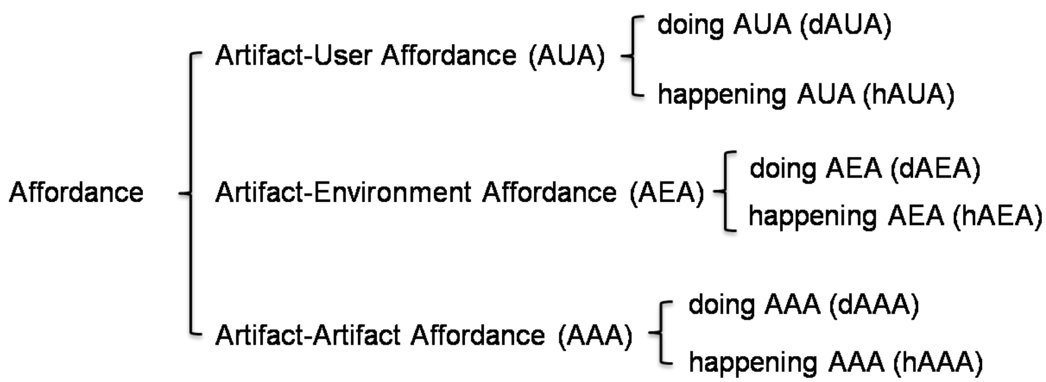


Figure 4.10: The new categorization of affordances

4.3.2 The workflow of justifying the new scheme

For the six different categories in the new scheme, the workflow of justifying the categorization is illustrated in Figure 4.11.

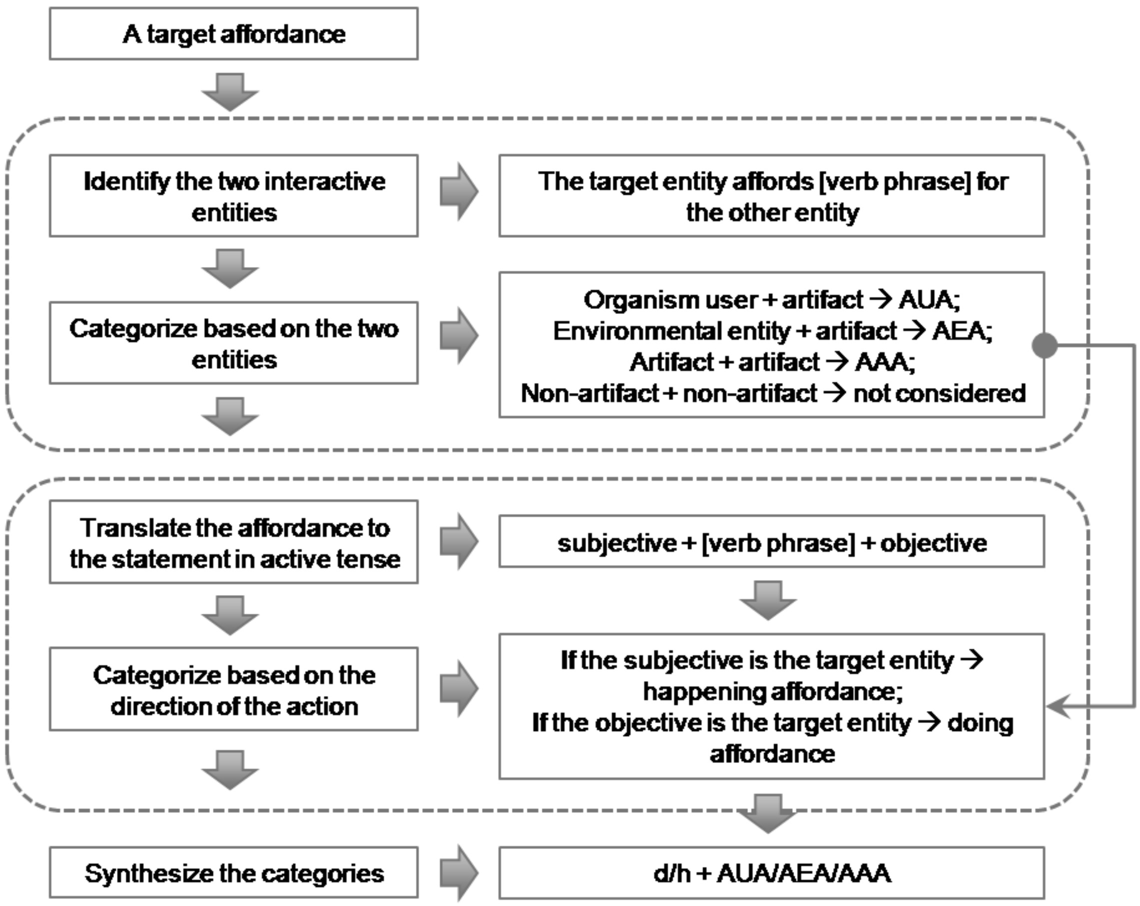


Figure 4.11: the workflow of the new proposed categorization

For a target affordance, the first step is to identify its two interactive entities. Affordance is defined to represent the potential interaction between two entities (Gibson, 1979) and, therefore, the target affordance can be represented as "the target entity affords [verb phrase] for the other entity." Then, the target affordance can be categorized based on the two entities: if the two entities are an organism user and an artifact, the target affordance is an AUA; if the two entities are an environmental entity (substance, medium, or natural object) and an artifact, the target affordance is an AEA; if the two entities are two artifacts, the target affordance is an AAA; if the two entities are two non-artifact entities, since this categorization scheme is dedicated to product design and the target entity should be an artifact, the target affordance is not considered in this scheme.

The next two steps are to categorize the target affordance based on the direction of the action. First, the representation of the target affordance can be translated to the statement in active sense as "subjective + [verb phrase] + objective." This statement reveals the direction of the action (represented by the verb phrase) from the subjective to the objective. Accordingly, the categorization of the target affordance can be justified as: if the objective is the target entity, the target affordance is a doing affordance, since the action is what the other entity does towards the target entity; if the subjective is the target entity, the target affordance is a happening affordance, since the action is what the target entity feedbacks towards the other entity.

Finally, since the two categorizations are justified from different aspects, they can be synthesized to six categories, including d/h AAA/AUA/AEA. The following subsection 4.3.3 is to validate the new scheme.

4.3.3 Validating the new scheme

According to Ostergaard and Summers (2009), validating taxonomy needs to specify on four aspects: orthogonality, spanning, precision, and usability. For the orthogonality, AAAs, AUAs, and AEAs are orthogonal to each other because the A (artifacts), U (users), and E (environmental entities) are apparently different; doing and happening affordances are orthogonal because they respectively represent two opposite directions in interactions; the two categorization schemes are orthogonal because categorizing AAA/AUA/AEA is based on the different types of entities interacting with the target artifact, whereas categorizing doing/happening affordances is based on the different direactions of actions.

Regarding validating the spanning and precision, the 283 affordances in the spreadsheet are categorized based on the workflow of the new proposed categorization as seen in Figure. The detailed justifications are listed in APPENDIX C: CATEGORIZING THE SUMMARIZED AFFORDANCES BASED ON THE NEW CATEGORIZATION PROPOSED IN THE RESEARCH. The results are shown in Table 4.4 and the associated charts:

Table 4.4: The statistic results of the new categorization in the spreadsheet

Class	*# %*		*#*	*%*	*Class*	*# %*		*#*	*%*
		dAUA	126	44.5			dAUA/hAEA	1	0.4
AUA	165	hAUA	37	13.1			dAUA/dAAA	1	0.4
	58.3%	dhAUA	2	0.7	Not sure	6	dhAUA/dhAEA	2	0.7
		dAEA	7	2.5		2.3%	dhAUA/dhAAA	1	0.4
AEA	37	hAEA	29	10.2			dAUA/hAAA	1	0.4
	13.1%	dhAEA	1	0.4			?	16	5.6
		dAAA	5	1.7	Neither	40	d?	12	4.2
AAA	35	hAAA	16	5.6		14.1%	h?	11	3.9
	12.2%	dhAAA	14	4.9			dh?	1	0.4

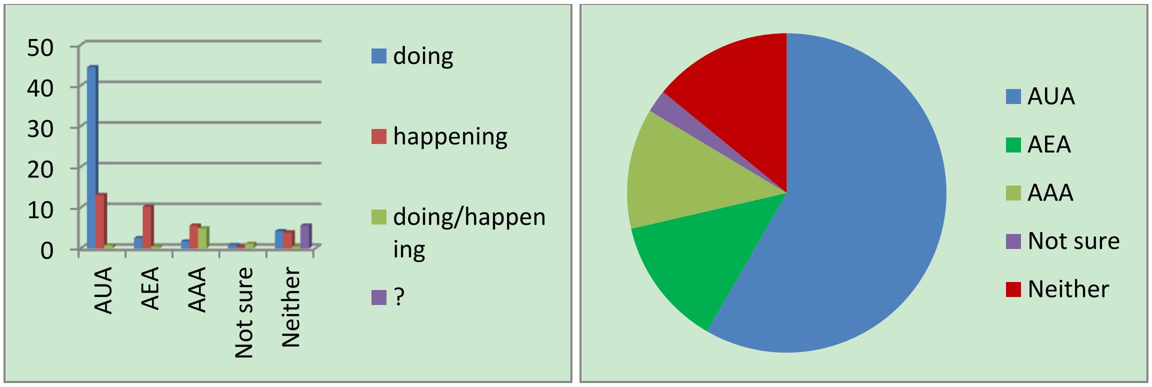


Figure 4.12: The associated charts of Table 4.4

Compared to Maier and Fadel's categorization, the new categorizaiton scheme reduces the unidentified affordances from 73 to 40. In addition, since the definitions of doing and happening affordances are extended from merely organism users (Scarantino, 2002) to any entities, the new categorization scheme sharply reduces the unidentified affordances from 92 to 16. Furthermore, the results of combining the two categorizations indicate:

1. Researchers tend to use affordances to represent the potential interactions between users and artifacts. This is why the percentage of AUAs is the highest.
2. In AUAs, the percentage of dAUAs is higher than hAUAs and dhAUAs, suggesting that researchers tend to use affordances to represent the potential actions by users on artifacts. In contrast, the percentage of hAEAs is higher than dAEAs and dhAEAs, suggesting that in AEAs affordances are more frequently used to represent artifacts' behaviors to the environmental entities.
3. In AAAs, the percentage of dhAAAs is the highest, proving that the doing and happening affordances inside the artifacts are usually represented exactly the same. To distinguish the dAAA and hAAA in the interaction between two

subsystems, the representations need to be added with the explanation that which subsystem is the actor and which is the acted upon entity.

Therefore, both of the spanning and precision of the new scheme are validated to be improved comparing to the current nine schemes. As for validating the usability of the new scheme, the primary work proceeds in building the affordance-based intersection model (Section 4.4 The affordance-based interaction models) and designing a virtual-reality (VR) treadmill (APPENDIX D: AFFORDANCES IN THE DESIGN OF A VR TREADMILL). In the future, a user study can further validate the usability of the new scheme.

4.4 The affordance-based interaction models

This section specifies a series of interaction models to specify the roles of the new categories of affordances in user-artifact-environment interactions. Actually there are several similar research papers that can be referred to. For example, Hartson (2003) illustrated in which stage his four types of affordances (i.e., cognitive, physical, sensory, and functional affordances) may act in the user-artifact interaction as seen in Figure 2.6. In addition, as shown in Figure 2.7 and Figure 2.10, Maier and Fadel (2009) proposed the DAU model that specified the roles of designers in affecting the AUAs and AAAs in the user-artifact interaction. Later on, Gero and Kennengiesser (2010) illustrated reflexive, reactive and reflective affordances in the FBS model. While also based on the FBS model but from a different perspective, Cascini (2010) proposed a situated framework as seen in Figure 2.9, in which he divided the human entity into designer and user entities, and discussed how the different types of affordances affect the designer and user entities when they interact with the artifact.

These four models have some distinct limitations as well as innovations. To be specific, Hartson's model only specifies the interaction between the user and the user-interface of the artifact, without discussing the affordances inside the artifact and involving the designer. Maier and Fadel's DAU model specifies the role of designer but does not further discuss the detailed processes of the user-artifact interaction like how the user perceives the affordances and reacts in the first time and then modifies the perceptions and operations after receiving the feedbacks from the artifact. Gero and Kennengiesser's improved FBS model classifies the world into three levels but do not explain the designer's role in the interaction. As for Cascini's situated model, the designer is involved and the detailed processes of the interaction are discussed but like Hartson's model, the affordances inside the artifact are not introduced. Therefore, a series of new interaction models can be built starting from absorbing the innovative perceptions from the four previous models and meanwhile break their limitations.

First of all, based on the definitions of the new categories of affordances, a general model of user-artifact-environment interactions can be built as shown in Figure 4.13:

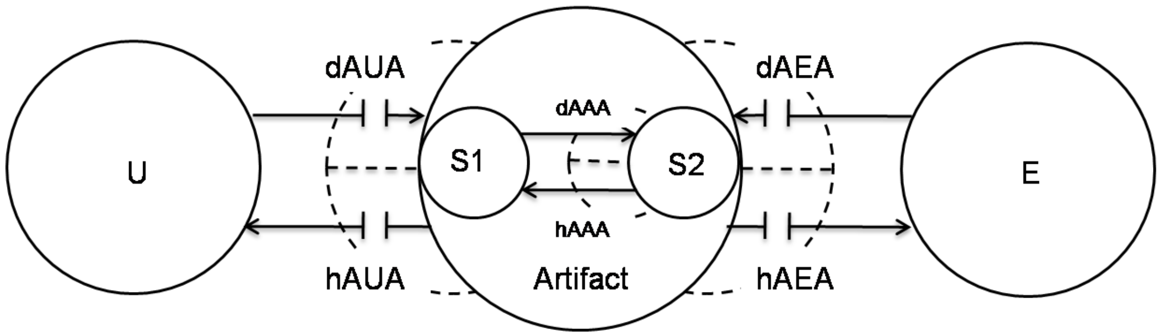


Figure 4.13: The general model of user-artifact-environment interactions (*U*: user; *E*: environment; *S*: subsystem)

This model illustrates the interactions inside and outside the artifact but not yet the interactive processes. Comparing the user-artifact and environment-artifact interactions, they are similar but the former one is more complicated because the user can perceive the affordances, operate the artifact with intent, and keep improving the operations based on the experience accumulation. Therefore, the model evolves to emphasize the user-artifact interaction as seen in Figure 4.14:

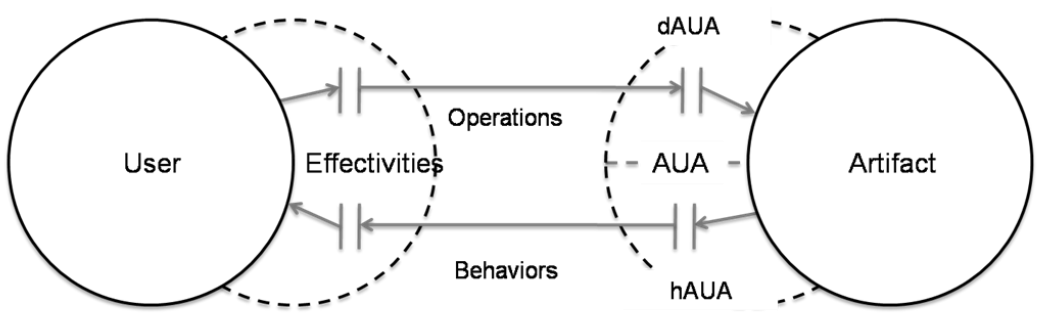


Figure 4.14: The evolved user-artifact interaction model

In Figure 4.14, the affordances are drawn attached to the artifact, illustrating that affordances are closely related to the structure but not the internal properties of the artifact. In addition, the concept of effectivity is introduced to represent the contributions from the user on the interaction. Two vertical lines illustrate the roles of affordances and effectivities of bridging the user and the artifact in the interaction.

The next evolving direction of the model is to specify the processes of the interactions. Therefore, the new model is shown in Figure 4.15:

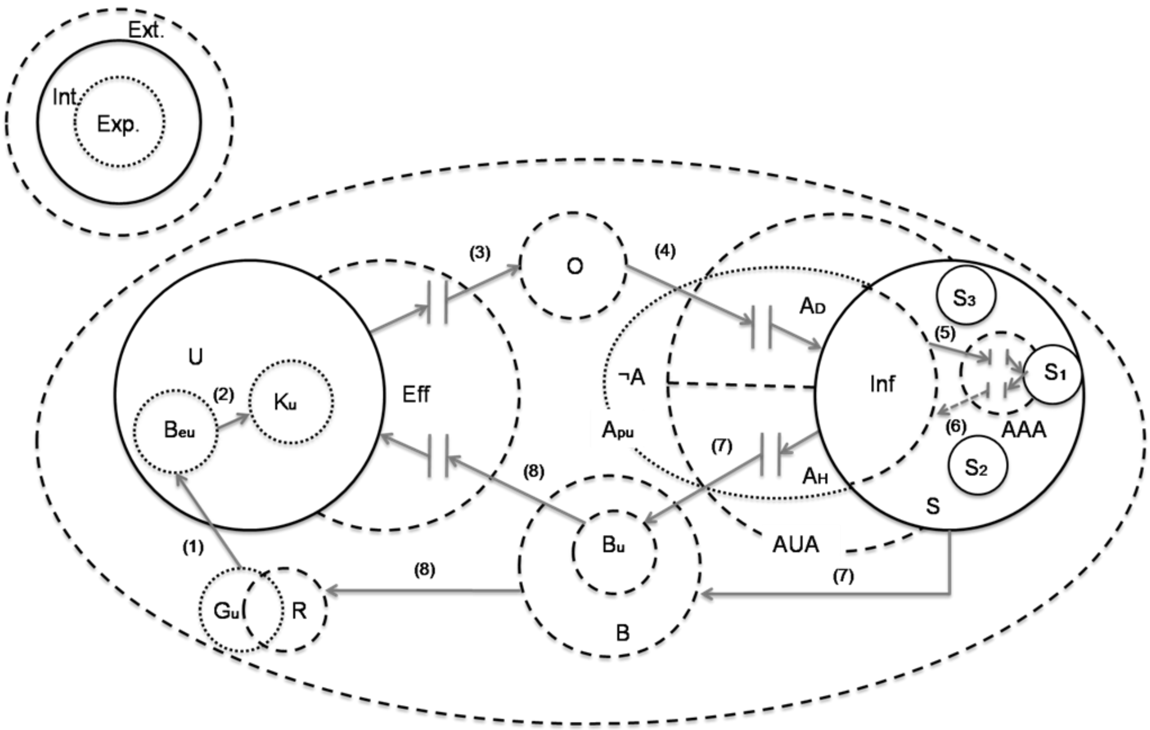


Figure 4.15: The interaction model with specified processes of interactions

In Figure 4.15, Gero’s theory of modeling situatedness (2002, 2010) is introduced. According to this theory, the world is divided into three levels, expected world, interpreted world, and external world, representing the three cognitive levels of the human agents. The external world is the world outside the user’s cognition, the interpreted world is the world representing the user’s cognition, and the expected world is the ideal world that the user expects. In Figure 4.15, the entities and concepts belonging to the different three worlds are illustrated by different line styles. Regarding the interaction processes, a unit loop consists of eight steps:

- Step 1: $G_u \rightarrow B_{eu}$; the user (*U*) is motivated by a goal (G_u) and expect to obtain some behaviors (B_{eu}) from the artifact.
- Step 2: $B_{eu} \rightarrow K_u$; according to the expectation and perceived affordances (A_{pu}), the user searches in the knowledge (K_u) for the analogical experience.
- Step 3: $U \rightarrow Eff \rightarrow O$; based on the effectivities (*Eff*), the user enacts operations (*O*) towards the structure of the artifact (*S*).
- Step 4: $O \rightarrow A_D \rightarrow Inf$; through the doing affordances (A_D), the operations can be acted on the interactive interface (*Inf*) of the artifact and activate the interactions inside the artifact. Since the *Inf* is a part of the artifact and interacts with the user, it is illustrated inside the structure and categorized to the external world. In addition, the affordances exist objectively based on the artifact, so they are categorized to the external world. However, due to the limitation of perceiving effectivity, the user can only perceive the perceived affordances (A_{pu}), in which some are real AUAs but others are false affordances ($\neg A$).
- Step 5: $Inf \rightarrow AAA \rightarrow S_1$; the actions are transferred to subsystems 1 via AAAs;
- Step 6: $S_1 \rightarrow AAA \rightarrow S_i \rightarrow AAA \rightarrow Inf$; the actions are transferred among subsystems (S_i) until finally back to the *Inf*;
- Step 7: $S \rightarrow B$, $Inf \rightarrow A_H \rightarrow B_u$; through the happening affordances (A_H), the artifact (*S*) outputs the behaviors (*B*) to the environment, including the user-related behaviors (B_u);

- Step 8: $B \rightarrow R$, $B_u \rightarrow Eff \rightarrow U$; the output behaviors result in some results (R), including the behaviors acting through the effectivities onto the user (B_u).

After each loop, the user can compare the final results with the initial goals to judge whether the results are acceptable. If not, the user can still learn some experience and then modify the knowledge and perception to operate again. So in the later loops, the user can perceive more and more real AUAs and become more and more skillful to operate the artifact; but the user may not perceive all the AUAs due to the constraints of user's private effectivities. The user will continue repeating this loop until the error between the results and the goals is satisfactory or the results cannot be improved any better.

So far, the model in Figure 4.15 has achieved the goal of building an affordance-based interaction model that can specify the roles of the new categories in the processes of user-artifact interactions. However, this topic can be discussed deeper if the model is rebuilt from the viewpoint of a designer as shown in Figure 4.16:

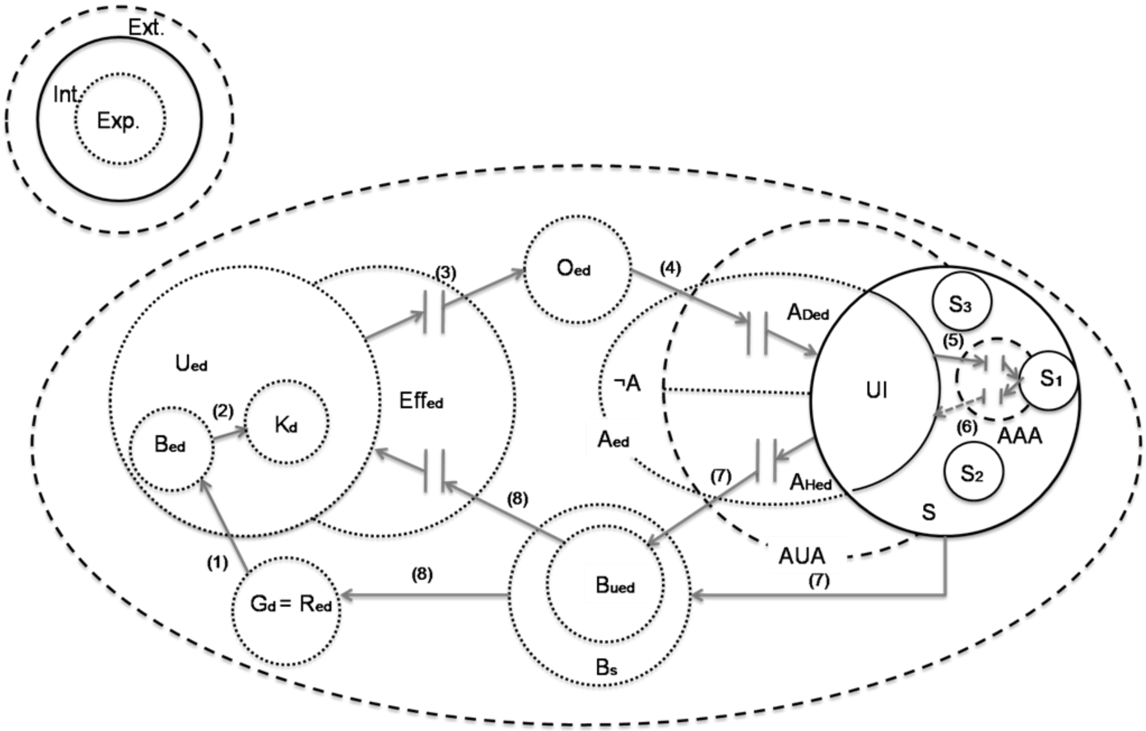


Figure 4.16: The designer-expected interaction model

The essential eight steps are still the same as in Figure 4.16. However, since this interaction model exists in the designer's mind (i.e., the expected world), all the concepts and entities except the artifact (suppose the artifact has already been built) are illustrated by the corresponding line style. And their symbols also need to be updated. In addition, in the ideal situation, the results completely match the goals. However, even the designer cannot completely perceive all the affordances; therefore, false affordances still exist. To show the errors between the practical and the designer-expected models, their illustrations are overlapped as seen in Figure 4.17:

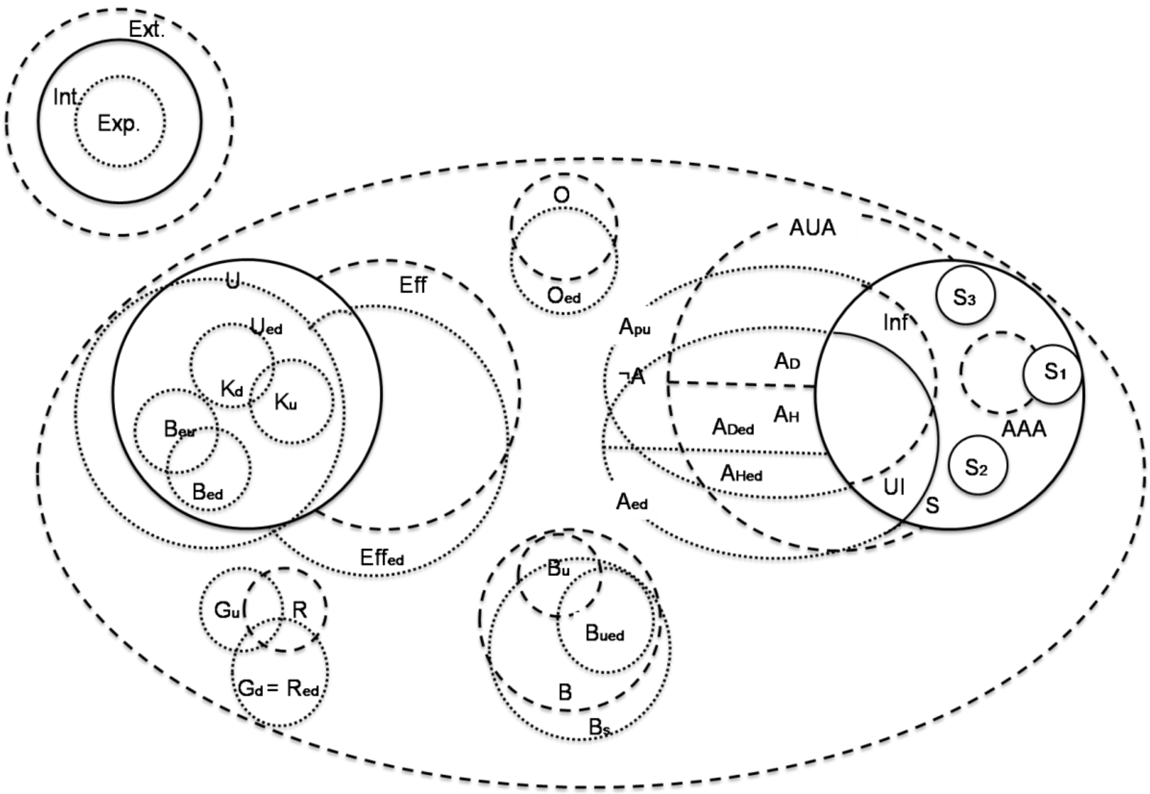


Figure 4.17: The comparison between the practical and the designer-expected models

The comparison is illustrated to emphasize that any of the concepts and entities between the two situations can be different. The errors essentially result from the designer's mind, the target user is a constant model built based on the market investigation and estimation, and, thus, its knowledge, effectivities, and perceived affordances are all correspondingly constant; however, the practical users with their knowledge and effectivities are changing. Similarly, if the environment is substituted to the user and the environment-artifact models are built, errors between expectation and practice are also inevitable due to the same reason. These inevitable errors, on the contrary, prove that in the design process, designers always need to use techniques like user studies and case studies to reduce the errors between expectation and practice and keep improving the design.

4.5 Summary

In this chapter, a new categorization scheme applicable to product design is proposed based on improving the current schemes. It is validated in the spreadsheet which summarizes the use of affordances in the literature. In addition, the roles of the new categories are illustrated in the user-artifact-environment models. In APPENDIX D: AFFORDANCES IN THE DESIGN OF A VR TREADMILL, the new scheme is applied to a case study of designing a VR treadmill. The application shows how each category can be used to improve different aspects of the design.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 Research Contributions

Generally, this thesis presents the research on re-categorizing affordances based on a spreadsheet summarizing the use of affordances in the literature and specifying the roles of these categories in the interaction models. The main contributions from this research include two aspects.

First, the spreadsheet summarizing the use of affordances in literature is built in this thesis. It contains 283 affordances collected from 55 publications of various research communities, including psychology, design, HCI, philosophy, and AI. Based on this spreadsheet, nine current categorization schemes are evaluated and a new scheme is proposed. In the new scheme, the AUA is redefined to represent not only the affordances between the human users and the artifact but also between the non-human organisms with the artifact; a new category of AEA is proposed to classify the affordances beyond the AAA and AUA, representing the affordances between the target artifact and a certain environmental entity. In addition, the doing and happening affordances are re-defined to extend their representing range from Scarantino's organism-entity interactions to entity-entity interactions in the new scheme. Furthermore, due to the orthogonality, the categorization scheme of doing and happening affordances is proposed to combine with the scheme of AUA, AAA, and AEA without any conflicts to categorize the affordances more specifically.

Second, the affordance-based interaction models are built. These models can not only specify the roles of the new categories in the interactive processes but also provide the designers with a general idea why the application of design techniques is significant.

In addition to the contributions from the new categorization, the case study in APPENDIX D: AFFORDANCES IN THE DESIGN OF A VR TREADMILL is the first attempt to use the affordances in combination with the kinematic analysis and energy-based function model to solve mechanism problems. The affordances are usually used to address the design problems of the user interfaces. In this research, however, the case study attempts to prove that the affordances can also be used to diagnose problems and improve mechanism. Since the process is still immature, this case study is finally attached in the appendix.

5.2 Answering the Research Question

RQ: Are the current categorization schemes of affordances applicable for product design to represent the potential interactions between an artifact and users, other artifacts, and natural environmental entities?

Based on the evaluation via a spreadsheet of summarizing the use of affordances in literature, the nine categorization schemes all have various limitations to be directly implemented in product design. However, based on the two basic requirements of product design, Maier and Fadel’s and Scarantino’s categorization schemes selected to be the basis of the new scheme. Therefore, a new categorization is proposed by redefining AUA and doing/happening affordances, adding a category of AEA to classify more affordances, and using doing and happening categories to further decompose AUA, AEA, and AAA.

5.3 Research Results

The results from the two research questions are shown in Table 5.1. The conclusions from this research work will therefore help design engineers to understand how to further develop the affordance-based approaches in mechanical design.

Table 5.1: Answers to the research question

Research Questions	Research Hypotheses	Accept/Reject	Conclusions
RQ: Are the current categorizations of affordances applicable enough to represent the potential interactions among the inner subsystems and between the artifacts with the user and other environmental entities?	**RH1:** The current categorizations of affordances are applicable enough and do not need to be improved.	Reject	All of the nine categorization schemes need to be improved
	RH2: A new categorization can improve the applicability of affordances in product design	Accept	Re-define AUA and doing/happening affordances. Categorize dAUA, hAUA, dAEA, hAEA, dAAA, and hAAA

5.4 Future Research Opportunities

Several other research opportunities have been identified that will further improve the affordance-based design. The recommendations for future work include:

- A user study can be used to validate the usability of the new categorization scheme. The workflow of justifying d/h AAA/AEA/AUA has been proposed in Figure 4.11, a user study can evaluate the objectivity of the proposal;
- When the mechanism need to be represented in 3D kinematic diagram instead of 2D, how to use affordances to diagnose the undesired movements;

- How to represent affordances is still a problem. This direction needs to start from building the vocabulary of the verbs in the affordances and stipulating the rules of representing affordances based on the vocabulary. In addition, building the hierarchy of affordances is also significant in this direction;
- TRIZ is the total name of a series of problem-solving techniques and theories. Among them, the ideal-final-result (IFR) theory and Su-field theory are possible to be combined with affordance-based approaches. To be specific, the IFR stipulates the ratio between beneficial functions and harmful functions representing the idealization of the practical design to the ideal objective. However, according to the theories of functions, functions cannot be considered positive or negative. In contrast, affordances can be. Therefore, redefining the idealization ratio by affordances can be an opportunity in the future. As for combining affordance theories with the Su-field theory, the Su-field theory provides the techniques of solving the problems based on the triangular model of object-actor-field. The model is similar to environment-user-artifact model in affordance-based theories. Therefore, the analogy between the two models could be an opportunity of developing the affordance-based problem-solving techniques.

APPENDIX A: SPREADSHEET OF SUMMARIZING AFFORDANCES USED IN LITERATURE

Reference	*No.*	*Affordances*	*Interactive entities*
[1]	**1**	Press-ability	User→button
[5]	**2**	Affords being held	User→pencil
	3	Affords walking or sitting	User→static horizontal environment
	4	Allow line of sight	User→corridor
	5	Reach	User→shelf
	6	Climb	User→stair riser
	7	Sit	User→chair
[6]	**8**	Be for pushing	User→plates
	9	Be for turning	User→knobs
	10	Be for inserting things into	Things→slots
	11	Be for throwing	User→balls
	12	Be for bouncing	User/artifacts/natural objects→balls→planes
	13	Edibility	User→something edible
	14	Manipulability	User→something manipulable
	15	Be for standing	User→a firm ground
	16	Drink-of-able	User→cup
	17	Afford letter-mailing	Mailbox→letters
[10]	**18**	Afford sitting	User→swing chair
	19	Afford pulling	User→metal door handle

Reference num.	*No.*	*Affordances*	*Interactive entities*
	20	Afford lift-ability	User→basket chair
	21	Afford pushing	User→keys in typewriter
	22	Afford opening horizontally	User→a certain window
	23	Afford titling vertically	User→a certain window
	24	Afford crossing	User→bridge
	25	Afford push-ability	User→pedal
[13]	**26**	Push-ability	User→lens cover
	27	Push-ability	User→battery slot cover
	28	Press-ability	User→shutter button
	29	Grasp-ability	User→mode dial
	30	Turn-ability	User→mode dial
	31	Push-ability	User→zoom lever
	32	Push-ability	User→terminal connector
	33	Press-ability	User→function/set button
	34	Press-ability	User→multi-control dial
	35	Turn-ability	User→multi-control dial
	36	Press-ability	User→AF frame selector
	37	Press-ability	User→playback button
[20]	**38**	Afford typing	User→keyboards
	39	Afford casting	?→Iron→?
	40	Allow use of carpet	Vacuum cleaner→carpet
	41	Dirt removal	Vacuum cleaner→dirt

Reference num.	*No.*	*Affordances*	*Interactive entities*
	42	Dirt disposal	Vacuum cleaner→dirt
	43	Quiet	Vacuum cleaner→noise
	44	Ergonomic	User→vacuum cleaner
	45	Dirt collection	Vacuum cleaner→dirt
	46	Weight	?
	47	Allow dirt in air	Vacuum cleaner→dirt
	48	Require user interaction	User→vacuum cleaner→user
	49	Require replacement	New bag→old bag
	50	Require maintenance	User→vacuum cleaner
	51	Require control	User→vacuum cleaner
	52	Power consumption	Power→vacuum cleaner
	53	Versatility/accessibility	User→vacuum cleaner
	54	Storability	Room→vacuum cleaner
	55	Mobility	User→vacuum cleaner→ground
	56	Dirt visualization	User→vacuum cleaner
	57	Emit noise	Vacuum cleaner→noise
	58	Loss of suction over time	?
	59	Clog-ability	Dirt→vacuum cleaner
[21]	**60**	Support-ability	Base→other parts
	61	Transportability	Handle→other parts
	62	Speed-ability	Buttons→motor
	63	Mix-ability	Blade→mixture

Reference num.	*No.*	*Affordances*	*Interactive entities*
	64	Remove-ability	Jar→mixture
	65	Clean-ability	User→water→mixture
	66	Measure-ability	User→marking lines→mixture
	67	Seal-ability	Cap→jar
	68	Monitor-ability	User→jar
	69	Serve-ability	Jar→mixture
	70	Spill-ability	Jar→mixture
	71	Cut-ability	Blade→user
	72	Fold-ability	User→cell phone
	73	Hold-ability	User→cell phone
	74	Pocket-ability	Pocket→cell phone
	75	Slide-ability	User→cell phone
	76	Read-ability	User→cell phone
	77	Select-ability	User→cell phone
	78	View-ability	User→cell phone
	79	Twist-ability	User→cell phone
	80	Mode-ability	User→cell phone
	81	Type-ability	User→cell phone
	82	Carry-ability	User→cell phone
[22]	**83**	Afford pulling	User→vertical door handles
	84	Afford pushing	User→flat horizontal plates
	85	Afford grasping	User→handle with particular dimensions

Reference num.	*No.*	*Affordances*	*Interactive entities*
	86	Afford passage	Cat→cat-door
	87	Afford drinking	User→water
	88	Afford falling	User→pit
	89	Afford scrolling	User→scrollbars
	90	Afford opening	User→door
	91	Afford grabbing	User→Macintosh scrollbox
	92	Afford uncovering	User→onscreen window
[24]	**93**	Affords breathing	User→air
	94	Affords unimpeded locomotion	Air→ground
	95	Affords visual perception	User→air
	96	Affords pouring	Container→fluid
	97	Affords washing/bathing	Water→?
	98	Afford walking	User→slope between vertical and horizontal
	99	Affords falling	User→a slope downward
	100	Afford lifting/carrying	User→some portable
	101	Affords wielding	User→an elongated object of moderate size and weight
	102	Affords cutting and scraping	A sharp dihedral angle/an edge→user
	103	Affords throwing	User→a graspable rigid object of moderate size and weight
	104	Affords knotting/binding/lashing/knittin g/weaving	An elongated elastic object→another
	105	Affords trace-making	A hand-held tool→surface

Reference num.	*No.*	*Affordances*	*Interactive entities*
	106	Affords human behaviors (e. g. sexual, nurturing, fighting, cooperative, economic, political)	A person→another person
	107	Afford nutrition/poisoning/ neutral	Some substances→a given animal
	108	Affords walking along	The brink of a cliff→?
	109	Affords falling off	The brink of a cliff→?
	110	Affords cutting	A knife→?
	111	Affords grasping	User→a middle-sized metallic object
	112	Affords electric shock	A middle-sized metallic object charged with current→user
[26]	**113**	Afford rotary movement	Steering wheel→mechanical system
	114	Affords changing the car's direction	Steering wheel→car
[27]	**115**	Affords a fine view	User→window
	116	Notice-ability	User→user interface
	117	Discern-ability	User→user interface
	118	Legibility	User→text
	119	Audibility	User→sound
	120	Operability	User→user interface
	121	Sense-ability	User→user interface
[30]	**122**	Knock-ability	User→office door
	123	Jam-ability	Chair→door
[32]	**124**	Travelers-ability	Mover→surface
	125	Reach-ability	User→an object
[33]	**126**	Giving instructions	PDA→user

Reference num.	*No.*	*Affordances*	*Interactive entities*
	127	Conversing	User→PDA→user
	128	Manipulating	User→PDA
	129	Navigating	PDA→user
	130	Exploring and browsing	User→PDA
	131	Afford (non)speech input	User→PDA
[36]	**132**	Afford walking upon	User→roads
	133	Afford reading/mounting	User→signs
	134	Afford shade	Oak trees→light
	135	Afford turning	User/tools→screws
	136	Afford securing	Screws→two or more surfaces
	137	Afford the admiration of beauty	Paintings→user
	138	Afford typing	User→keyboards
	139	Afford collection	Keyboards→dirt
	140	Afford grasping	User→pencils and pens
	141	Afford writing	Pencils and pens→paper
	142	Afford thinking	Brain→idea
	143	Afford meshing	One gear→the other gear
	144	Afford transferring energy	One gear→the other gear
	145	Afford life	Organisms
	146	Affords raising the elevation	Ladder→user
	147	Afford storage	Ladder→room
	148	Afford transport	User→ladder

Reference num.	*No.*	*Affordances*	*Interactive entities*
	149	Afford all weather use	User→ladder
	150	Afford stepping	User→ladder
	151	Afford human use	User→artifact
	152	Afford aesthetics	Artifact→user
	153	Afford improvement	User→artifact
	154	Afford manufacture	User→artifact
	155	Afford maintenance	User→artifact
	156	Afford retirement	?→artifact
	157	Afford sustainability	User→artifact
[39]	**158**	Ergonomics	User→razor
	159	Close shave-ability	Razor→user
	160	Clean-out-ability	?→razor
	161	Shave-ability	Razor→user
	162	Hydrate-ability	Razor→water
	163	Pleasing user with aesthetics	Razor→user
	164	Ability to shave precisely	Razor→user
	165	Hold-ability	User→razor
	166	Annoying user with noise	Noise→user
	167	Electric shock ability	Electricity→user
	168	Cutting user	Razor→user
	169	Accidentally turning off vibration	Razor→razor
	170	Pinching user	Razor→user

Reference num.	*No.*	*Affordances*	*Interactive entities*
	171	Irritating user skin	Razor→user
	172	Transportability	User→razor
	173	Rusting	?
[40]	**174**	The use of up to a 21 inch (CRT) monitor	User→monitor
	175	A view of the monitor vertically as close as possible to its height on the desk without a PCDSMS	User→monitor→desk
	176	Access to buttons, levers, and ports on the PC and docking stations	User→PC and docking stations
	177	No additional weight onto the laptop computer	?
	178	No interference to the portable computer and docking station beneath it	?
	179	No damage when a monitor is dropped from a height of three inches on it	Monitor→PCDSMS
	180	Human injury/frustration	PCDSMS→human
	181	Product degradation	?
[43]	**182**	Transportation of occupants	Vehicle→occupants
	183	Transportation of cargo	Vehicle→cargo
	184	Comfort to occupants	Vehicle→occupants
	185	Entertainment of occupants	Vehicle→occupants
	186	Communication to others	Vehicle→others
	187	Injuring occupants	Vehicle→occupants
	188	Injuring others	Vehicle→pedestrian
	189	Damaging other vehicles	Vehicle→other vehicles
	190	Pollution to the environment	Vehicle→environment

Reference num.	*No.*	*Affordances*	*Interactive entities*
	191	Turn-ability	Gear→the other gear
	192	Ability to produce heat	Gears→heat
	193	Ability to produce noise	Gears→noise
	194	Ability to wear each other	Gear→the other gear
	195	Ability to grind other objects	Gears→other objects
	196	Translational move-ability	Users→vacuum cleaner→ground
	197	Transport-ability	Users→vacuum cleaner
	198	Store-ability	Vacuum cleaner→room
	199	Stability	?
	200	Annoying user with noise	Noise→user
	201	Cutting user	Vacuum cleaner→user
	202	Pinching user	Vacuum cleaner→user
	203	Electric shock-ability	Electricity→user
	204	Dirt remove-ability	Vacuum cleaner→dirt
	205	Dirt contain-ability	Vacuum cleaner→dirt
	206	Floor clean-ability	Vacuum cleaner→floor
	207	Furniture clean-ability	Vacuum cleaner→furniture
	208	Drapes clean-ability	Vacuum cleaner→drapes
	209	Loss of clean-ability by blocked air flow path	Dirt→air flow path
	210	Blowing dirt in front of machine	Vacuum cleaner→dirt
	211	Overheating	Vacuum cleaner→heat
	212	Accessibility of all windows to passenger	Switches→windows

Reference num.	*No.*	*Affordances*	*Interactive entities*
	213	Pleasing user with aesthetics of flushed surfaces	Switches→users
	214	Usability of the same hand for shifting, radio controls, and window controls	Users→switches
	215	Frustrating user by unnatural mapping to window locations	Switches→users
	216	Frustrating user by unnatural mapping of up/down operation	Switches→users
	217	Ability to accidentally activation window up operation	Users→switches
	218	Reduces weight	?
	219	Reduces electronic redundancy	?
	220	Collecting dirt (loose crumbs)	Switches→dirt
	221	Becomes stuck (due to spillage)	Bottom→switches
	222	Maneuverability	Users→vacuum cleaner
	223	Pleasing the user with aesthetics	Vacuum cleaner→user
	224	Ability of the user to reach various surfaces	Vacuum cleaner→surfaces
	225	Ability of the user to clean effectively with suction capability	Vacuum cleaner→dirt
[44]	**226**	Injuring the user by electric shock	Vacuum cleaner→user
	227	Costing the user with power consumption	?
[48]	**228**	Afford chasing	Person→butterfly
	229	Afford writing/editing	User→a word processor
	230	Afford clicking	User→a word processor
	231	Afford dragging	User→a word processor
	232	Afford dropping	User→a word processor

Reference num.	*No.*	*Affordances*	*Interactive entities*
	233	Depress-ability	Piano keys→users
[51]	**234**	Afford tilting	User→button
	235	Afford turning	User→button
	236	Afford pushing	User→button
[52]	**237**	Afford touching	User→computer
	238	Afford looking	User→computer
	239	Afford touching	User→screen
[54]	**240**	Affords sitting	User→chair
	241	Seeing through	User→glass
	242	Breaking	User→glass
	243	Carving	Tools→wood
	244	Writing on	Pen→flat, porous, smooth surfaces
	245	Pushing	User→plates
[61]	**246**	Afford viewing	User→monitor
	247	Afford moving through	Person→open entrance
	248	Enter different buses and trains	Public transportation→person
	249	Afford remembering and selecting	Person→path
	250	Afford orienting and deciding	Person→decision point
	251	Afford pushing	Robot→obstacle
	252	Afford communication	Robot→another robot
[63]	**253**	Divide-by-two-able	User→number
	254	Score-with-able	Flying ball→?

Reference num.	*No.*	*Affordances*	*Interactive entities*
[66]	**255**	Afford throwing	Animal→rock
[69]	**256**	Afford rehabilitation	The life stories of recovering alcoholics in AA meeting→patients
	257	Afford gambling	User→poker chips→?
	258	Afford gender stereotyping	Sexy clothing→person
[71]	**259**	Roll-ability	Robot→cylinder
[79]	**260**	Finger grip-ability	User→rotary knobs
	261	Turn-ability	User→rotary knobs
	262	Press-ability	User→sliding switches
	263	Slid-ability	User→sliding switches
	264	Press-ability	User→push buttons
	265	Push-ability	User→push doors
	266	Seeing through	User→see-through windows
[85]	**267**	Afford flipping	User→switch
	268	Afford turning on	User→lighting system
	269	Afford dialing friend	Phone→friend
	270	Afford selecting digits	User→phone
	271	Afford pressing the dial key	User→dial keys
	272	Afford dialing the chosen number	Phone→other phone
	273	Afford preventing terrorist attacks	Luggage monitoring system→terrorist
	274	Afford improving the safety of plane travelers	Luggage monitoring system→travelers
	275	Afford writing a paper	Computer→paper

Reference num.	*No.*	*Affordances*	*Interactive entities*
	276	Afford pulling a trigger	User→trigger
	277	Afford hitting a glass pane	Hammer→glass pane
	278	Afford firing a gun	User→gun
	279	Afford breaking a glass pane	Hammer→glass pane
	280	Afford shooting a person	Gun→a person
	281	Afford obtaining a hammer	User→hammer
	282	Afford murdering an enemy	Gun→enemy
	283	Afford detecting bombs	Scanner→bomb

APPENDIX B: CATEGORIZING THE SUMMARIZED AFFORDANCES BASED ON THE NINE CATEGORIZATION SCHEMES

No. of the affordances	*Sequential, nested*	*Perceptible, hidden*	*Physical, social-institutional, mental*	*Goal, happening*	*Cognitive, physical, sensory, functional*	*Functional, operational*	*AAA, AUA*	*Reflexive, reactive, reflective*	*Manipulation, effect, use, activity*
1	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
2	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
3	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
4	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
5	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
6	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
7	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
8	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
9	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
10	seq./nested	percep./hidden	physical	?	physical	functional	AAA	rlx/rec/rlc	manipulation
11	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
12	seq./nested	percep./hidden	physical/?	goal/?	physical/functional	functional	AUA/AAA	rlx/rec/rlc	manipulation/effect
13	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
14	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
15	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
16	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
17	seq./nested	percep./hidden	social-inst.	?	functional	functional	AAA	rlx/rec/rlc	use
18	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
19	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
20	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
21	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
22	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
23	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
24	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
25	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
26	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
27	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
28	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
29	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
30	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
31	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
32	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
33	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
34	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
35	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
36	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
37	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
38	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
39	seq./nested	percep./hidden	physical/?	goal /?	physical/?	functional	?	rlx/rec/rlc	manipulation/effect
40	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	use
41	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	effect
42	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	effect
43	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	effect
44	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
45	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	effect
46	?	?	?	?	?	?	?	?	?
47	seq./nested	percep./hidden	physical	?	functional	functional	?	rlx/rec/rlc	effect
48	seq./nested	percep./hidden	physical	goal /happening	physical	functional	AUA	rlx/rec/rlc	manipulation
49	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
50	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
51	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
52	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
53	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
54	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
55	seq./nested	percep./hidden	physical/?	goal /?	physical/functional	functional	AUA/AAA	rlx/rec/rlc	manipulation/effect
56	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
57	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	effect
58	?	?	?	?	?	?	?	?	?
59	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	effect
60	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
61	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
62	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
63	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	?
64	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	?
65	seq./nested	percep./hidden	physical/?	?	physical/functional	functional	?	rlx/rec/rlc	?
66	seq./nested	percep./hidden	physical/?	?	cognitive/sensory	functional	?	rlx/rec/rlc	?
67	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
68	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
69	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
70	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	?
71	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect

72	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
73	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
74	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	effect
75	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
76	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
77	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
78	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
79	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
80	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
81	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
82	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
83	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
84	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
85	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
86	seq./nested	percep./hidden	?	?	physical	functional	?	rlx/rec/rlc	manipulation
87	seq./nested	percep./hidden	physical	goal	physical	functional	?	rlx/rec/rlc	manipulation
88	seq./nested	percep./hidden	physical	happening	physical	functional	?	rlx/rec/rlc	effect
89	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
90	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
91	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
92	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
93	seq./nested	percep./hidden	physical	goal	physical	functional	?	rlx/rec/rlc	manipulation
94	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
95	seq./nested	percep./hidden	physical	goal	physical	functional	?	rlx/rec/rlc	manipulation
96	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
97	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
98	seq./nested	percep./hidden	physical	goal	physical	functional	?	rlx/rec/rlc	manipulation
99	seq./nested	percep./hidden	physical	happening	physical	functional	?	rlx/rec/rlc	effect
100	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
101	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
102	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	manipulation/effect
103	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
104	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
105	seq./nested	percep./hidden	physical	goal	physical	functional	?	rlx/rec/rlc	?
106	seq./nested	percep./hidden	physical	goal/happening	physical	functional	?	rlx/rec/rlc	effect/use/activity
107	seq./nested	percep./hidden	physical	happening	physical	functional	?	rlx/rec/rlc	?
108	seq./nested	percep./hidden	physical	happening	physical	functional	?	rlx/rec/rlc	effect
109	seq./nested	percep./hidden	physical	happening	physical	functional	?	rlx/rec/rlc	effect
110	seq./nested	percep./hidden	physical	happening	physical	functional	?	rlx/rec/rlc	effect
111	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
112	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
113	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
114	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
115	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
116	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
117	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
118	seq./nested	percep./hidden	mental	goal	cognitive/sensory	functional	?	rlx/rec/rlc	manipulation
119	seq./nested	percep./hidden	physical	goal	cognitive/sensory	functional	?	rlx/rec/rlc	manipulation
120	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
121	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
122	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
123	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	effect
124	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
125	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
126	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
127	seq./nested	percep./hidden	physical	goal/happening	physical	functional	AUA	rlx/rec/rlc	manipulation/effect
128	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
129	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
130	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
131	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
132	seq./nested	percep./hidden	physical	goal	physical	functional	?	rlx/rec/rlc	manipulation
133	seq./nested	percep./hidden	mental	goal	cognitive/sensory	functional	AUA	rlx/rec/rlc	manipulation
134	seq./nested	percep./hidden	?	happening	?	functional	?	rlx/rec/rlc	?
135	seq./nested	percep./hidden	physical	goal	physical/functional	functional	AUA/AAA	rlx/rec/rlc	manipulation
136	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
137	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	use
138	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
139	seq./nested	percep./hidden	?	?	physical	functional	?	rlx/rec/rlc	?
140	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
141	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	effect
142	seq./nested	percep./hidden	mental	?	cognitive/sensory	functional	?	rlx/rec/rlc	?
143	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
144	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
145	?	?	?	?	?	?	?	?	?
146	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
147	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	?
148	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
149	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
150	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
151	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
152	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
153	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation

154	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
155	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
156	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
157	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
158	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
159	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
160	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
161	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	use
162	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
163	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
164	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
165	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
166	seq./nested	percep./hidden	mental	happening	cognitive/sensory	functional	?	rlx/rec/rlc	effect
167	seq./nested	percep./hidden	physical	happening	physical	functional	?	rlx/rec/rlc	effect
168	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
169	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
170	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
171	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
172	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
173	?	?	?	?	?	?	?	?	?
174	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
175	seq./nested	percep./hidden	physical	doing/happening	physical	functional	AUA/AAA	rlx/rec/rlc	?
176	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
177	?	?	?	?	?	?	?	?	?
178	?	?	?	?	?	?	?	?	?
179	seq./nested	percep./hidden	?	?	?	functional	AAA	rlx/rec/rlc	?
180	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
181	?	?	?	?	?	?	?	?	?
182	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	use
183	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
184	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	use
185	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	use
186	seq./nested	percep./hidden	physical	happening	physical	functional	AAA/AUA	rlx/rec/rlc	use
187	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
188	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
189	seq./nested	percep./hidden	?	?	?	functional	AAA	rlx/rec/rlc	?
190	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
191	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
192	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
193	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
194	seq./nested	percep./hidden	?	?	?	functional	AAA	rlx/rec/rlc	?
195	seq./nested	percep./hidden	?	?	?	functional	AAA	rlx/rec/rlc	?
196	seq./nested	percep./hidden	physical/?	goal/?	physical/functional	functional	AUA/AAA	rlx/rec/rlc	manipulation
197	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
198	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
199	?	?	?	?	?	?	?	?	?
200	seq./nested	percep./hidden	mental	happening	cognitive/sensory	functional	?	rlx/rec/rlc	effect
201	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
202	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
203	seq./nested	percep./hidden	?	?	physical	functional	?	rlx/rec/rlc	effect
204	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	effect
205	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	effect
206	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	use
207	seq./nested	percep./hidden	?	?	physical	functional	AAA	rlx/rec/rlc	use
208	seq./nested	percep./hidden	?	?	physical	functional	AAA	rlx/rec/rlc	use
209	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	?
210	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	effect
211	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	effect
212	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	use
213	seq./nested	percep./hidden	physical	happening	cognitive/sensory	functional	AUA	rlx/rec/rlc	use
214	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
215	seq./nested	percep./hidden	mental	happening	cognitive/sensory	functional	AUA	rlx/rec/rlc	activity
216	seq./nested	percep./hidden	mental	happening	cognitive/sensory	functional	AUA	rlx/rec/rlc	activity
217	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
218	?	?	?	?	?	?	?	?	?
219	?	?	?	?	?	?	?	?	?
220	seq./nested	percep./hidden	?	?	?	functional	?	rlx/rec/rlc	?
221	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
222	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
223	seq./nested	percep./hidden	mental	happening	cognitive/sensory	functional	AUA	rlx/rec/rlc	activity
224	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
225	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
226	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
227	seq./nested	percep./hidden	social-inst.	?	?	functional	?	rlx/rec/rlc	activity
228	seq./nested	percep./hidden	physical	goal	physical	functional	?	rlx/rec/rlc	manipulation
229	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
230	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
231	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
232	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
233	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	use
234	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
235	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation

236	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
237	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
238	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
239	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
240	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
241	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
242	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
243	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	effect
244	seq./nested	percep./hidden	?	?	functional	functional	?	rlx/rec/rlc	effect
245	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
246	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
247	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
248	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	effect
249	seq./nested	percep./hidden	mental	?	cognitive/sensory	functional	?	rlx/rec/rlc	?
250	seq./nested	percep./hidden	mental	?	cognitive/sensory	functional	?	rlx/rec/rlc	?
251	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
252	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
253	seq./nested	percep./hidden	mental	?	cognitive/sensory	functional	?	rlx/rec/rlc	?
254	seq./nested	percep./hidden	social-inst.	happening	functional	functional	?	rlx/rec/rlc	activity
255	seq./nested	percep./hidden	physical	?	physical	functional	?	rlx/rec/rlc	manipulation
256	seq./nested	percep./hidden	social-inst.	happening	physical	functional	?	rlx/rec/rlc	use
257	seq./nested	percep./hidden	social-inst.	goal/happening	physical	functional	?	rlx/rec/rlc	use
258	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	activity
259	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	?
260	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
261	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
262	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
263	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
264	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
265	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
266	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
267	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
268	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
269	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	activity
270	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
271	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
272	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	effect
273	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	activity
274	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	activity
275	seq./nested	percep./hidden	social-inst.	?	functional	functional	AAA	rlx/rec/rlc	use
276	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
277	seq./nested	percep./hidden	?	?	functional	functional	AAA	rlx/rec/rlc	effect
278	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	effect
279	seq./nested	percep./hidden	?	?	physical	functional	AAA	rlx/rec/rlc	use
280	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	use
281	seq./nested	percep./hidden	physical	goal	physical	functional	AUA	rlx/rec/rlc	manipulation
282	seq./nested	percep./hidden	physical	happening	physical	functional	AUA	rlx/rec/rlc	activity
283	seq./nested	percep./hidden	social-inst.	?	physical	functional	AAA	rlx/rec/rlc	use

APPENDIX C: CATEGORIZING THE SUMMARIZED AFFORDANCES BASED ON THE NEW CATEGORIZATION PROPOSED IN THE RESEARCH

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
[1]	Press-ability	User→button	dAUA
[5]	Affords being held	User→pencil	dAUA
	Affords walking or sitting	User→static horizontal environment	dAUA
	Allow line of sight	User→corridor	dAUA
	Reach	User→shelf	dAUA
	Climb	User→stair riser	dAUA
	Sit	User→chair	dAUA
[6]	Be for pushing	User→plates	dAUA
	Be for turning	User→knobs	dAUA
	Be for inserting things into	Things→slots	dAAA
	Be for throwing	User→balls	dAUA
	Be for bouncing	User/artifacts/natural objects→balls→planes	dhAUA/dhAEA
	Edibility	User→something edible	dAUA
	Manipulability	User→something manipulable	dAUA
	Be for standing	User→a firm ground	dAUA
	Drink-of-able	User→cup	dAUA
	Afford letter-mailing	Mailbox→letters	hAAA
[10]	Afford sitting	User→swing chair	dAUA
	Afford pulling	User→metal door handle	dAUA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Afford lift-ability	User→basket chair	dAUA
	Afford pushing	User→keys in typewriter	dAUA
	Afford opening horizontally	User→a certain window	dAUA
	Afford titling vertically	User→a certain window	dAUA
	Afford crossing	User→bridge	dAUA
	Afford push-ability	User→pedal	dAUA
[13]	Push-ability	User→lens cover	dAUA
	Push-ability	User→battery slot cover	dAUA
	Press-ability	User→shutter button	dAUA
	Grasp-ability	User→mode dial	dAUA
	Turn-ability	User→mode dial	dAUA
	Push-ability	User→zoom lever	dAUA
	Push-ability	User→terminal connector	dAUA
	Press-ability	User→function/set button	dAUA
	Press-ability	User→multi-control dial	dAUA
	Turn-ability	User→multi-control dial	dAUA
	Press-ability	User→AF frame selector	dAUA
	Press-ability	User→playback button	dAUA
[20]	Afford typing	User→keyboards	dAUA
	Afford casting	?→Iron→?	dhAAA
	Allow use of carpet	Vacuum cleaner→carpet	hAAA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Dirt disposal	Vacuum cleaner→dirt	hAEA
	Dirt removal	Vacuum cleaner→dirt	hAEA
	Quiet	Vacuum cleaner→noise	hAEA
	Ergonomic	User→vacuum cleaner	dAUA
	Dirt collection	Vacuum cleaner→dirt	hAEA
	Weight	?	?
	Allow dirt in air	Vacuum cleaner→dirt	hAEA
	Require user interaction	User→vacuum cleaner→user	dhAUA
	Require replacement	New bag→old bag	dhAAA
	Require maintenance	User→vacuum cleaner	dAUA
	Require control	User→vacuum cleaner	dAUA
	Power consumption	Power→vacuum cleaner	dAEA
	Versatility/accessibility	User→vacuum cleaner	dAUA
	Storability	Vacuum cleaner→room	hAEA
	Mobility	User→vacuum cleaner→ground	dAUA/hAEA
	Dirt visualization	User→vacuum cleaner	dAUA
	Emit noise	Vacuum cleaner→noise	hAEA
	Loss of suction over time	?	?
	Clog-ability	Dirt→vacuum cleaner	dAEA
[21]	Support-ability	Base→other parts	dhAAA
	Transportability	Handle→other parts	dhAAA
	Speed-ability	Buttons→motor	dhAAA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Remove-ability	Jar→mixture	hAEA
	Clean-ability	User→water→mixture	?
	Mix-ability	Blade→mixture	hAEA
	Measure-ability	User→marking lines→mixture	?
	Seal-ability	Cap→jar	dhAAA
	Monitor-ability	User→jar	dAUA
	Serve-ability	Jar→mixture	hAEA
	Spill-ability	Jar→mixture	hAEA
	Cut-ability	Blade→user	hAUA
	Fold-ability	User→cell phone	dAUA
	Hold-ability	User→cell phone	dAUA
	Pocket-ability	Pocket→cell phone	dAAA
	Slide-ability	User→cell phone	dAUA
	Read-ability	User→cell phone	dAUA
	Select-ability	User→cell phone	dAUA
	View-ability	User→cell phone	dAUA
	Twist-ability	User→cell phone	dAUA
	Mode-ability	User→cell phone	dAUA
	Type-ability	User→cell phone	dAUA
	Carry-ability	User→cell phone	dAUA
[22]	Afford pulling	User→vertical door handles	dAUA
	Afford pushing	User→flat horizontal plates	dAUA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Afford passage	Cat→cat-door	dAUA
	Afford drinking	User→water	?
	Afford grasping	User→handle with particular dimensions	dAUA
	Afford falling	User→pit	?
	Afford scrolling	User→scrollbars	dAUA
	Afford opening	User→door	dAUA
	Afford grabbing	User→Macintosh scrollbox	dAUA
	Afford uncovering	User→onscreen window	dAUA
[24]	Affords breathing	User→air	d?
	Affords unimpeded locomotion	Air→ground	d?
	Affords visual perception	User→air	d?
	Affords pouring	Container→fluid	hAEA
	Affords washing/bathing	Water→?	d?
	Afford walking	User→slope between vertical and horizontal	dAUA
	Affords falling	User→a slope downward	dAUA
	Afford lifting/carrying	User→some portable	dAUA
	Affords wielding	User→an elongated object of moderate size and weight	dAUA
	Affords cutting and scraping	A sharp dihedral angle/an edge→user	hAUA
	Affords throwing	User→a graspable rigid object of moderate size and weight	dAUA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Affords human behaviors (e. g. sexual, nurturing, fighting, cooperative, economic, political)	A person→another person	dh?
	Afford nutrition/poisoning/ neutral	Some substances→a given animal	h?
	Affords knotting/binding/lashing/knitting/weaving	An elongated elastic object→another	dhAAA
	Affords trace-making	A hand-held tool→surface	dAEA
	Affords walking along	The brink of a cliff→?	h?
	Affords falling off	The brink of a cliff→?	h?
	Affords cutting	A knife→?	h?
	Affords grasping	User→a middle-sized metallic object	dAUA
	Affords electric shock	A middle-sized metallic object charged with current→user	hAUA
[26]	Afford rotary movement	Steering wheel→mechanical system	hAAA
	Affords changing the car's direction	Steering wheel→car	hAAA
[27]	Affords a fine view	User→window	dAUA
	Notice-ability	User→user interface	dAUA
	Discern-ability	User→user interface	dAUA
	Legibility	User→text	d?
	Audibility	User→sound	d?
	Operability	User→user interface	dAUA
	Sense-ability	User→user interface	dAUA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
[30]	Knock-ability	User→office door	dAUA
	Jam-ability	Chair→door	dhAAA
[32]	Travers-ability	Mover→surface	dAUA
	Reach-ability	User→an object	dAUA
[33]	Giving instructions	PDA→user	hAUA
	Conversing	User→PDA→user	dhAUA
	Manipulating	User→PDA	dAUA
	Navigating	PDA→user	hAUA
	Exploring and browsing	User→PDA	dAUA
	Afford (non)speech input	User→PDA	dAUA
[36]	Afford walking upon	User→roads	d?
	Afford reading/mounting	User→signs	dAUA
	Afford shade	Oak trees→light	h?
	Afford turning	User/tools→screws	dAUA/dAAA
	Afford securing	Screws→two or more surfaces	hAAA
	Afford the admiration of beauty	Paintings→user	hAUA
	Afford typing	User→keyboards	dAUA
	Afford collection	Keyboards→dirt	hAEA
	Afford grasping	User→pencils and pens	dAUA
	Afford writing	Pencils and pens→paper	hAAA
	Afford thinking	Brain→idea	?
	Afford meshing	One gear→the other gear	dhAAA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Afford storage	Ladder→room	hAEA
	Afford transport	User→ladder	dAUA
	Afford transferring energy	One gear→the other gear	dhAAA
	Afford life	Organisms	?
	Affords raising the elevation	Ladder→user	hAUA
	Afford all weather use	User→ladder	dAUA
	Afford stepping	User→ladder	dAUA
	Afford human use	User→artifact	dAUA
	Afford aesthetics	Artifact→user	hAUA
	Afford improvement	User→artifact	dAUA
	Afford manufacture	User→artifact	dAUA
	Afford maintenance	User→artifact	dAUA
	Afford retirement	?→artifact	dhAEA
	Afford sustainability	User→artifact	dAUA
[39]	Ergonomics	User→razor	dAUA
	Close shave-ability	Razor→user	hAUA
	Clean-out-ability	?→razor	dAEA
	Shave-ability	Razor→user	hAUA
	Hydrate-ability	Razor→water	hAEA
	Pleasing user with aesthetics	Razor→user	hAUA
	Ability to shave precisely	Razor→user	hAUA
	Hold-ability	User→razor	dAUA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Accidentally turning off vibration	Razor→razor	dhAAA
	Pinching user	Razor→user	hAUA
	Annoying user with noise	Noise→user	h?
	Electric shock ability	Electricity→user	h?
	Cutting user	Razor→user	hAUA
	Irritating user skin	Razor→user	hAUA
	Transportability	User→razor	dAUA
	Rusting	?	?
[40]	The use of up to a 21 inch (CRT) monitor	User→monitor	dAUA
	A view of the monitor vertically as close as possible to its height on the desk without a PCDSMS	User→monitor→desk	dhAUA/AAA
	Access to buttons, levers, and ports on the PC and docking stations	User→PC and docking stations	dAUA
	No additional weight onto the laptop computer	?	?
	No interference to the portable computer and docking station beneath it	?	?
	No damage when a monitor is dropped from a height of three inches on it	Monitor→PCDSMS	dAAA
	Human injury/frustration	PCDSMS→human	hAUA
	Product degradation	?	?
[43]	Transportation of occupants	Vehicle→occupants	hAUA
	Transportation of cargo	Vehicle→cargo	hAAA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Injuring occupants	Vehicle→occupants	hAUA
	Injuring others	Vehicle→pedestrian	hAUA
	Comfort to occupants	Vehicle→occupants	hAUA
	Entertainment of occupants	Vehicle→occupants	hAUA
	Communication to others	Vehicle→others	hAUA
	Damaging other vehicles	Vehicle→other vehicles	hAAA
	Pollution to the environment	Vehicle→environment	hAEA
	Turn-ability	Gear→the other gear	dhAAA
	Ability to produce heat	Gears→heat	hAEA
	Ability to produce noise	Gears→noise	hAEA
	Ability to wear each other	Gear→the other gear	dhAAA
	Ability to grind other objects	Gears→other objects	hAEA
	Translational move-ability	Users→vacuum cleaner→ground	dhAUA/dhAEA
	Transport-ability	Users→vacuum cleaner	dAUA
	Store-ability	Vacuum cleaner→room	hAEA
	Stability	?	?
	Annoying user with noise	Noise→user	h?
	Cutting user	Vacuum cleaner→user	hAUA
	Pinching user	Vacuum cleaner→user	hAUA
	Electric shock-ability	Electricity→user	h?
	Dirt remove-ability	Vacuum cleaner→dirt	hAEA
	Dirt contain-ability	Vacuum cleaner→dirt	hAEA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Loss of clean-ability by blocked air flow path	Dirt→air flow path	dAAA
	Blowing dirt in front of machine	Vacuum cleaner→dirt	hAEA
	Floor clean-ability	Vacuum cleaner→floor	hAEA
	Furniture clean-ability	Vacuum cleaner→furniture	hAAA
	Drapes clean-ability	Vacuum cleaner→drapes	hAEA
	Overheating	Vacuum cleaner→heat	hAEA
	Accessibility of all windows to passenger	Switches→windows	hAAA
	Pleasing user with aesthetics of flushed surfaces	Switches→users	hAUA
	Usability of the same hand for shifting, radio controls, and window controls	Users→switches	dAUA
	Frustrating user by unnatural mapping to window locations	Switches→users	hAUA
	Frustrating user by unnatural mapping of up/down operation	Switches→users	hAUA
	Ability to accidentally activation window up operation	Users→switches	dAUA
	Reduces weight	?	?
	Reduces electronic redundancy	?	?
	Collecting dirt (loose crumbs)	Switches→dirt	hAEA
	Becomes stuck (due to spillage)	Bottom→switches	hAAA
[44]	Maneuverability	Users→vacuum cleaner	dAUA
	Pleasing the user with aesthetics	Vacuum cleaner→user	hAUA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Injuring the user by electric shock	Vacuum cleaner→user	hAUA
	Costing the user with power consumption	?	?
	Ability of the user to reach various surfaces	Vacuum cleaner→surfaces	hAEA
	Ability of the user to clean effectively with suction capability	Vacuum cleaner→dirt	hAEA
[48]	Afford chasing	Person→butterfly	d?
	Afford writing/editing	User→a word processor	dAUA
	Afford clicking	User→a word processor	dAUA
	Afford dragging	User→a word processor	dAUA
	Afford dropping	User→a word processor	dAUA
	Depress-ability	Piano keys→users	hAUA
[51]	Afford tilting	User→button	dAUA
	Afford turning	User→button	dAUA
	Afford pushing	User→button	dAUA
[52]	Afford touching	User→computer	dAUA
	Afford looking	User→computer	dAUA
	Afford touching	User→screen	dAUA
[54]	Affords sitting	User→chair	dAUA
	Seeing through	User→glass	dAUA
	Breaking	User→glass	dAUA
	Carving	Tools→wood	dAEA
	Writing on	Pen→flat, porous, smooth surfaces	dAEA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Pushing	User→plates	dAUA
[61]	Afford viewing	User→monitor	dAUA
	Afford moving through	Person→open entrance	dAUA
	Enter different buses and trains	Public transportation→person	hAUA
	Afford remembering and selecting	Person→path	d?
	Afford orienting and deciding	Person→decision point	d?
	Afford pushing	Robot→obstacle	dAEA
	Afford communication	Robot→another robot	dhAAA
[63]	Divide-by-two-able	User→number	d?
	Score-with-able	Flying ball→?	h?
[66]	Afford throwing	Animal→rock	d?
[69]	Afford rehabilitation	The life stories of recovering alcoholics in AA meeting→patients	h?
	Afford gambling	User→poker chips→money	dAUA/hAAA
	Afford gender stereotyping	Sexy clothing→person	hAUA
[71]	Roll-ability	Robot→cylinder	dAAA
[79]	Finger grip-ability	User→rotary knobs	dAUA
	Turn-ability	User→rotary knobs	dAUA
	Press-ability	User→sliding switches	dAUA
	Slid-ability	User→sliding switches	dAUA
	Press-ability	User→push buttons	dAUA
	Push-ability	User→push doors	dAUA

Reference num.	*Affordances*	*Interactive entities*	*dAUA, hAUA, dAEA, hAEA, dAAA, hAAA*
	Seeing through	User→see-through windows	dAUA
[85]	Afford flipping	User→switch	dAUA
	Afford turning on	User→lighting system	dAUA
	Afford dialing friend	Phone→friend	hAUA
	Afford selecting digits	User→phone	dAUA
	Afford pressing the dial key	User→dial keys	dAUA
	Afford dialing the chosen number	Phone→other phone	hAAA
	Afford preventing terrorist attacks	Luggage monitoring system→terrorist	hAUA
	Afford improving the safety of plane travelers	Luggage monitoring system→travelers	hAUA
	Afford writing a paper	Computer→paper	hAAA
	Afford pulling a trigger	User→trigger	dAUA
	Afford hitting a glass pane	Hammer→glass pane	hAAA
	Afford firing a gun	User→gun	dAUA
	Afford breaking a glass pane	Hammer→glass pane	hAAA
	Afford shooting a person	Gun→a person	hAUA
	Afford obtaining a hammer	User→hammer	dAUA
	Afford murdering an enemy	Gun→enemy	hAUA
	Afford detecting bombs	Scanner→bomb	hAAA

APPENDIX D: AFFORDANCES IN THE DESIGN OF A VR TREADMILL

D.1 Preprocessing in conceptual design

The aim of the design case study is to develop a virtual-reality treadmill and apply the new proposed affordances categorization into the design process. This section details the preprocessing stage of the design to identify the objective, the requirements, and the subsystems.

D.1.1 Design objective

The objective of the case study is to design a non-motorized treadmill outfitted with (1) automatic controls and mechanism so that its platform incline can be adjusted automatically within a range according to terrain elevation data downloaded from Google Street View and (2) a commercial head-mounted display (HMD) to display the head tracked imagery of a panoramic environment in Google Street View and update the images as the user walks on the treadmill. Therefore, the total system should realize the simulated integration of both the visual virtual reality and the physical locomotion.

D.1.2 Requirements list

Having defined the objectives, next a list of requirements has to be specified to be used in the decision process. The requirements list is compiled based on the methodology proposed by Pahl *et al.* (2007) as seen in Table 0.1. “Demand” indicates the requirement that must be satisfied; otherwise, the design fails to achieve its objective. While “Wish” means the expected requirement may or may not be achieved, but it can be used to identify the better designs. The requirements list is obtained by interviewing potential users, and Table 0.1 shows a subset of the entire list:

Table 0.1: Partial requirements list of the VR treadmill

Main headings	*D/W*	*Requirements*
1. Geometry	Demand	The elevating mechanism must not interfere in the operating zone of the user;
	Wish	The elevating mechanism should fit in the space under the platform;
	Wish	The number of components of the mechanism should be as few as possible;
2. Kinematics	Demand	Gradient adjustment range must = -5 ° to 0 °;
	Wish	Gradient range should = -10 ° to 5 °;
3. Force	Demand	Must carry a person of 250 lbs and sustain an additional 200 lbs impact load;
	Demand	Must control the error rate ≤ 3% when loaded;
4. Energy	Demand	Must use grid power;
	Demand	Must be clean, steady, quiet and powerful;
5. Safety	Demand	Must obey OSHA standards;
6. Cost	Demand	Must cost less than 800 $;
7. Others	Wish	Display frequency ≥ 24 fps;
	Wish	Resolution of HMD ≥ 640 × 480;
	Wish	Error of synchronicity ≤ 1 s;
…	…	…

The requirements list can be used to formalize the design objective from an abstract statement to a specific set of technical criteria. Based on the requirements, an ideal-final-result (IFR) model (Altshuller, 1984, 1996) is proposed assuming that in this model all the demands and wishes could be satisfied. The IFR model is used as a reference to compare candidate solutions in latter sections.

D.1.3 Decomposition and workflow

The requirements list defines the design boundaries of the VR treadmill. The next step is decomposing the system to divide the large difficult problem into several small simple problems. Based on the statement of the objective, the design task can generally be divided into three subtasks, including (1) designing the elevating mechanism to adjust the incline of the treadmill's platform, (2) setting the automatic control devices to exchange data between the mechanism and the computer, and (3) building a VR system to simulate the panoramic environment for the user. Correspondingly, the VR treadmill can be decomposed into mechanical, control, and VR subsystems. Therefore, the designer-expected interaction model is built as seen in Figure 0.1:

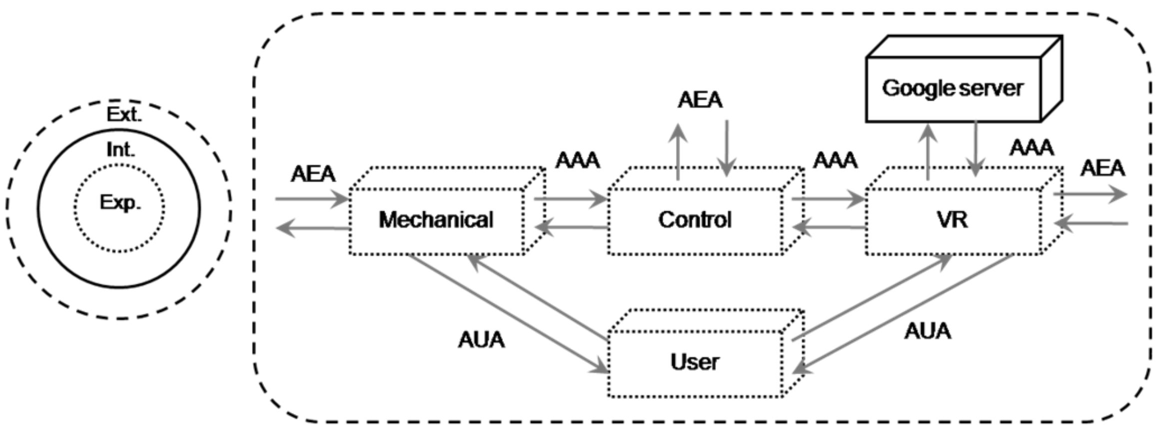


Figure 0.1: The designer-expected interaction model of the system

The significant expected affordances in the model are roughly summarized as:

- Between the user and the mechanical subsystem: stand/walk-ability (user→mechanical subsystem, dAUA), support/elevate-ability (mechanical subsystem→user, hAUA);
- Between the user and the VR subsystem: wear/view/select-path-ability (user→VR subsystem, dAUA), track-ability (VR subsystem→user, hAUA);
- Between the mechanical subsystem and the control subsystem: detect-ability (control subsystem→mechanical subsystem, dhAAA), control-ability (control subsystem→mechanical subsystem, dhAAA);
- Between the control subsystem with the VR subsystem: exchange-data-ability (control subsystem→VR subsystem→control subsystem, dhAAA);
- Between the VR subsystem with the Google server: exchange-data-ability (VR subsystem→Google server→VR subsystem, dhAAA);
- Between the subsystems and the environment: place/store-ability (environment→ subsystems, dAEA), emit-sound/heat-ability (subsystems→environment, hAEA);

Based on the expected affordances, some components can be easily identified and purchased from the market. For example, in mechanical subsystem, a non-motorized treadmill is clearly identified as the refitted target; in the control subsystem, a sensor is needed to detect the rotation of the treadmill, and a controller is required to realize the automatic control; in addition, a HMD and a computer are essential in the VR subsystem. Therefore, the general function structure can be sketched as seen in Figure 0.2 via energy and signal flows stringing up the functions of those identified components:

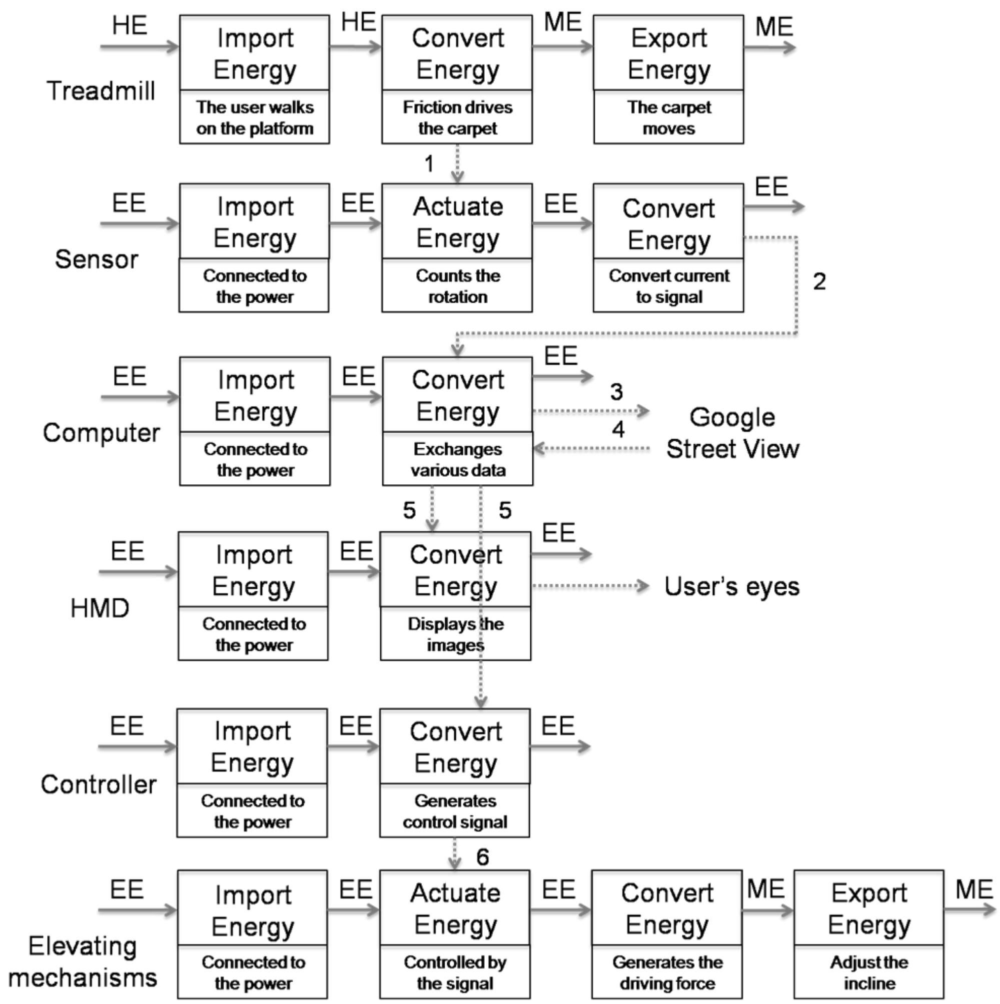


Figure 0.2: Function structure of the system. EE: electric energy; ME: mechanical energy; HE: human energy

In a single loop of the signal transformation, the workflow proceeds as follows:

- Step 1: the sensor collects data from the rotating carpet of the treadmill to calculate the user's walking speed and displacement;
- Step 2: the collected data are transferred to the computer;
- Step 3: the computer uploads the data to the Google Street View server to identify the position of the user;

- Step 4: the computer downloads the terrain and photographic data according to the identified position;
- Step 5: the computer supplies the photographic data to the HMD to display to the user; meanwhile, it computes elevation change from the terrain data and sends it to the controller;
- Step 6: the controller translates the terrain elevation data to power-device-control signals and transfers these signals to the elevating mechanism to adjust the incline of the platform.

So far, the three subsystems and several components have been identified. In the subsequent sections the foci are on the design process of the remaining components in the three subsystems, especially a mechanical assembly adjusting the incline of the platform and a plug-in in computer exchanging data with the Google Street View server, the HMD, and the controller.

Since the mechanical subsystem and the VR subsystem is not directly related in this research, to shorten the research period, the research team was split to two groups and respectively worked on the two subsystems. Then after the two subsystems were finished, the research team reunited and worked on the control subsystem until it completed the entire system.

D.2 The mechanical subsystem

The mechanical subsystem consists of a non-motorized treadmill and an elevating assembly. The non-motorized treadmill is purchased from the market. This treadmill does not include any motors to control the carpet's rotating speed or adjust the platform's incline. Its working principle is based on the difference between the friction coefficients on the two opposite surfaces of the carpet. The friction coefficient of the top surface contacting with the user's shoes must be larger than that of the bottom one contacting with a supporting platform, and hence when the user steps on the carpet and walks forwards, the force applied on the top surface can overcome the reversed friction force on the bottom, driving the carpet to move backwards. The normal walking motion is thereby simulated. Note that the decision to use such a non-motorized treadmill is specifically to allow the user to stop and look around in the virtual environment.

In contrast to the treadmill purchased from the market, the elevating assembly needs to be built in this research. Therefore, the design and improving processes of this assembly are the two foci in this section.

D.2.1 Designing the first prototype

Based on TRIZ (Altshuller, 1997, 2000) and Pailhès *et al.*'s energy-based function decomposition (2011), the elevating assembly can be decomposed into a converter, a transmitter, and an operator. The converter converts different forms of energy to the driving energy for the operator. Since the operator is usually not directly connected to the converter, the transmitter is needed to bridge the distance between the operator and the converter to transmit the energy. In this elevating assembly, the power device is the converter, the platform is the operator, and the mechanism between the power device and the operator are considered together as the transmitter. The platform is a component of the treadmill and, thus, it can be directly used in the design. In contrast, the power device and the mechanism need to be selected and designed.

To select the power device, three options are available: hydraulic devices, pneumatic devices, and electric motor. According to the requirements list, the IFR of power devices should be cheap, simple, powerful, silent, quickly responding, and not easily interfered with. Such an ideal solution is proposed as a reference and compared with the three options through weighing with quantitative scales (1, 4, 9: 1 = low, 4 = moderate, 9 = high) (Maier *et al.*, 2009) in a decision matrix (DM) as seen in Table 0.2:

Table 0.2: Power devices comparison

Criteria (weight)	*Hydraulic*	*Pneumatic*	*Electric*	*IFR*
Cost (9)	1	4	9	9
Complexity (4)	1	1	4	9
Thrust (9)	9	1	4	9
Noise (4)	9	1	4	9
Responding speed (4)	1	4	9	9
Anti-interference (4)	9	9	1	9
Total	30 (170)	20 (105)	31 (189)	54 (306)
Ratio to IFR	56% (56%)	37% (34%)	57% (62%)	-

Note that a DM is used to roughly evaluate the items in the column according to the criteria in the row, and the quantitative scales (1, 4, 9) only represent the hierarchy of the three levels of quality rather than the real differences among the levels. Therefore, options obtaining near equal final scores mean that they are equivalently acceptable. For example, in Table 0.2 the comparison indicates that using either an electric motor is practically equivalent to a set of hydraulic devices to drive the mechanism. However, the hydraulic is graded with three low scores on a high-priority criterion: cost, and two moderate-priority criteria, complexity and responding speed; while the electric solution obtains only one low score on a moderate-priority criterion: anti-interference. Hence, the electric motor is preferred in this project because its performance is preferred to that of the hydraulic solution according to the six criteria.

Once the actuation energy source is selected, the mechanism that induces the elevation change has to be designed. It should be driven by a motor and transform the rotating power of the motor into an elevating force applied on the platform of the treadmill; meanwhile, it should be installed preferably beneath the platform of the treadmill in order not to protrude and accidentally injure the user. Based on this functional description and the requirements list in Table 0.1, the IFR's characteristics are identified: cheap, steady, accurate, simple, small, quickly responding, anti-interference and driven efficiently. These characteristics actually constrain the selection scope of the mechanism. Although numerous mechanisms can perform the desired elevation, the more components contained in the mechanism, the more difficult is the mechanism to manufacture within the requirements constraints. Using brainstorming, six candidate mechanisms are sketched as seen in Figure 0.3:

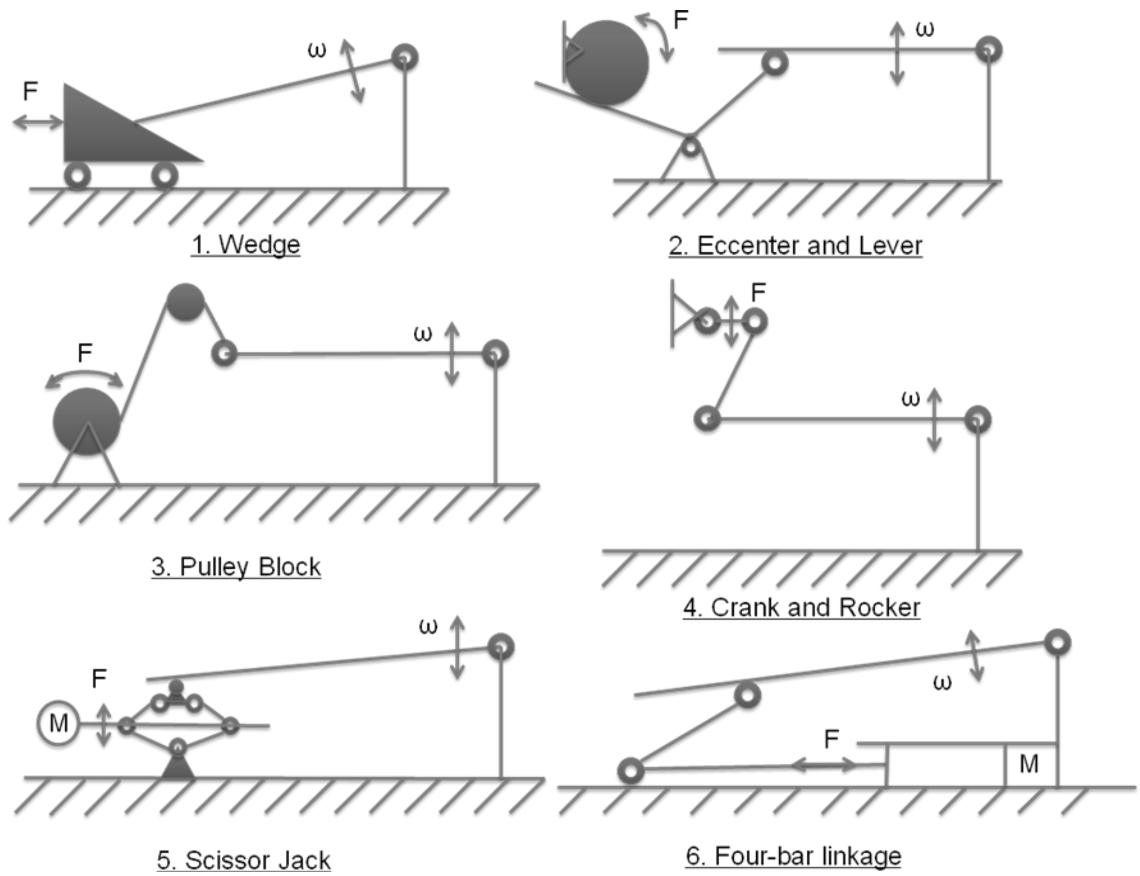


Figure 0.3: Sketches of six alternative mechanisms

Comparing the IFR with the six alternatives in the decision matrix is shown in Table 0.3:

Table 0.3: Mechanism comparison

Criteria (weight)	*1*	*2*	*3*	*4*	*5*	*6*	*IFR*
Cost (4)	1	1	4	1	4	4	9
Strength (9)	9	1	1	4	9	4	9
Accuracy (1)	9	4	1	9	1	9	9
Anti-interference (4)	9	4	1	4	9	9	9
Occupied space (9)	1	1	4	4	4	9	9
Complexity (9)	1	1	4	1	1	4	9
Driven efficiency (9)	4	1	4	1	1	1	9
Responding speed (4)	1	9	4	9	1	9	9
Total	35	22	23	33	30	49	72

	(188)	(96)	(154)	(155)	(192)	(259)	(441)
Ratio to IFR	49% (43%)	31% (22%)	32% (35%)	46% (35%)	42% (44%)	68% (59%)	-

The comparison in Table 0.3 indicates that the four-bar linkage is the winner of the selection.

D.2.2 AUA-based improvement

However, this selected plan still obtains a low score on driven efficiency because of the situation shown in Figure 0.4:

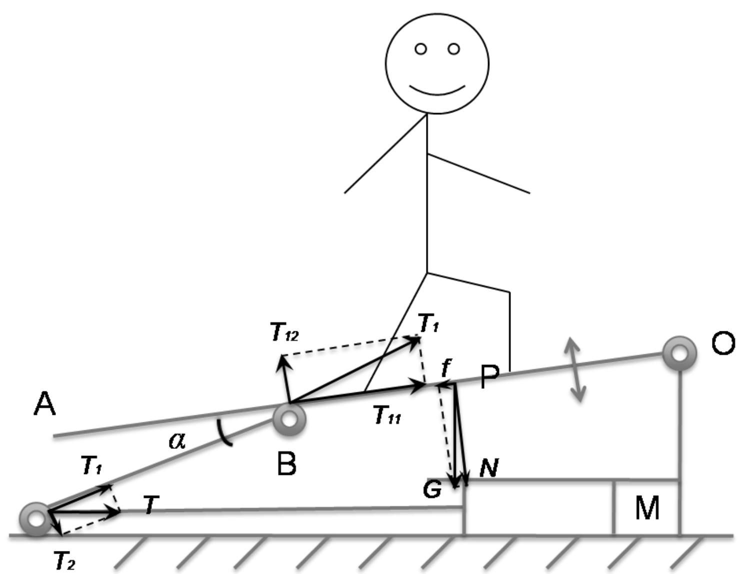


Figure 0.4: Problem of the four-bar linkage

In this situation, when the push rod works to elevate the user, since the angle α approaches 0, no matter how large is the driving force T, the component force T_{12} $(= T_1 \sin\alpha)$ also approaches 0 and therefore may not be large enough to lift up the platform with a user on it. It is even worse when the user is standing on the AB section of the platform as shown in Figure 0.5, because OP, the moment arm of the user's force *N*, is longer than OB, the moment arm of the elevating force T_{12}.

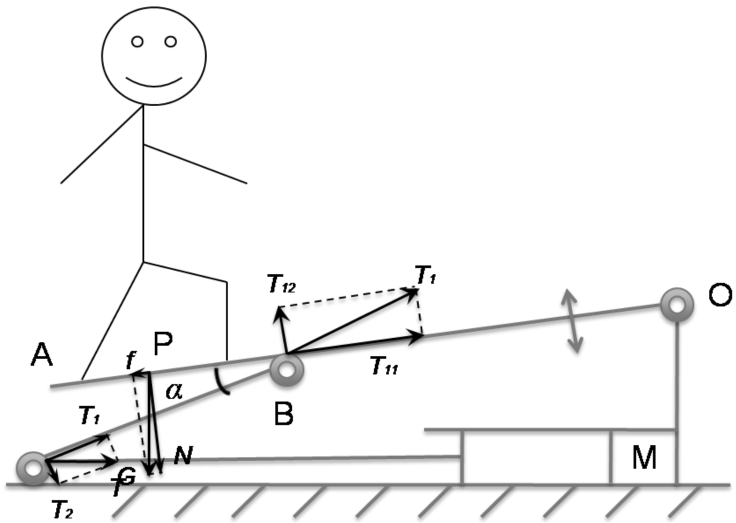


Figure 0.5: The elevate-ability fails when the user stands on the AB

Analyzing affordances can help evaluate and resolve this problem. In this project, the elevating assembly's expected hAUA is to afford elevating the user to realize the incline change. However, according to the mechanics analysis, this hAUA fails when the user walks on AB. So one solution to guarantee the whole platform offering the evaluate-ability is to extend the moment arm of the supporting force T_{12} as long as possible; therefore, the position of the joint between the mechanism with the platform is changed from B to A as shown in Figure 0.6:

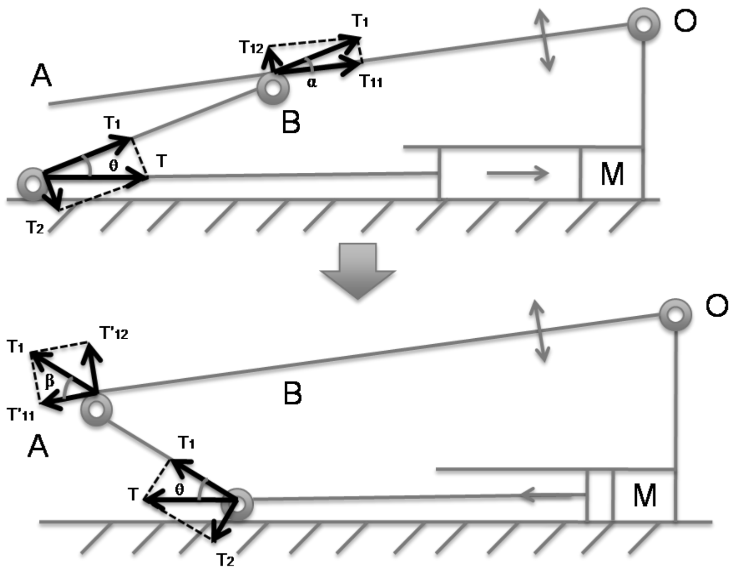


Figure 0.6: Mechanical analysis and comparison

After the modification, the mechanics analysis can prove that the supporting force T'_{12} is larger than force T_{12}, because:

$$T_1 = T\cos\theta \quad (1)$$

$$T_{12} = T_1 \sin\alpha = T\cos\theta\sin\alpha \quad (2)$$

$$T'_{12} = T_1 \sin\beta = T\cos\theta\sin\beta \quad (3)$$

$$\alpha < \theta < \beta \quad (4)$$

$$T_{12} < T'_{12} \quad (5)$$

A prototype implementing this mechanism has therefore been built and delivered to the client.

D.2.3 AAA-based improvement

Different from the initial plan shown in Figure 0.6, since the manufactured prototype needed to be packaged and mailed from the manufacturer, the mechanism was modified to afford the disassembling/assembling for convenient delivery; therefore, the joints as seen in Figure 0.7 were manufactured to be connected by pin bolts:

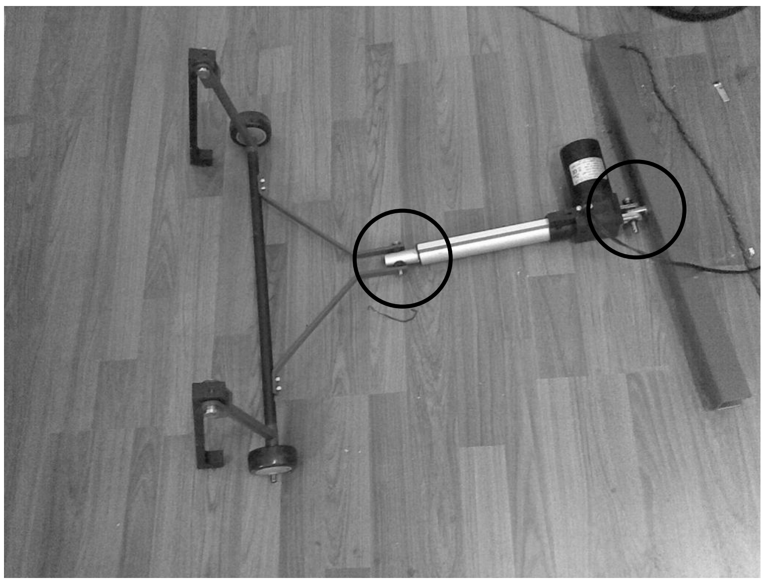


Figure 0.7: The circle-marked joints are manufactured to be connected by pin bolts

Due to the property of form-dependence, modifying the structure can usually result in a change of affordances. However, as discussed in the section of the affordance-based innovation models, the new affordances can be either desired and perceivable like the assemble/disassemble-abilities, or undesired and hidden like the fold-ability of the links as seen in Figure 0.8 after the mechanism is installed onto the treadmill:

Figure 0.8: The connections by pin bolts afford the unexpected folding of the links

Based on the theories of affordances, the folding is caused by the undesired hAAAs of the related links. To diagnose these hAAAs and then improve the mechanism, a method to combine affordance theory with kinematic analysis (Marghitu, 2005) and an energy-based approach (Paihès *et al.*, 2011) is proposed in this research.

To be specific, the first step of the method is to build the kinematic diagram of the target mechanism and specify the links and joints. Then the kinematic methods can be used to calculate the mechanism's number of DOF. If the number of DOF is less than the number of driver links, some driver links conflict with others; if the number of DOF is larger than the number of driver links, some moving links are not controlled by the driver links. For both of the problems, there are two solutions: changing the number of driver links or modifying the mechanism to change the number of DOF. Usually designers adopt the second solution because it is comparatively more economic and efficient.

If the number of DOF does not equal to the number of driver links, the second step is to build the energy-based function structure based on the mechanism. This step has two purposes: first, the functional role (converter, transmitter, operator, or reference) of each link can be identified so that the links having undesired roles need to be modified; second, the energy flow on each joint can be identified to help diagnose the undesired hAAAs in the latter steps. There are two reasons to select Paihès *et al.*'s energy-based function structure (2011) instead of the Pahl *et al.*'s classic version (2007): first it is because Paihès *et al.* divide the mechanical energy into translational and rotational, which match the kinematic classification; second, Paihès *et al.* used the virtual work principles to represent non-transformative functions as shown in Table 0.4:

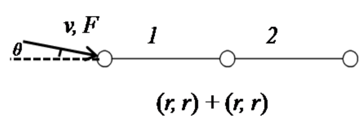
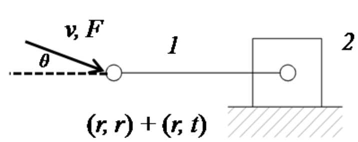
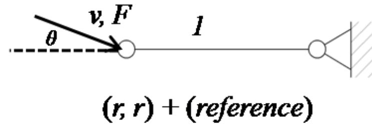
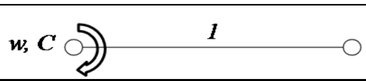
Table 0.4: Energy-based representation of forces and movements (Paihès *et al.*, 2010)

Type of energy	*Relevant conjugate variables*		*Energy flow (power)*
	Temporal Variables	*State Variables*	
Mechanical (translation)	Speed (*v*)	Force (*F*)	*v*, *F*
Mechanical (rotation)	Rotation speed (*w*)	Couple (*C*)	*w*, *C*
Static mechanical (translational)	Virtual speed (*v**)	Force (*F*)	0
Static mechanical (rotation)	Virtual rotation speed (*w**)	Couple (*C*)	0

The third step is to analyze the hAAAs of the moving links in the mechanism. In the kinematic analysis, only the velocities and the directions of forces, not the mass, types of materials, magnitude of forces, deformation, and friction of the ideally rigid components are considered. Therefore, the forces can be translational (push, pull, and support) or rotational (rotate and support), while the movements can also be rotational or translational. This categorization of forces and movements matches Table 0.4. Note that in mechanisms for the joints connected by the pin bolts, one component actually does not directly act on the connected one; instead, it acts on the pin bolt and then the pin bolt transfers the actions to the next component. However, since the friction is not considered, the pin bolts do not affect the actions and just convert them.

Corresponding to the forces and movements, the essential doing AAAs between two connected components can be push-ability, pull-ability, and rotate-ability; and the happening AAAs can be rotational-move-ability (RMA), translational-move-ability (TMA), and support-ability. Among these affordances, the two types of move-abilities indicate how the components may behave; hence, the research on what situations can determine the RMA and TMA is of great value for identifying which components can results in the undesired movements. A summary of the situations is built as seen in Table 0.5, in which the rotational joint is marked with *r* and the translational joint is marked with *t*:

Table 0.5: The situations determine the RMA and TMA of links

		When $\theta \neq 180°$, 1 and 2 afford RMA.
		When $\theta = 180°$ or $0°$, 1 affords TMA; when $\theta = \pm 90°$, 1 affords RMA; Otherwise, 1 affords TMA and RMA. 2 always affords TMA
		When $\theta = 180°$ or $0°$, 1 affords neither RMA nor TMA; otherwise, 1 affords RMA.
		1 always affords RMA.

The last step is to compare the hAAAs of the links with the energy-based function structure and diagnose the undesired ones. Then the joints and links related to the undesired hAAAs are modified to change those hAAAs or just cancel them.

Above are the four steps of the method and the subsequent part is to implement this method to the improvement of the elevating mechanism. First of all, the mechanism can be illustrated as a 2D kinematic diagram shown in Figure 0.9:

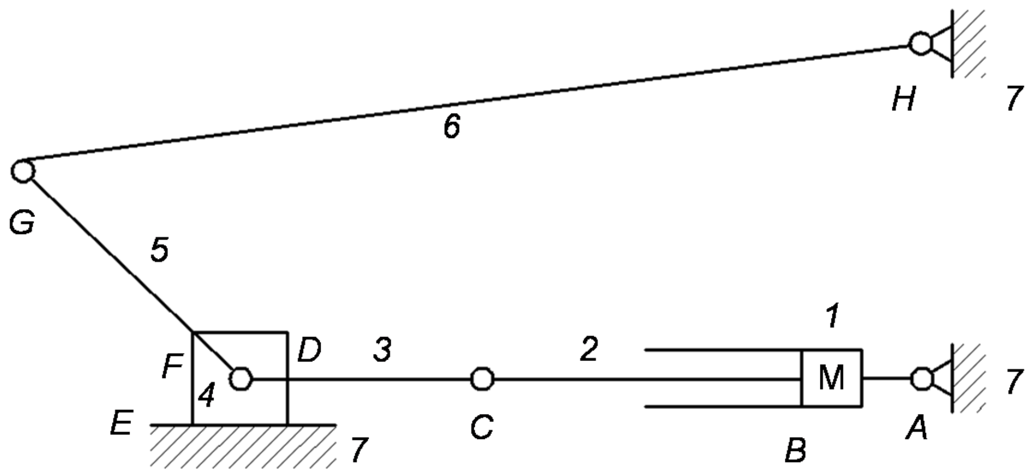


Figure 0.9: Kinematic diagram of the mechanism

Based on the principle of kinematic analysis (Marghitu, 2005), link 1, 2, 3, 4, 5, 6 are moving links and link 7 is the reference; hence, the number of moving links is 6, noted as $n = 6$. In addition, there are eight joints of class 5 ($C_5 = 8$) (class 5 means the number of degree-of-freedom (DOF) of the joint is one):

- At A there is one rotational joint between link 1 and link 7;
- At B there is one translational joint between link 1 and link 2;
- At C there is one rotational joint between link 2 and link 3;
- At D there is one rotational joint between link 3 and link 4;

- At E there is one translational joint between link 4 and link 7;
- At F there is one rotational joint between link 4 and link 5;
- At G there is one rotational joint between link 5 and link 6;
- At H there is one rotational joint between link 6 and link 7;

Therefore, the number of DOF for this mechanism is given by:

$$M = 3n - 2C_5 = 18 - 16 = 2 \quad (6)$$

$M = 2$ indicates that this mechanism needs to be driven by two driver links to control the movement of all the moving links. However, in this mechanism, there is only one driver link (the push rod), meaning that the movement of some links cannot be controlled by the only driver link. This is why the undesired folding occurs.

The second step is to build the expected energy-based function structure as seen in Figure 0.10:

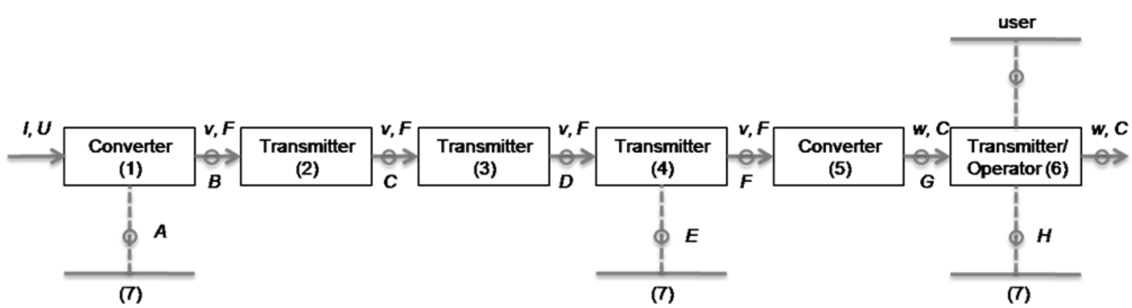


Figure 0.10: The expected energy-based function structure of the mechanism in Figure 0.9

The analysis of hAAAs is shown in Table 0.6:

Table 0.6: The analysis of hAAAs for the mechanism in Figure 0.9

<table>
<tr><th>Moving links</th><th colspan="2">Combining the links</th><th>AAAs</th></tr>
<tr><td>1 = (A, B): (r, t)</td><td rowspan="2">1, 2 = (A, C): (r, r)</td><td rowspan="3">1, 2, 3 = (r, r) + (r, r)</td><td rowspan="3">1, 2, 3: RMA
2: TMA</td></tr>
<tr><td>2 = (B, C): (t, r)</td></tr>
<tr><td>3 = (C, D): (r, r)</td><td>3 = (C, D): (r, r)</td></tr>
<tr><td>4 = (D, E): (r, t)
= (E, F): (t, r)</td><td>4 = (D, E): (r, t)
= (E, F): (t, r)</td><td>4 = (D, E): (r, t)
= (E, F): (t, r)</td><td>4: TMA</td></tr>
<tr><td>5 = (F, G): (r, r)</td><td rowspan="2">5, 6 = (r, r) + (r, r)</td><td rowspan="2">5, 6 = (r, r) + (r, r)</td><td rowspan="2">5, 6: RMA</td></tr>
<tr><td>6 = (G, H): (r, r)</td></tr>
</table>

Note that Table 0.6 shows that link 2 affords both TMA and RMA; however, the energy-based function model in Figure 0.10 shows that link 2 should be a transmitter and the energy flows on joint B and joint C are both translational. Link 2's RMA can change the functional role of link 2 and the energy flow on joint C as seen in Figure 0.11:

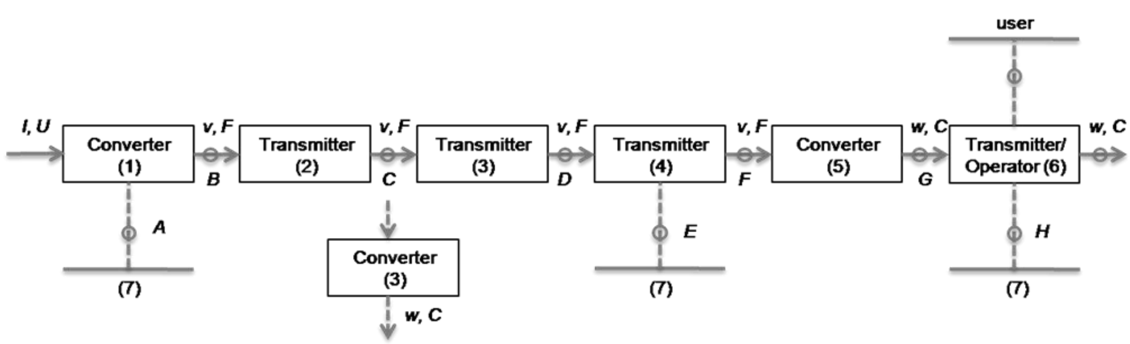


Figure 0.11: Link 2's undesired RMA results in the changes in the energy-based function structure

To cancel the undesired RMA, the way is to break the combination (r, r) + (r, r) by link 1, 2, and 3. Therefore, fixing any one of joints A, C, or D can be applicable. If joint C is fixed, the mechanism becomes as shown in Figure 0.12:

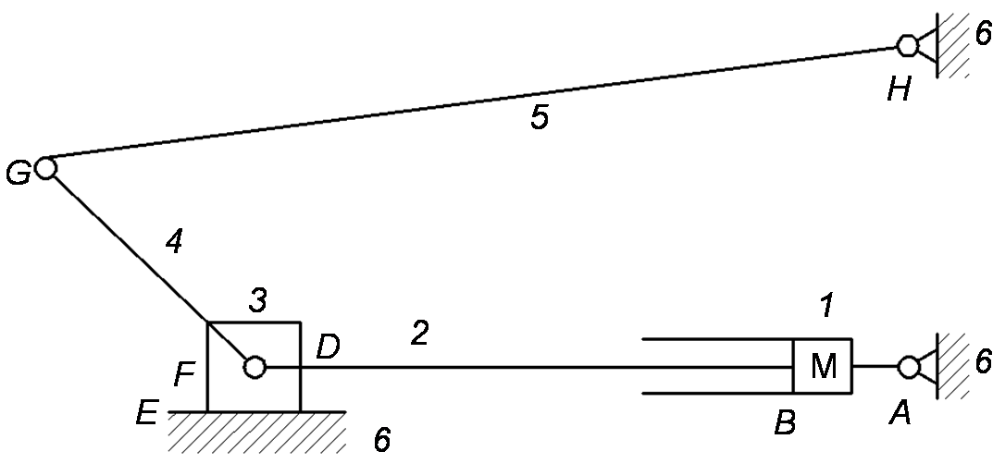


Figure 0.12: The diagram of the mechanism if joint C is fixed

Then $n = 5$, $C_5 = 7$, and the number of DOF for the mechanism in Figure 0.12 is given by:

$$M = 3n - 2C_5 = 15 - 14 = 1 \quad (7)$$

The number of DOF equals to the number of driver link. The energy-based function structure becomes as seen in Figure 0.13:

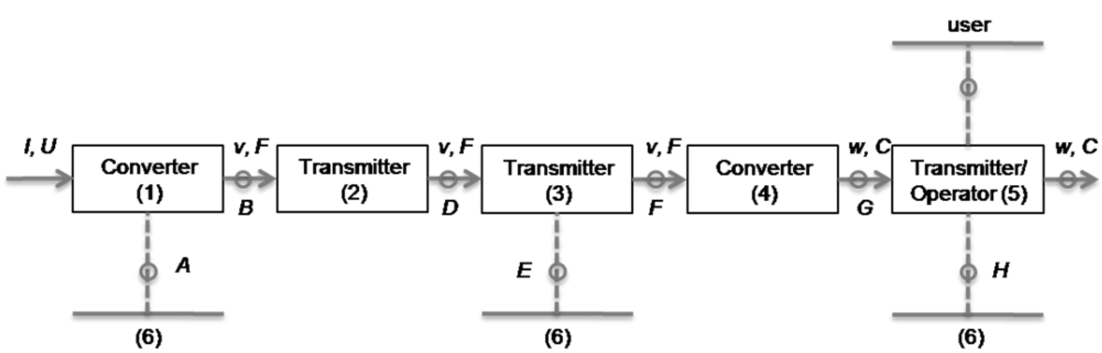


Figure 0.13: The improved energy-based function structure if joint C is fixed

Or, if joint A is fixed, the mechanism becomes as shown in Figure 0.14:

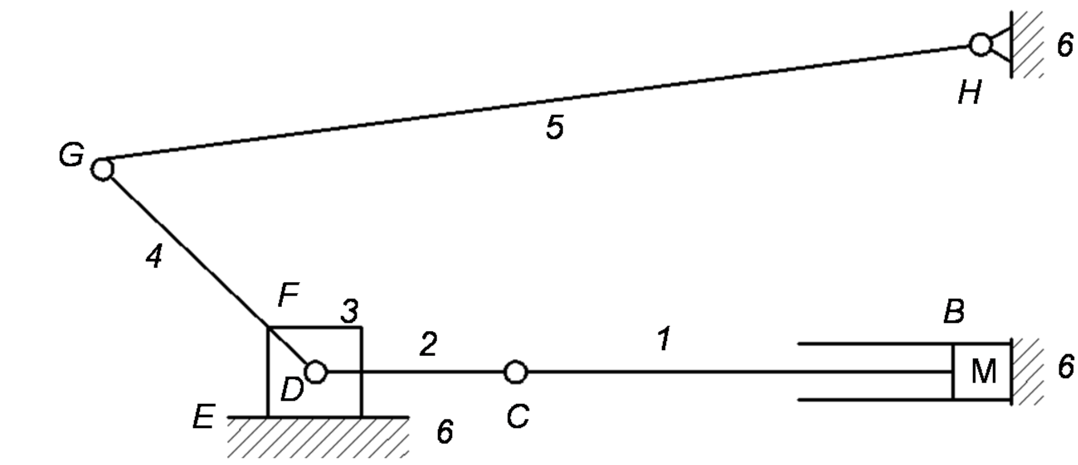


Figure 0.14: The diagram of the mechanism if joint A is fixed

Same with equation (7), $n = 5$, $C_5 = 7$, and then $M = 1$. The energy-based function structure is as seen in Figure 0.15:

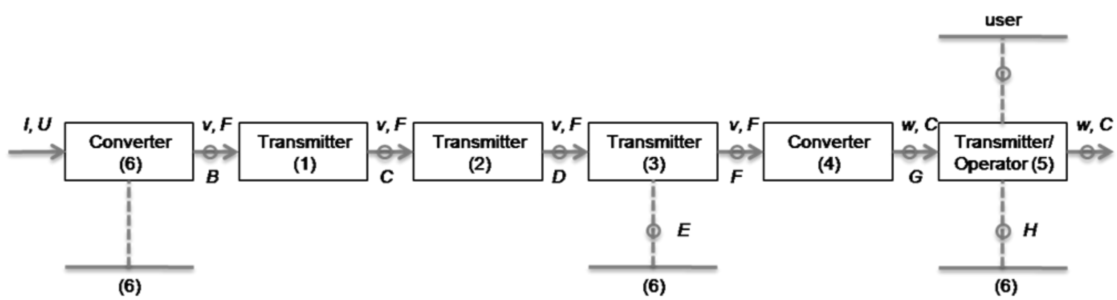


Figure 0.15: The improved energy-based function structure if joint A is fixed

Or, if joint D is fixed, the mechanism becomes as shown in Figure 0.16:

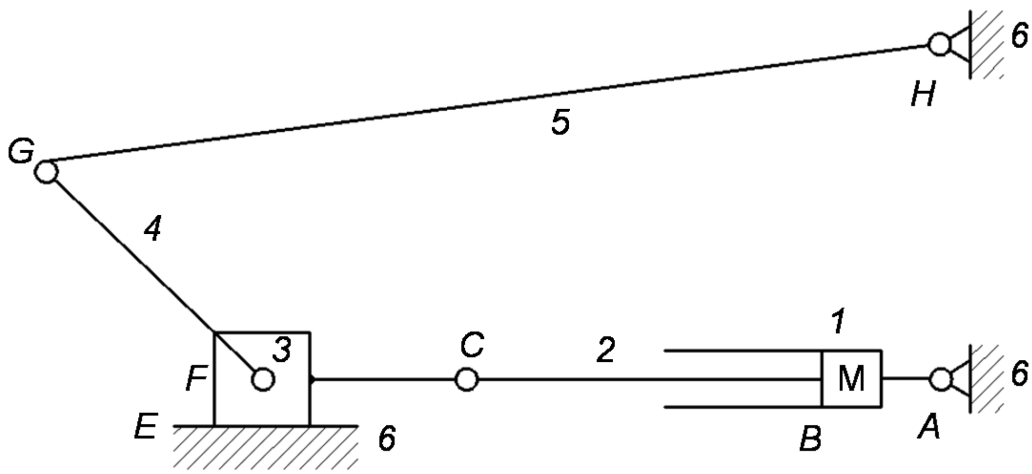


Figure 0.16: The diagram of the mechanism if joint D is fixed

Same with equation (7), $n = 5$, $C_5 = 7$, and then $M = 1$. The energy-based function structure is shown in Figure 0.17:

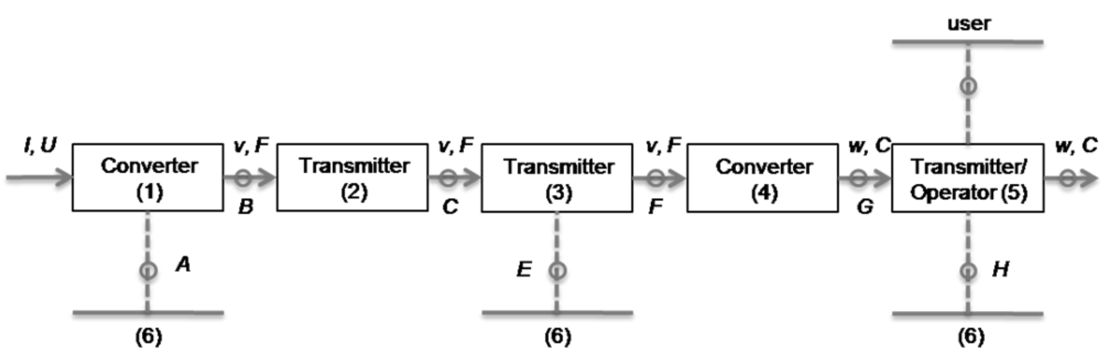


Figure 0.17: The improved energy-based model if fixing the pair D in Figure 0.14

Compared with the other two plans of modification, fixing joint A is easier to be realized in the prototype. Therefore, the push rod is constrained by a metal fixture to the base of the treadmill as seen in Figure 0.18:

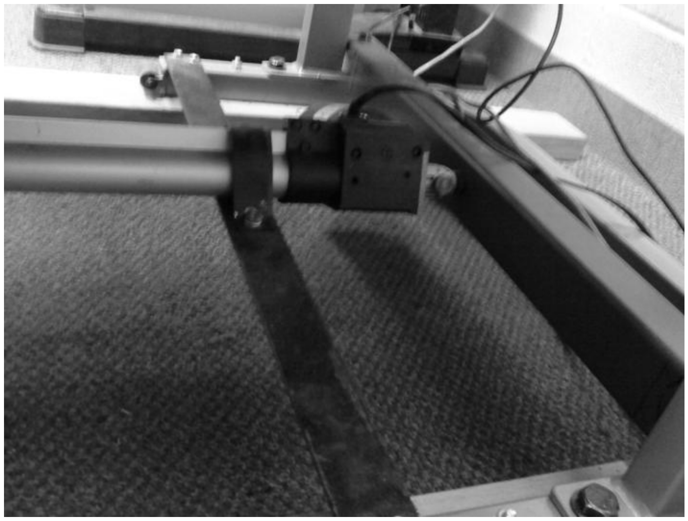


Figure 0.18: The practical modification to fix joint A

After the modification, however, another undesired movement appears in another test. Since the front frame of the treadmill is always straight and steady to the ground before the elevating mechanism is installed beneath the platform, the stability is assumed in the designer's mind and so the front frame is viewed as the fixed reference in the previous rounds of kinematic analyses. However, when the push rod is fixed to the base of the front straight frame as shown in Figure 0.18 and turned on to push the elevating mechanism, the front straight frame suddenly tilts. The undesired tilting indicates that the front frame is actually not a fixed reference but a moving link. Therefore, the kinematic diagram of the mechanism is shown in Figure 0.19:

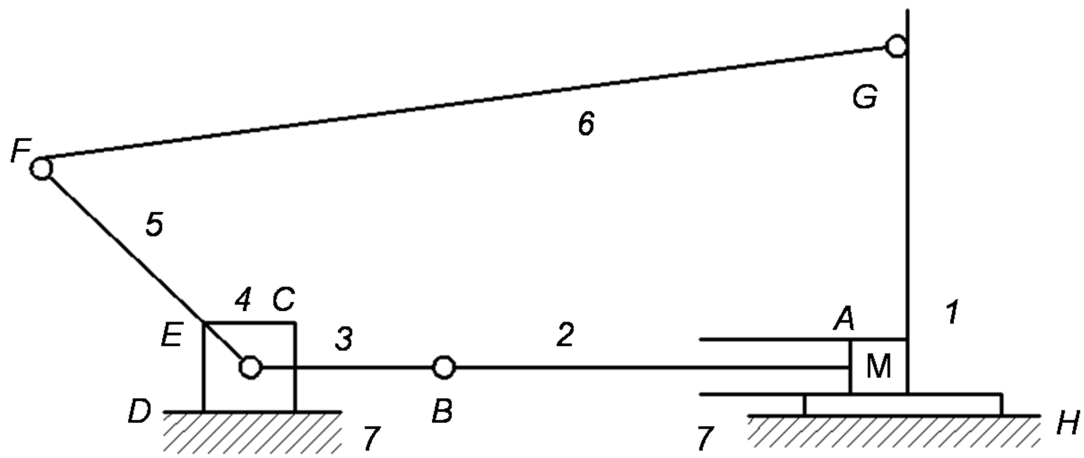


Figure 0.19: The kinematic diagram of the mechanism with the front frame

In this mechanism, there are seven joints of class 5 ($C_5 = 7$), one joint of class 4 (C4 = 1), and six moving links:

- At A there is one translational joint between link 1 and link 2;
- At B there is one rotational joint between link 2 and link 3;
- At C there is one rotational joint between link 3 and link 4;
- At D there is one translational joint between link 4 and link 7;
- At E there is one rotational joint between link 4 and link 5;
- At F there is one rotational joint between link 5 and link 6;
- At G there is one rotational joint between link 6 and link 1;
- At H there is one rotational and translational joint between link 1 and link 7;

Therefore, the number of DOF for this mechanism is given by:

$$M = 3n - 2C_5 - C_4 = 18 - 14 - 1 = 3 \quad (8)$$

Again, the only one driver link cannot control the movements of all the links. The expected energy-based function structure is shown in Figure 0.20:

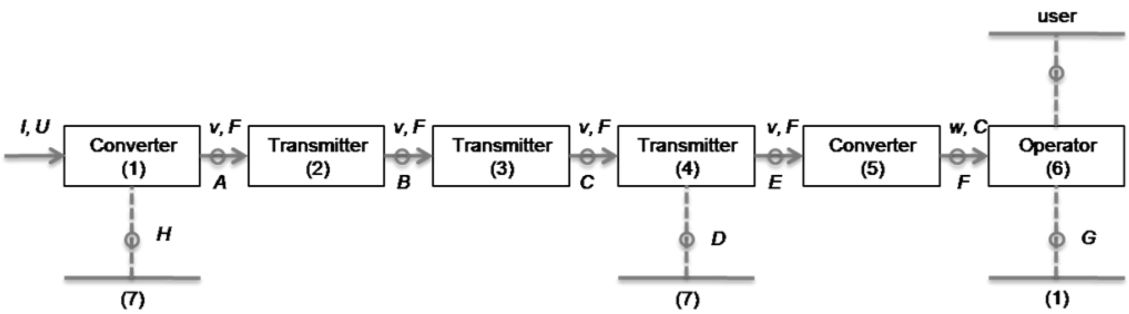


Figure 0.20: The expected energy-based function structure of the mechanism in Figure 0.19

The analysis of hAAAs is shown in Table 0.7:

Table 0.7: The analysis of hAAAs of the mechanism in Figure 0.19

<table>
<tr><th>Moving links</th><th colspan="2">Combining the links</th><th>hAAAs</th></tr>
<tr><td>1 = (A, H): (t, r t)</td><td rowspan="2">1, 2 = (H, B): (r t, r)</td><td rowspan="3">1, 2, 3 =(r t, r) + (r, r)</td><td rowspan="3">1, 2, 3: RMA;
1, 2: TMA</td></tr>
<tr><td>2 = (A, B): (t, r)</td></tr>
<tr><td>3 = (B, C): (r, r)</td><td></td></tr>
<tr><td>4 = (C, D): (r, t)
= (D, E): (t, r)</td><td></td><td></td><td>4: TMA</td></tr>
<tr><td>5 = (E, F): (r, r)</td><td rowspan="2">5, 6 = (r, r) + (r, r)</td><td></td><td>5: RMA</td></tr>
<tr><td>6 = (F, G): (r, r)</td><td rowspan="2">6, 1 = (r, r) + (r, r t)</td><td rowspan="2">6: RMA</td></tr>
<tr><td>1 = (G, H): (r, r t)</td><td></td></tr>
</table>

Table 0.7 shows that link 1 affords both the RMA and TMA; however, it is expected to be a reference. Therefore, link 1 needs to be modified. The energy-based function structure with the undesired energy flows is shown in Figure 0.21:

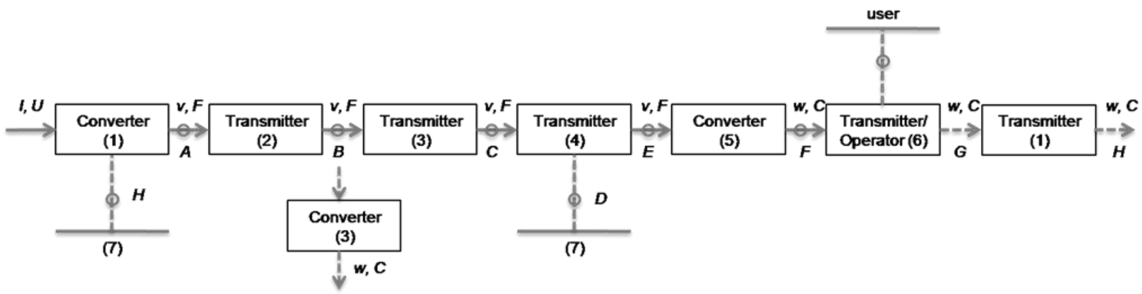


Figure 0.21: The energy-based function structure of the mechanism with the undesired energy flows caused by link 1's hAAAs

To solve this problem, since the hAAAs of link 1 can result in the undesired movements with either link 2 and 3 or link 6, one possible solution is to fix joint H, the common joint in both of the undesired movements. However, in practice the VR treadmill is required to afford place/store-ability; fixing it onto the ground is therefore not applicable. The way adopted in this research is to modify link 1 to be a real reference by adding two wood piers longer than the farthest point that the block can reach under the base of the treadmill. The result of the improvement is shown in Figure 0.22:

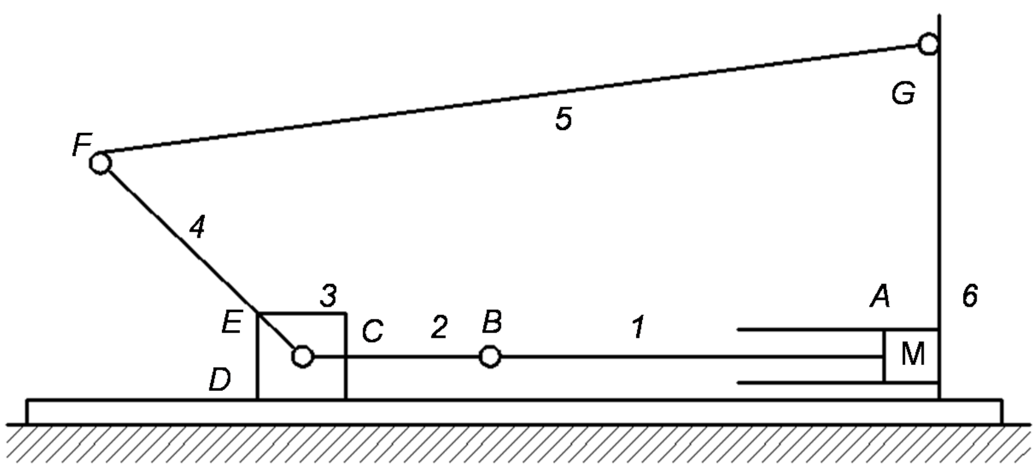


Figure 0.22: The modified mechanism after adding two wood piers under the base

Then $n = 5$, $C_5 = 7$, $C_4 = 0$, and M = 1. In addition, the new energy-based model is as seen in Figure 0.23:

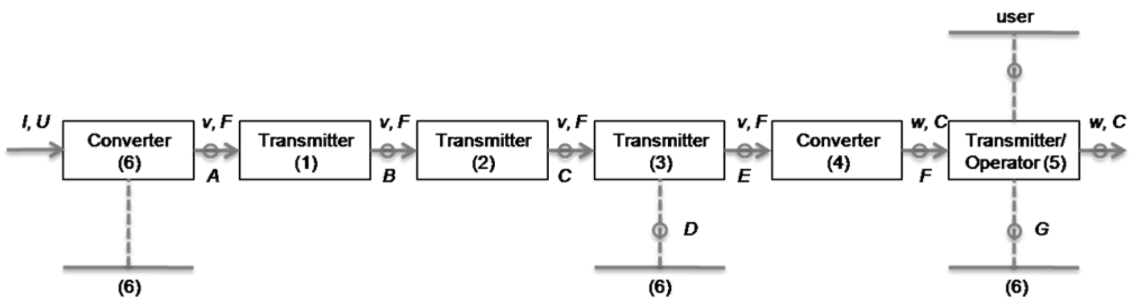


Figure 0.23: The energy-based model after adding two wood piers under the base

Therefore, the undesired movements of the elevating mechanism are prevented based on the proposed affordance-based method. The next section discusses the role of the last category AEA in the improvement of the design.

D.2.4 AEA-based improvement

Since this VR treadmill is just an experimental prototype, currently the environment interacting with it is only the laboratory. Compare to the initial treadmill, the VR treadmill is not significantly enlarged in the size since the outfitted elevating mechanism is installed in the space beneath the platform. Therefore, the VR treadmill affords placing and storing in the laboratory and on this aspect it does not need to be improved. In addition, although the AEA emit-noise-ability is inevitable, the entire design process obeys the OSHA standards of controlling noise level.

So far, the mechanical subsystem has been designed and improved successfully and the next step is to connect it with the control subsystem. Before that step, the work on VR subsystem by the other research group is briefly introduced in the following section.

D.3 The VR subsystem

While the mechanical subsystem was developed, the work on the VR subsystem also proceeded. The VR subsystem created provides an interface between the HMD (with a build-in tracker), the treadmill motion sensor, and the Google Maps API. The interface affords users navigating in a first person perspective in the virtual reality, feeling more like they were really in the street captured in the panorama by looking around naturally via the HMD, rather than dragging the panorama with a mouse.

To simulate the natural navigation, it is not sufficient for this VR subsystem to provide the user only the view-ability in the virtual reality via the HMD; furthermore, when the user walks to a road intersection, the system needs to afford the path-select-ability for the user. To achieve this path-select-ability, this VR subsystem is programmed to deduct the user's selection in the way shown in Figure 0.24:

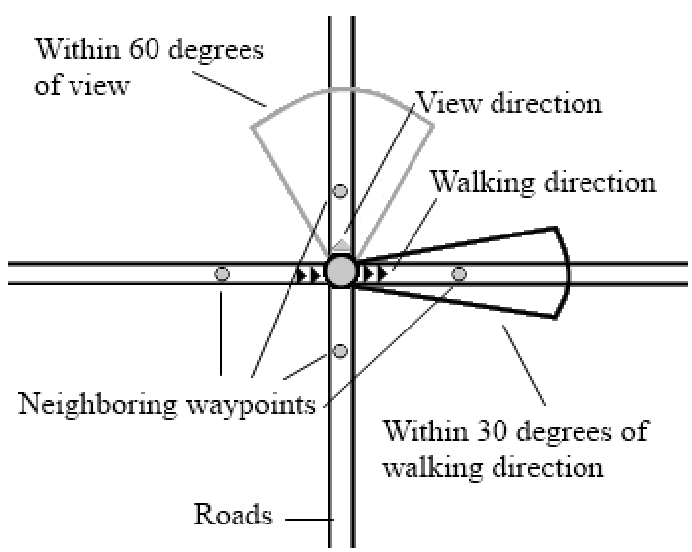


Figure 0.24: This diagram illustrates how the system determines potential paths for moving forward from the middle of an intersection

In Figure 0.24, the dots represent waypoints linked to the current panorama. The light gray wedge represents 60 ° about the user's current view direction, while the black wedge represents 30 ° about the user's walking direction. The user can move to a new panoramic environment if the system first determines that there is a waypoint within 60 ° of their current view direction, or, alternatively, if there is a waypoint within 30° of the user's walking direction.

Finally, the last but vital step is to translate the requirements and desired affordances to an integrated computer program. Therefore, the high-level system architecture is built as shown in Figure 0.25:

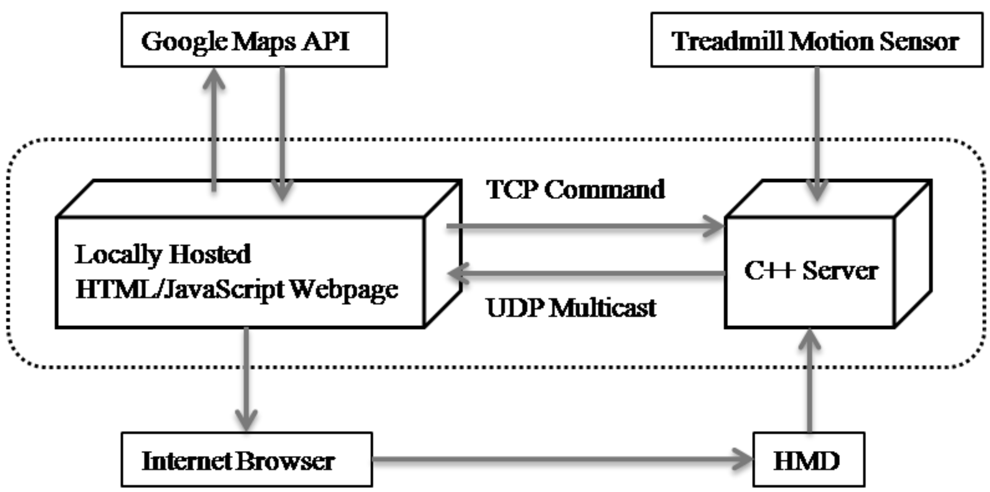


Figure 0.25: High-level system architecture of the VR subsystem

In Figure 0.25, the C++ Server manages input devices, communicates with the Webpage through the JNEXT TCP/UDP browser plug-in, and the Webpage communicates with Google Maps API to provide the user with VR images displayed simultaneously in the Internet browser and the HMD.

So far both the mechanical and VR subsystems have been built, the next step is to develop the control subsystem and integrate the three together.

D.4 The control subsystem

The control subsystem consists of a magnet sensor, a digital counter, and a motor controller. The magnetic sensor is installed on the frame of the treadmill platform, pointing from a certain distance at a flywheel concentric with the front axle of the carpet. On the side of the flywheel facing the sensor, a small iron patch is fixed that can pass through the detectable zone of the sensor once per rotation. Hence when a user walks on the treadmill, the carpet drives the rotating axles, and consequently the patch triggers the sensor to generate a high-level voltage signal once per rotation. The digital counter connected to the sensor can receive the signal and display the total number of signals in decimal format on its screen. Meanwhile, the signal is transferred to a C++ server in the computer through an RS232 COM connection. The number of signals and the perimeter of the patch orbit can be calculated together, with the result indicating the moving distance of the user on the treadmill in a certain time, i.e. the average moving speed in this distance. Then these data can be uploaded from the C++ server to the Google Street View server to download the panoramic photograph and altitude data from Google.

The gradient is calculated by comparing the altitude change from one waypoint to the next with the distance between the two neighboring waypoints. Next, the gradient is translated to the motor-control command. In this research, the DC motor is controlled through pulse-width-modulation (PWM) commands. To be specific, the relationships of the control parameters can be derived by a hypothesis:

Suppose two neighboring waypoints P_1 and P_2 in Google Street View have corresponding altitudes A_1 and A_2. The distance between the two waypoints is S. If simulating a user moving from P_1 to P_2, the gradient can be obtained as

$$\gamma = \arctan \frac{A_1 - A_2}{S} \tag{9}$$

The exact function between the control command PWM values and the motor's rotating speed R cannot be derived, so we use a general form to represent the function as:

$$R = f(PWM) \tag{10}$$

Similarly, the unknown function between the R and the elevating angular velocity of the mechanism can be expressed as:

$$W = g(R) \tag{11}$$

Thus,

$$W = p(PWM) \tag{12}$$

Hence, the motor needs to run for t seconds to reach the new altitude,

$$t = \frac{\arctan \frac{A_1 - A_2}{S}}{p(PWM)} \tag{13}$$

If the user needs to spend t_r seconds walking through the distance S on the treadmill, when $t \leq t_r + 1$, the synchronicity of the simulation is acceptable.

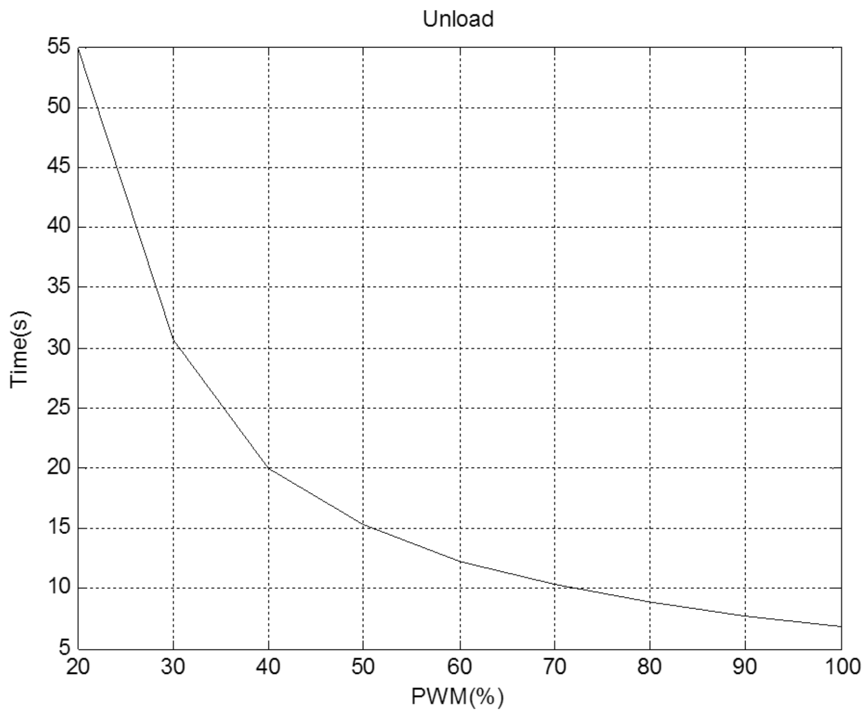
However, the angular velocity W is difficult to measure directly because of its nonlinearity. One way to solve this problem is to measure the linear extending and retreating speeds of the push rod, and then derive the W. Therefore, an experiment was created to test for this.

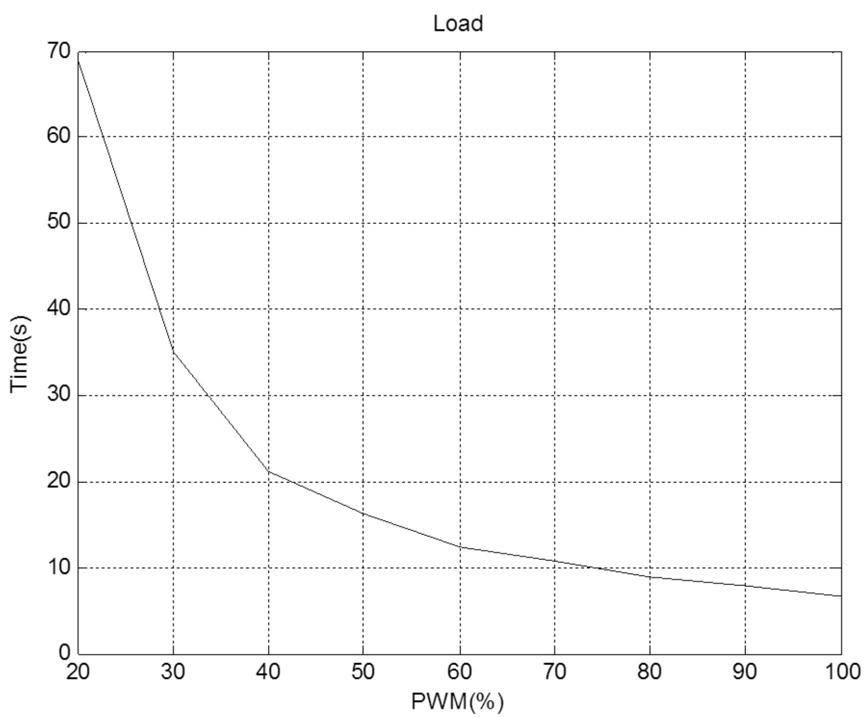
The objective of the experiment is to identify according to different PWM values, how much time the push rod needs in order to extend and pull back 50 mm. The push rod is installed under the treadmill and works under the load of the treadmill and a 200 lbs person walking on it. The results are shown in Table 0.8 and Figure 0.26:

Table 0.8: Experiment to test the relationship between PWM values and the speed of the push rod

PWM (%)		*Counted time*		*Average time*
-100	6.7	6.7	6.8	6.7
-90	7.9	7.8	7.9	7.9
-80	8.8	8.9	8.9	8.9
-70	11.1	10.8	10.4	10.8
-60	12.1	12.4	-	10.3
-50	16.3	16.1	-	16.2
-40	19.7	22.1	21.7	21.2
-30	34.6	35.8	-	35.2
-20	50.8	84.3	71.3	68.8
-15	N/A*	N/A	N/A	N/A
-10	N/A	N/A	N/A	N/A
10	N/A	N/A	N/A	N/A
15	N/A	N/A	N/A	N/A
20	49.3	57.4	57.6	54.8
30	30.4	31.0	-	30.7
40	19.3	20.5	20.1	20.0
50	15.4	15.2	-	15.3
60	12.3	12.3	-	12.3
70	10.4	10.3	10.4	10.4
80	8.8	9.0	8.8	8.9

* N/A means under this PWM the push rod cannot work.


Unload
Time(s)
55
50
45
40
35
30
25
20
15
10
5
20
30
40
50
60
70
80
90
100
PWM(%)


Load
Time(s)
70
60
50
40
30
20
10
0
20
30
40
50
60
70
80
90
100
PWM(%)

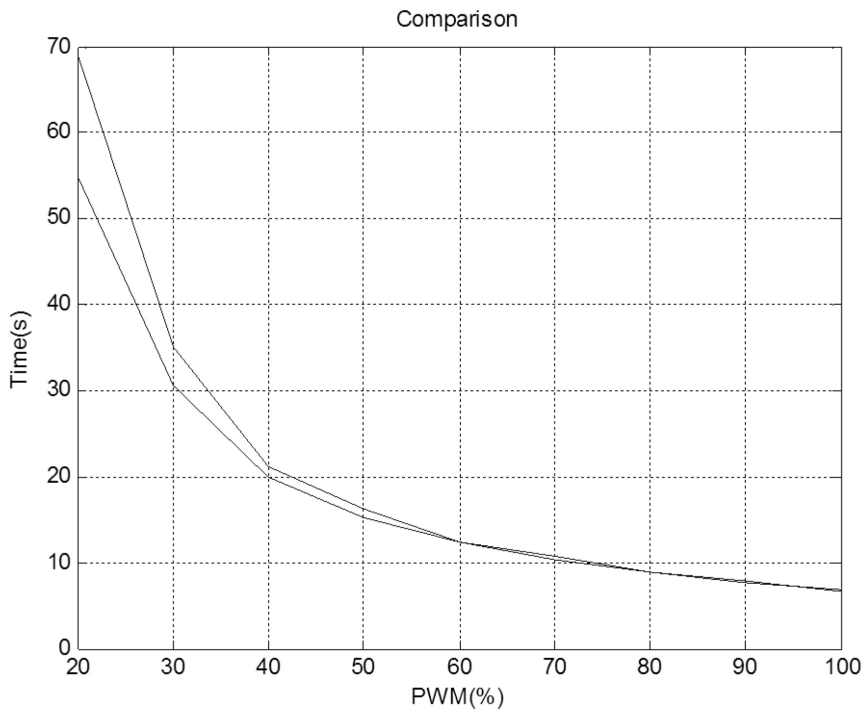


Figure 0.26: The relationships between the working time extending or pulling back 50 mm of the push rod and PWM values

Based on the results of the experiment, it can be concluded that the larger the PWM value is, the longer time the motor can run in full speed and thus the faster the push rod can work through the 50 mm. Furthermore, when the PWM value is under 50%, the performance of the push rod becomes not steady and is easily affected by the load; in contrast, when the PWM value is over 60%, the push rod works steadily and is not easily affected by the load.

After installation, the push rod can elevate the platform of the treadmill from -8 ° to 0 °, then the push rod needs to extend about 66.2 mm, and the corresponding average angular velocity *W* to the different PWM values can be calculated as seen in Table 0.9:

Table 0.9: Calculate the average *W* from -8 ° to 0 °, according to the different PWM values from 60% to 100%

PWM (%)	*60*	*70*	*80*	*90*	*100*
Time t (s)	16.3	14.3	11.8	10.5	8.9
Average (W)	0.5	0.6	0.7	0.8	0.9

In practice, a person walking at a speed of 1 m/s needs 10 s to move through 10 m, the distance between the two neighboring waypoints in Google Street View. According to the synchronicity requirement discussed above, $t \leq t_r + 1 = 11$ s, and thus, the PWM value should be set over 80%.

Finally, the three subsystems are integrated after debugging errors and setting the parameters. The final step is to compare the integrated system with the objective and the requirements list to validate the design and identify its limitations.

D.5 Limitations in the prototype

Based on the validation, the latest prototype satisfies the design objective and all of the demand requirements; therefore, the VR treadmill is built successfully. However, the unsatisfied wish requirements suggest that there are still a few limitations in every subsystem. First of all, in the mechanical subsystem, the non-motorized treadmill can afford the user walking uphill and horizontally but not downhill as seen in Figure 0.27:

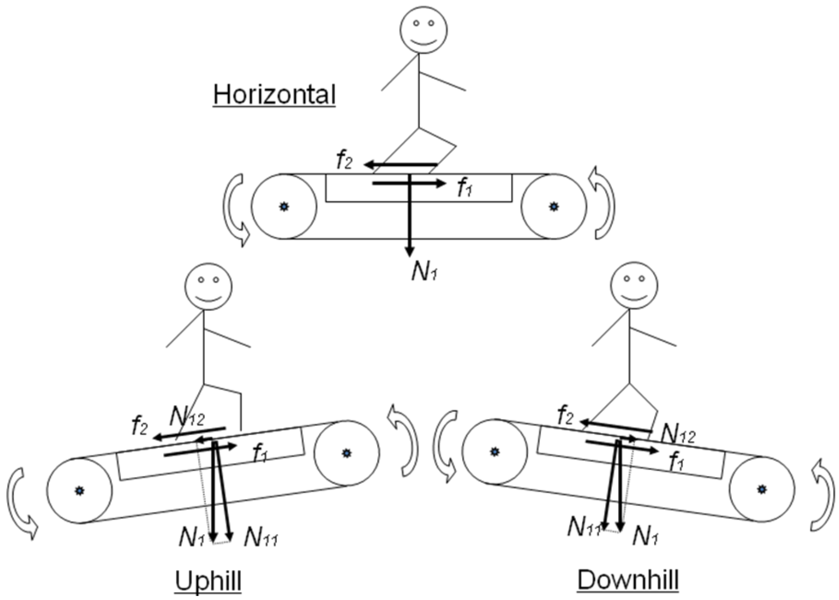


Figure 0.27: The limitation of simulating the real walking feeling

The illustration shows why the user walking downhill cannot be simulated in this prototype, and why walking on a horizontal plane is more difficult than walking uphill. N_1: the pressing force on the platform caused by the user's weight; N_{11} and N_{12}: two component forces of N_1 parallel and perpendicular to the surface of the platform; f_2: the friction force between the user's shoes and the upper surface of the carpet; f_1: the friction force between the lower surface of the carpet and the supporting board. The difference between the reversed friction forces on the two sides of the carpet, i.e. f_2 - f_1, drives the carpet to move backward. Therefore, when simulating going uphill, since a component N_{12} of the force N_1 exerted by gravity on the user is parallel with the carpet motion, that force helps drive the carpet backwards. The user is thus fooled in finding it easier to walk on the carpet going uphill than walking on a horizontal plane. This feeling, however, sharply contradicts with the reality that the user should exert more effort when walking uphill than when walking on horizontal ground. Similarly, going downhill cannot be simulated by this prototype since under this condition the component force N_{12} is in the same direction with f_1 and $N_{12} + f_1$ may exceed f_2. To solve this problem, the next generation of the prototype should be installed with a motor to control the rotation of the axle, however, the cost constraint and the control error caused by the inertia of frequently starting and stopping the motors need to be considered.

In the control subsystem, a normal DC motor is used to drive the push rod, with its rotating velocity and direction controlled by PWM commands. Both the structure of the motor and the PWM method are inaccurate, so the error in the elevation can be as high as 1°. A stepping or servo motor can solve this problem; however, since a user can hardly feel the 1° error, it may not be necessary to update the motor.

As for the VR subsystem, when the user needs to select a path in a road intersection in virtual reality, the panorama can afford the user's vision to turn to a new direction but the treadmill cannot offer the turn-ability to the user's body in the natural world. Such a lack of coordination affects the quality of the simulation. In addition, in this research the user is suggested to turn the head to the desired direction and the tracker in the HMD can guide the person virtually along the chosen path. However, when the separation angle between two neighboring routes is smaller than a certain angle, it is difficult to select the desired path efficiently via the tracker. Therefore, the VR treadmill still has room for improvement.

D.6 Discussion

In this design, the affordance-based approaches are widely implemented in various stages to solve problems in user-artifact, artifact-artifact, and artifact-environment interactions. The final result is satisfactory. Furthermore, during the implementation, the affordances are applied together with other concepts, and meanwhile the underlying comparisons are inevitable. For example, in the early stage of conceptual design, the expected affordances are given based on the designer-expected interaction model. Compared with the requirements listed in the same stage, the affordances are only constrained to discuss the potential interactions between entities, without concerning any specific information like parameters, time, or cost.

In addition, different from using functions to build workflow and derive working principles before prototyping, the affordances are mainly used to improve existing prototypes because they are form-dependent and sensitive to any structure change. Even in the improvement, it often happens that modifying a structure results in various affordances, perceivable or hidden, desired or undesired.

REFERENCES

[1] Albrechtsen, H.; Andersen, H.H.K.; Bdker, S.; Pejtersen, A.M. (2001): Affordances in Activity Theory and Cognitive Systems Engineering. Denmark.

[2] Altshuller, G.S.; Vertkin, I.-M. (1994): How to Become a Genius: the Life Strategy of a Creative Person.

[3] Altshuller, G.S. (1997): 40 Principles: TRIZ Keys to Technical Innovation. Technical Innovation Center, Worcester, MA.

[4] Altshuller, G.S. (2000): The innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity. Technical Innovation Center, Worcester, MA.

[5] Amant, R. (1999): User Interface Affordances in a Planning Representation. Human-Computer Interaction: Volume 14, Issue 3.

[6] Bærentsen, K.B.; Trettvik, J. (2002): An Activity Theory Approach to Affordance. NordiCHI 10/02, Århus, Denmark: pp. 51-60.

[7] Brown, D.C.; Blessing, L. (2005): The Relationship between Function and Affordance. DETC2005-85017, Long Beach, CA.

[8] Cagan, J (2002): Creating Breakthrough Products: Innovation from Product Planning to Program Approval. Prentice Hall.

[9] Caldwell, B.W. (2009): An Evaluation of Function-based Representation and Information Archival in Engineering Design, MS thesis, Clemson University, Clemson, SC.

[10] Cascini, G.; Frate, L.D.; Fantoni, G.; Montagna, F. (2010): Beyond the Design Perspective of Gero's FBS Framework. Design Computing and Cognition DCC'10: pp. 77-96.

[11] Cesari, P. (2005): An Invariant Guiding Stair Descent by Young and Old Adults. Experimental Aging Research: pp. 441-455.

[12] Chemero, A. (2003): An Outline of a Theory of Affordances. Ecological Psychology.

[13] Chen, L.H.; Lee, C.F.; Kiong, S.G. (2009): Affordance Conditions of Product Parts in User-Product Interaction. Universal Access in HCI, Part I, HCII 2009, LNCS 5614: pp. 460-469.

[14] Crilly, N. (2010): The Roles that Artefats Play: Technical, Social, and Aesthetic Functions. Design Studies, Elsevier: Vol. 31, pp. 311-344.

[15] Dorst, K.; Vermaas, P.E. (2005): John Gero's Function-Behavior-Structure Model of Designing: a Critical Analysis. Research in Engineering Design, 16: pp. 17-26. DOI 10.1007/s00163-005-0058-z.

[16] Ehrlenspiel, K.; Kiewert, A.; Lindemann, U. (2007): Cost-Efficient Design. Springer: pp. 31-48.

[17] Ericsson, A.; Erixon, G. (1999): Controlling Design Variants, Modular Product Platforms. SME: pp. 17-55.

[18] Fey, V.; Rivin, E. (2005): Innovation on Demand: New Product Development Using TRIZ.

[19] Frey, D.D.; Dym, C.L. (2006): Validation of Design Methods: Lessons from Medicine. Research in Engineering Design, 17: pp. 45-57. DOI 10.1007/s00163-006-0016-4.

[20] Gaffney, E.S.; Maier, J.R.A.; Fadel, G.M. (2007): Roles of Function and Affordance in the Evolution of Artifacts. ICED'07/592, Paris, France.

[21] Galvao, A. (2007): Design Relationships, Integrating User Information into Product Development. VDM Verlag.

[22] Gaver, W. (1991): Technology Affordances, ACM: pp. 79-84.

[23] Gero, J.; Kannengiesser, U. (2002): The Situated Function-Behavior-Structure Framework. Artificial Intelligence in Design'02, Netherland: pp. 89-104.

[24] Gibson, J.J. (1979): The Theory of Affordances. The Ecological Approach to Visual Perception. Houghton Mifflin, Hopewell: pp. 127-143.

[25] Gibson, E.J. (2000): Where is the Information for Affordances? Ecol Psychol 12(1): pp. 53-56.

[26] Greeno, J.J. (1994): Gibson's Affordances. Psychological Review: Vol. 101, No. 2, pp. 336-342.

[27] Hartson, H. (2003): Cognitive, Physical, Sensory, and Functional Affordances in Interaction Design. Behavior & Information Technology: Vol. 22, NO. 5, pp. 315-338.

[28] Houkes, W.; Vermaas, P. (2010): Technical Functions, on the Use and Design of Artefacts. Springer: pp. 45-100.

[29] Hirtz, J.; Stone, R.B.; McAdams, D.A.; Szykman, S.; Wood, K.L. (2002): A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts. NIST Technical Note 1447.

[30] Kannengiesser, U.; Gero, J. (2010): A Process Framework of Affordances in Design.

[31] Kirschman, C.F.; Fadel, G.M.; Jara-Almonte, C.C. (1996): Classifying Functions for Mechanical Design. 96-DETC/DTM-1504, Irvine, CA.

[32] Konczak, J.; Meeuwsen, H. J.; Cress, M.E. (1992): Changing Affordances in Stair Climbing: The Perception of Maximum Climbability in Young and Older Adults. Journal of Experimental Psychology, Human Perception and Performance: Vol. 18, pp. 691-697.

[33] Larsen, L.B.; Jensen, K.L.; Larsen, S.; Rasmussen, M.H. (2007): Affordance in Mobile Speeach-based User Interaction. Mobil HCI’07, Singapore: pp. 285-288.

[34] Lee, D.G.; Suh, N.P. (2006): Axiomatic Design and Fabrication of Composite Structures: Applications in Robots, Machine Tools, and Automobiles. Oxford University Press.

[35] Leung, P.; Ishii, K.; Benson, J. (2005): Modularization of Work Tasks for Global Engineering. IMECE2005-82137, Orlando, Florida.

[36] Maier, J.R.A.; Fadel, G.M. (2001): Affordance: The Fundamental Concept in Engineering Design. DETC2001/DTM-21700, Pittsburgh, PA.

[37] Maier, J.R.A.; Fadel, G.M. (2009a): Affordance Based Design: a Relational Theory for Design. Res Eng Design, 20: pp. 13-27. DOI 10.1007/s00163-008-0060-3.

[38] Maier, J.R.A.; Fadel, G.M. (2002): Comparing Function and Affordance as Bases for Design. DETC2002/DTM-34029, Montreal, Canada.

[39] Maier, J.R.A.; Sachs, R.; Fadel, G.M. (2009): A Comparative Study of Quantitative Scales to Populate Affordance Structure Matrices. DETC2009-86524, San Diego, CA.

[40] Maier, J.R.A.; Fadel, G.M. (2005): A Case Study Contrasting German Systematic Engineering Design with Affordance Based Design. DETC2005-84954, Long Beach, CA.

[41] Maier, J.R.A.; Sandel, J.; Fadel, G.M. (2009): Experiments Comparing Function Structures to Affordance Structures. ICED’09/321, Stanford, CA.

[42] Maier, J.R.A.; Fadel, G.M. (2009b): An Affordance-based Approach to Architectural Theory, Design, and Practice. Design Studies 30, Elsevier Ltd.: pp. 393-414.

[43] Maier, J.R.A.; Fadel, G.M. (2009c): Affordance-based Design Methods for innovative Design, Redesign and Reverse Engineering.

[44] Maier, J.R.A.; Ezhilan, T.; Fadel, G.M. (2007): The Affordance Structure Matrix – A Concept Exploration and Attention Directing Tool for Affordance-based Design. DETC2007-34526, Las Vegas, NV.

[45] Maier, J.R.A.; Fadel, G.M. (2006): Understanding the Complexity of Design. Complex Engineered Systems, Science Meets Technology, Springer: pp. 122-140.

[46] Maier, J.R.A.; McLellan, J.M.; Mocko, G.; Fadel, G.M. (2009); Brudnak, M.: Lightweight Engineering of Military Vehicles through Requirements Analysis and Function Integration. DETC2009-86562, San Diego, CA.

[47] Mark, L.S. (1987): Eyeheight-Scaled Information about Affordances: A Study of Sitting and Stair Climbing. Journal of Experimental Psychology, Huamn Perception and Performance: Vol. 13, pp. 361-370.

[48] McGrenere, J.; Ho, W. (2000): Affordances: Clarifying and Evolving a Concept. Proceedings of Graphics Interface 2000, Montreal, Canada.

[49] McLellan, J.M.; Maier, J.R.A.; Fadel, G.M.; Mocko, G.M. (2009): A Method for Identifying Requirements Critical to Mass Reduction Using DSMs and DMMs. DSM'09, Greenville, SC: pp. 197-205.

[50] Michaels, C.F. (1988): S-R Compatibility between Response Position and Destination of Apparent Motion: Evidence of the Detection of Affordances. Journal of Experimental Psychology, Human Perception and Performance: Vol. 14, pp. 231-240.

[51] Murakami, T.; Higuchi, M.; Yanagisawa, H. (2009): Trial of Formulating Affordance Features for Product Design. Virtual and Mixed Reality, LNCS 5622, Springer-Verlag Berlin Heidelberg: pp. 586-595.

[52] Norman, D.A. (1999): Affordance, Conventions, and Design. Interactions: pp. 38-42.

[53] Norman, D.A. (2003): Emotional Design: Why We Love (or Hate) Everyday Things: pp. 47-65.

[54] Norman, D.A. (1990): The Design of Everyday Things. Doubleday.

[55] Oshlyansky, L.; Thimbleby, H.; Cairns, P. (2004): Breaking Affordance: Culture as Context. NordiCHI'04, Tampere, Finland.

[56] Oudejans, R.R.D.; Michaels, C.F.; Bakker, F.C.; Dolné, M.A. (1996): The Relevance of Action in Perceiving Affordances: Perception of Catchableness of Fly Balls. Journal of Experimental Psychology, Human Perception and Performance: Vol. 22, pp. 879-891.

[57] O'Sullivan, B. (2002): Constraint-Aided Conceptual Design. Professional Engineering Publishing Ltd., London and Bury St Edmunds, UK: pp. 7-56.

[58] Orloff, M.A. (2006): Inventive Thinking through TRIZ: A Practical Guide. Springer, Berlin, Germany.

[59] Paul, G.; Beitz, W.; Feldhusen, J.; Grote, K.H. (2007): Engineering Design, a Systematic Approach. Springer.

[60] Pailhès, J.; Sallaou, M.; Nadeau, J.P.; Fadel, G.M. (2011): Energy Based Functional Decomposition in Preliminary Design. Journal of Mechanical Design: Vol. 133/DOI: 10.1115/1.4004193.

[61] Raubal, M.; Moratz, R. (2006): A Functional Model for Affordance-based agents. Proceeding of the 2006 international conference on towards affordance-based robot control.

[62] Salamatov, Y.P. (1990): How to Become an Inventor: 50 Hours of Creativity.

[63] Scarantino, A. (2002): Affordances Explained. Philosophy of Science, 70: pp. 949-961.

[64] Schwer, L.E. (2007): Guide for Verification and Validation in Computational Solid Mechanics. ASME.

[65] Shepherd, A. (2000): HTA as a Framework for Task Analysis. Task Analysis, Tayler-Francis: pp. 9-24.

[66] Stoffregen, T. (2000): Affordances and Events. Ecological Psychology, 12(1): pp. 1-28.

[67] Suh, N.P. (2001): Axiomatic Design: Advances and Applications. Oxford.

[68] Torenvilet, G. (2003): We Can't Afford It. Interactions: pp. 12-17.

[69] Turner, P. (2005): Affordance as Context. Interacting with Computers 17: pp. 787-800. DOI: 10.1016/j.incom.2005.04.003.

[70] Turvey, M.T. (1992): Affordances and Prospective Control: An Outline of the Ontology. Ecological Psychology, 4(3): pp. 173-187.

[71] Ugur, E.; Sahin, E.; Oztop, E. (2009): Predicting Future Object States Using Learned Affordance. ISCIS: pp. 415-419

[72] Vermaas, P.E. (2011): Accepting Ambiguity of Engineering Functional Descriptions. ICED11, København, Demark.

[73] Warren, W.H. Jr. (1985): Constructing an Econiche. ICEPA, Uppsala, Sweden: pp. 211-233.

[74] Warren, W.H. Jr. (1984): Perceiving Affordances: Visual Guidance of Stair Climbing. Journal of Experimental Psychology: Human Perception and Performance: Vol. 10, No. 5, pp. 683-703.

[75] van Leeuwen, L.; Smitsman, A.; van Leeuwen, C. (1994): Affordances, Perceptual Complexity, and the Development of Tool Use. Journal of Experimental Psychology, Human Perception and Performance: Vol. 20, pp. 174-191.

[76] Wells, A.J. (2002): Gibson's Affordances and Turing's Theory of Computation. Ecological Psychology, 14(3): pp. 140-180. DOI: 10.1207/S15326969ECO1403_3.

[77] Yang, K.; EI-Haik, B. (2003): Design for Six Sigma: A Roadmap for Product Development. McGraw-Hill.

[78] Yang, Q. (2006): How Inventions Are Born: an Introduction to TRIZ. Mechanical industry press, Beijing, China.

[79] You, H.; Chen, K. (2006): Applications of Affordance and Semantics in Product Design. Design Studies, Elsevier: Vol. 28, pp. 23-38.

[80] Montesano, L.; Lopes, M.; Bernardino, A.; Victor, J.S. (2007a): Affordances, Development and Imitation: International Conference on Development and Learning, London, UK.

[81] Sweeney, J.D.; Grupen, R. (2005): A Model of Shared Grasp Affordances from Demonstration.

[82] Montesano, L.; Lopes, M.; Bernardino, A.; Victor, J.S. (2007b): Modeling Affordances using Bayesian Networks, International Conference on Intelligent Robots and Systems, San Diego, USA.

[83] Uyanik, K.F.: Learning Object Affordances based on Structural Object Representation.

[84] Castellini, C.; Tommasi, T.; Noceti, N.; Odone, F.; Caputo, B. (2011): Using Object Affordances to Improve Object Recognition, IEEE Transaction on Autonomous Mental Development.

[85] Pols, A.J.K. (2011): Characterising Affordances: The Descriptions-of-affordances-model, Design Studies, doi: 10.1016/j.destud.2011.07.007.

[86] Maier, J.R.A.; Fadel, G.M. (2003): Affordance-based Methods for Design, DETC 2003, Chicago, USA.

[87] Marghitu, D.B. (2005): Kinematic Chains and Machine Components Design, Elsevier: pp. 51- 140.

[88] McAdams, D.A.; Wood, K.L. (2002): A Quantitative Similarity Metric for Design-by-Analogy. Journal of Mechanical Design, ASME: Vol. 124, pp. 173 – 182.

[89] Ostergaard, K.J.; Summers, J.D. (2009): Development of a Systematic Classification and Taxonomy of Collaborative Design Activities, Journal of Engineering Design: Vol. 20, No. 1, pp. 57- 81.