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ABSTRACT

The rapid development of information and communication technologies (ICTs) and cyber–physical systems (CPSs) has paved the way for the increasing popularity of smart products. Context-awareness is an important facet of product smartness. Unlike artifacts, various bio-systems are naturally characterized by their extraordinary context-awareness. Biologically inspired design (BID) is one of the most commonly employed design strategies. However, few studies have examined the BID of context-aware smart products to date. This paper presents a structured design framework to support the BID of context-aware smart products. The meaning of context-awareness is defined from the perspective of product design. The framework is developed based on the theoretical foundations of the situated function–behavior–structure ontology. A structured design process is prescribed to leverage various biological inspirations in order to support different conceptual design activities, such as problem formulation, structure reformulation, behavior reformulation, and function reformulation. Some existing design methods and emerging design tools are incorporated into the framework. A case study is presented to showcase how this framework can be followed to redesign a robot vacuum cleaner and make it more context-aware.

1. Introduction

The rapid advancement of information and communication technologies (ICTs) and cyber–physical systems (CPSs) has paved the way for the increasing popularity of various smart products [1]. Product smartness is a multifaceted notion in which context-awareness is a critical facet. *Context-awareness* refers to a product's ability to accurately interpret a unique setting in which it is situated, in order to purposefully perform appropriate actions. Many context-aware information systems (e.g., recommender systems and mobile applications) have already been developed [2]. It has been shown that extra consideration of context significantly enhances the effectiveness of these information systems [2]. To date, however, relatively few efforts have been devoted to developing context-aware products and manufacturing systems, apart from some notable exceptions [3]. No design framework is available to guide the conceptual design of context-aware products.

Unlike artifacts, bio-systems are naturally characterized by their extraordinary context-awareness. For example, bees can sense a foreign environment via polarized light, locate flower pollen and detect thunderstorms via electroreception, and communicate contextual information with their peers via waggle dancing. As a design approach, biologically inspired design (BID) is not unfamiliar to the design community. On the one hand, BID has been proven to be useful for enhancing design creativity, increasing ideation diversity, and sparking design innovations [4]. On the other hand, BID is associated with inherent difficulties such as communication barriers between biologists and engineers, difficulty establishing an initial analogy, and design fixation [5]. Although BID has been employed to design countless artifacts (including many manufacturing systems [5]) in the past, there has been little research on the BID of smart products. Therefore, this paper proposes a new framework for the biologically inspired design of smart products

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(BID-SP). The framework is referred to as the "BID-SP framework."

2. Research background and motivation

The notion of "context" has been extensively studied from different disciplinary perspectives such as cognition and computer science [2]. There are two typical views about context [6]: The representational view regards context as a form of information that can be described by a set of observable and appropriate attributes [6]. In contrast, the interactional view regards a context and action(s) occurring within the context as an undivided whole (i.e., an action is triggered by a context, and the context is subsequently changed by the action). The representational view is adopted in this study. To be specific, context is defined as a set of information that will collectively characterize a certain situation, within which a product is desired to behave in appropriate ways to satisfy user needs. Accordingly, context-awareness involves a product's ability to perceive, interpret, learn, and integrate contextual information in order to guide decision-making, adjust behaviors, and adapt structure. Contextual information can be acquired in different ways such as through explicit means (e.g., direct communication among the product, user, and environment), implicit means (e.g., user surveys, product reviews, and usage reports), and statistical means (e.g., data analytics to discover meaningful patterns shared by many products). Contextual information acquired at different time points can be combined to build a holistic context-awareness. Historical data is useful for context modeling and mining, and real-time data is useful for context matching and learning. Ubiquitous computing data is useful for context prediction and adaptation [2].

Seeking inspiration from bio-systems is a promising direction to develop more context-aware products. First, various bio-systems can achieve the same context-awareness via different biological mechanisms. For example, the hermit crab, snake, and elephant can communicate with their peers via sound, taste, and vibration, respectively. Second, the same biological mechanism can enable different kinds of context-awareness. For example, the octopus relies on polarized light to navigate direction, detect danger, and track prey. Third, many bio-systems are equipped with a comprehensive awareness of multiple contexts. For example, the worm depends on magnetoreception, chemical receptors, and sensitive skin to navigate direction, locate food, and avoid predators, respectively. Furthermore, certain bio-systems can integrate a variety of contextual information to serve the same purpose. For example, a platypus can detect prey through holistic consideration of electroreception, smell, and touch. Finally, due to natural selection, the members of most bio-systems manage to achieve context-awareness in highly cost-effective and energy-efficient ways, against extreme constraints.

3. Context-aware product design framework

3.1. Theoretical foundations

The BID-SP framework has been developed based on the function–behavior–structure (FBS) ontology [7], where "function," "behavior," and "structure" describe "what an object is for," "what the object does," and "what the object is," respectively. The design entities, relationships, and operations of FBS are all defined in a solution-neutral manner, which make them applicable for both bio-systems and artifacts (i.e., especially for smart products, which are distinguished by their seamless integration of hardware, software, and service). FBS relies on the notion of behavior to form a bridge between function and structure. Since behaviors are defined as "attributes derived from an object's structure" to describe "what the object does" [7], it is possible to derive the same set of behaviors from both bio-systems and artifacts; such shared behaviors are the key enablers of the BID-SP framework. To our best knowledge, no previous efforts have been devoted to supporting BID based on the FBS ontology.

From the situated cognition perspective [7], the BID-SP framework guides designers to travel back and forth through three interrelated "worlds": that is, the expected, interpreted, and external worlds. First, the *expected world* is made of the designer's wishlist for how and in what ways a product should function, behave, and be structured in order to satisfy customer requirements. Second, the *interpreted world* is made of the designer's interpretations of how bio-systems function, behave, and are structured in order to survive natural selection, and of how artifacts function, behave, and are structured in order to win market competition. Finally, the *external world* means the real world in which bio-systems and artifacts live. Many smart products now exist in two external worlds—the physical world and the digital world. Fig. 1(a) illustrates three kinds of typical biological inspirations for product design:

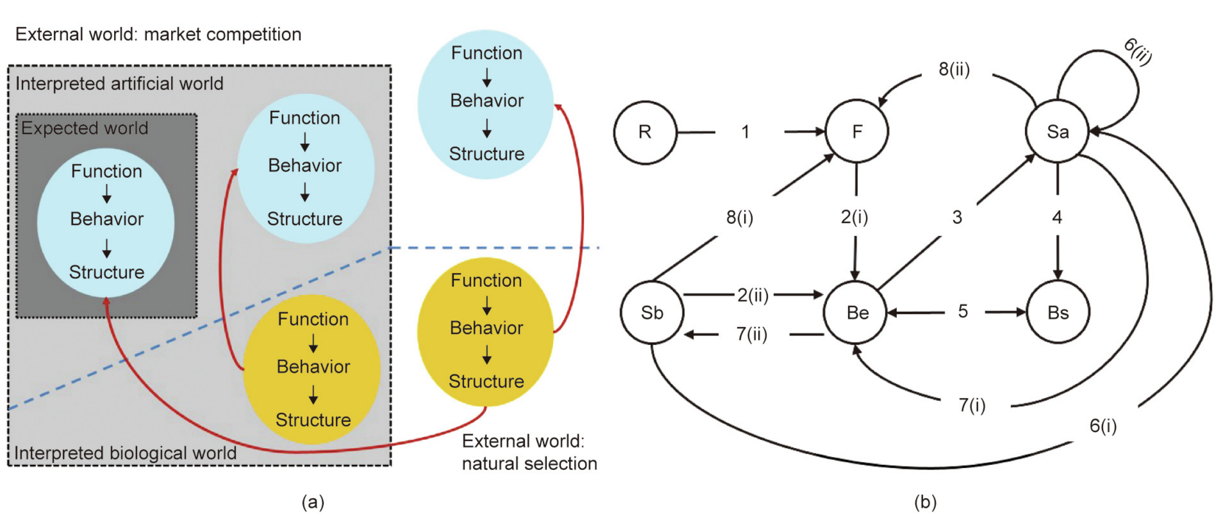

Fig. 1. Biologically inspired design in the situated FBS framework. (a) Three kinds of typical biological inspirations for product design; (b) biologically inspired smart product design process. R: requirement; F: function; Be: expected behaviors; Bs: actual behaviors; Sb: biological structure; Sa: artificial structure.

Type I: Interpretations of bio-systems inspire designers to adjust their expectations of what, how, in what ways, and to what extent an artifact can or cannot possibly do something. For example, the observation of how bees coordinate their actions caused designers to wonder to what extent drones can synchronize actions in a similar way [8]. This type of biological inspiration mainly occurs in the task clarification phase of a systematic design process [9].

Type II: In the interpreted world, understandings of bio-systems affect the understandings of artifacts. This kind of biological inspiration has been the emphasis of many previous design studies. In essence, it involves establishing an analogy between a bio-system and an artifact by formulating a set of solution-neutral functions, generalizing the working principles of the bio-system, and applying these working principles to the artifact. This type of biological inspiration mostly occurs in the conceptual design phase of a systematic design process [9].

Type III: In the external world, design inspirations can be triggered by directly observing, analyzing, and measuring the physical structure and mechanism of a bio-system. Although this type of biological inspiration is the most straightforward, it rarely leads to breakthrough innovations, because its emphasis heavily lies in the embodiment design. Also, back-and-forth interactions exist between bio-systems and artifacts in the external world, where artificial behaviors keep imposing intentional/unintentional influences on the evolvement of bio-systems.

3.2. Step-by-step design process

As illustrated in Fig. 1(b), a biologically inspired smart product design process consists of eight steps. This process covers the key activities of conceptual design, including problem formulation (Steps 1 and 2), concept generation (Step 3), concept evaluation (Steps 4 and 5), and concept improvement (Steps 6, 7, and 8). The proposed framework is used to equip an existing artifact with new, higher, and more holistic context-awareness, which is essentially a redesigning process.

3.2.1. Step 1: Formulate a context-awareness-related design problem

The first step is to translate customer requirements into product functions. In practice, design methods can be employed to solicit, understand, and organize customer requirements, such as the Kano model [10] and contextual design [11]. Inspired by the functional basis [12], a selection of basic function entities and flow entities are prescribed to compose the context-awareness-related functions, as listed in Table 1. Functions are represented in the format of <verb + object>. Designers can freely combine the basic functions (verbs) and flows (objects) to formulate context-awareness-related functions. This modified functional basis is developed in a solution-neutral manner, so that the composed functions are equally applicable to both bio-systems and artifacts.

The four basic function classes are "perceive context," "process context," "learn context," and "respond context," which are further decomposed into more specific entities. Contexts for product design are categorized into four classes: physical context (i.e., information about the surrounding environment), social context (i.e., information about nearby products and services), user context (i.e., information about the user and user–product interaction), and operation context (i.e., information about a product's operational state). For example, a user-context-aware coffee machine should alter the coffee taste to cater to user demographics, preference, and health. A social-context-aware coffee machine should recognize nearby peer products (e.g., coffee grinder and milk frother) and available resources (e.g., coffee pods and milk in the refrigerator).

Table 1
Context-awareness-related functional basis.

Basic function		Flow	
Function entity	Basic "verbs"	Flow entity	Basic "objects"
Perceive context	Detect	Physical context	Time
	Confirm		Location/territory
	Display		Weather
	Monitor		Temperature
	Navigate		Humidity
	Search		Direction
	Request		Air/water quality
	Recognize	Social context	Peer products
	Import/export		Hostility/danger
Process context	Translate		Hospitality
	Compare		Complementary service
	Clean/filter		Resource supply
	Integrate/fuse	User context	User demographics
	Uncouple		User habit
Learn context	Communicate		User preference
	Validate		User knowledge
	Memorize		User mood/health
	Track	Operation context	Power/energy
	Analyze		Degree of wear
	Diagnose		Computing power
Respond context	Change		Intelligence
	Actuate		Maintenance record
	Escape		Software update

The hierarchical structure is used both by information systems to organize contextual information and by designers to organize functions. Hence, the context-awareness-related functions can be organized into a hierarchy according to their abstraction levels and dependency relationships. For example, the general function <sense physical context> can be decomposed into the more specific sub-functions <sense temperature>, <sense humidity>, and <sense location>. The hierarchical structure is especially useful when multiple contexts (e.g., physical context + user context) must be considered at the same time.

3.2.2. Step 2: Identify relevant bio-systems and formulate expected behaviors

Next, the above-formulated functions are transformed into expected behaviors. Unlike the FBS framework, where the expected behaviors are formulated purely based on functions, in the proposed framework, the expected behaviors are directly derived from bio-systems. It is arguably more straightforward to derive behaviors from tangible bio-systems than from intangible functions. In other words, the "expectations" are set by biological inspirations of how, in what ways, and to what extent bio-systems demonstrate context-awareness. This corresponds to Type I of biological inspiration.

The biological world is made up of over 8 million species. This study analyzed a total of 74 bio-systems that are known for their strong context-awareness, as summarized in Table 2. These bio-systems were identified, compared, and selected by following Shu's method [13], based on a search engine and the BID database [14]. Analogous bio-systems can be retrieved based on the function–behavior pairings. The specific part/mechanism/principle of the analogous bio-systems will then supply design inspirations for the later steps (i.e., the reformulation of function, behavior, and structure). A semi-structured function–behavior matrix (the function–behavior matrix) is prescribed to facilitate the retrieval of analogous bio-systems, as shown in Table 3. The first column of the matrix is filled with nine common functions, whereas the second row is filled with ten key behaviors extracted from the selection of bio-systems. Within each cell of the matrix, the numbers correspond to the bio-systems in Table 2. In other words, once a

Table 2
A selection of context-aware bio-systems.

No.	Bio-system	No.	Bio-system	No.	Bio-system
1	Snake	26	Moth	51	Cuttlefish
2	Armadillo	27	Cricket	52	Cod fish
3	Crocodile	28	Firefly	53	Goby fish
4	Chameleon	29	Wolf	54	Remora
5	Sandfish lizard	30	Mite	55	Pigeon
6	Gecko	31	Caterpillar	56	Polar bear
7	Green frog	32	Octopus	57	Peacock
8	Fruit fly	33	Giant squid	58	Raven
9	Honey bee	34	Jaguar	59	Ostrich
10	Black garden ant	35	Ghost crab	60	Reindeer
11	Gravel ant	36	Spiny lobster	61	Aardvark
12	Badger	37	Sea turtle	62	African elephant
13	Dung beetle	38	Flashlight fish	63	Bat
14	Jewel beetle	39	Mantis shrimp	64	Whale
15	Carrion beetle	40	Snails	65	Manatee
16	Woodworm	41	Rhinoceros	66	Bloodhound
17	Earthworm	42	Plankton	67	Platypus
18	Glowworm	43	Catfish	68	Rat
19	Echidnas	44	Salmon	69	Seal
20	Spider	45	Shark	70	Star-nosed mole
21	Butterfly	46	Piranha	71	Rabbit
22	Monarch butterfly	47	Damselfish	72	Pig
23	Mosquito	48	Electric ray	73	Monkey
24	Cockroach	49	Elephantnose fish	74	Zebra
25	Stick insect	50	Anglerfish		

function–behavior pairing is established, the matrix serves to navigate designers to locate a set of analogous bio-systems.

Different function–behavior pairings will lead to different bio-systems; even the same function–behavior pairing may result in multiple candidate bio-systems. Therefore, when multiple function–behavior pairings are considered, the same bio-system may emerge more than once in different cells. In that case, the emergence frequency of a bio-system is an indicator of its degree of analogy to the target product. Note that the function–behavior matrix covers ten functions that are generally applicable to most smart products, while other functions can be formulated in practice.

3.2.3. Step 3: Synthesize an artificial structure based on the expected behaviors

Next, an artificial structure is synthesized to manifest the above-formulated expected behaviors by artificial means. The notion of an "artificial structure" is used to differentiate this structure from the structure of bio-systems. Since an artificial structure is composed of multiple components (design parameters), and many alternatives exist for the same component, the morphological chart can be employed to synthesize different structures. The solution synthesis is limited by the design constraints (DCs). Inspiration can be gained from bio-systems in terms of how they maintain context-awareness under harsh conditions. For example, Sahara Desert ants can track travel distance via an internal pedometer and calculate the best route via the sun's angle, since they cannot remain in extreme heat conditions (up to 70 °C) for long.

3.2.4. Step 4: Analyze the artificial structure to derive actual behaviors

Next, actual behaviors are derived from the above-synthesized artificial structure. The derivation of actual behaviors involves initially building an interpreted structure, and then deriving interpreted behaviors [7]. The interpreted structure can be built either in physical space using rapid prototyping methods [15] or in virtual space using simulation-based and virtual reality (VR)-based design tools [16]. Since an artificial structure is composed of multiple components (design parameters), it can be analyzed through the design structure matrix [17] in terms of the dependency relationships among different components.

3.2.5. Step 5: Compare actual behaviors with expected behaviors

The actual behaviors derived from the artificial structure are compared with the expected behaviors derived from the biological structure. The comparison will trigger three subsequent reformulation steps (i.e., Steps 6, 7, and 8). If the actual behaviors are significantly lower than the expected behaviors, designers should reformulate the artificial structure, expected behavior, or function accordingly. In practice, the expected behaviors–actual behaviors comparison can be enhanced by emerging technologies such as a digital twin, through which data regarding actual behaviors (i.e., derived from a physical product) can be compared with data regarding expected behaviors (i.e., derived from the product's digital representation) in real time [18].

3.2.6. Step 6: Reformulate the artificial structure based on biological inspirations

According to the FBS ontology, design innovations are mostly triggered by the three reformulation steps (i.e., the reformulation of structure, behavior, and functions). In the proposed framework, the reformulations are all supported by biological inspirations. The purpose of structure reformulation is to eliminate the inconsistency between expected behaviors and actual behaviors gradually. Hence, the reformulation steps are only necessary when the actual behaviors fail to meet the expected behaviors. Based on the BID process prescribed in Ref. [4], this step can be further divided into three sub-steps: ① Redefine the biological solution, ② extract solution-neutral working principles, and ③ apply the working principle to the artificial structure. Such a process corresponds to Type III biological inspiration. The artificial structure can be reformulated by imposing more demanding DCs.

3.2.7. Step 7: Reformulate expected behaviors based on biological inspirations

If the expected behaviors–actual behaviors inconsistency cannot be fully eliminated through structure reformulation, the expected behaviors may be reformulated based on biological

Table 3
Function–behavior matrix for retrieving relevant bio-systems.

Function	Behavior									
	Taste sense	Olfactory sense	Touch sense	Infrasound	Heightened sight/sound	Chemical signals	Vibration signals	Polarized/UV light	Echolocation	Magnetoreception
Navigate direction	32	1, 9, 10, 21, 22, 23, 43, 45, 55, 66, 68	20, 68	9, 32, 33, 52, 64	6, 10	10, 24, 40, 43	11, 20, 62, 66, 68, 69	10, 32, 39, 60, 66, 68	63, 64	9, 16, 23, 36, 37, 42, 44, 45, 48, 55
Detect nearby bio-systems	1, 32, 33, 43, 71, 72	1, 8, 9, 22, 26, 43, 45, 68	20, 43, 65	32, 43	6, 7	9, 33, 43, 62, 66	1, 5, 7, 20, 27, 43, 52, 62, 65, 66	21, 22, 32, 39, 60, 66	63, 64	42, 45, 67
Communicate with peers		9, 10	9, 10, 62	27, 57, 62	4, 6	40	62	28	63, 64	
Detect predators		2, 40, 43, 73	10, 16, 32	57, 62	6, 32, 33, 51	4, 32, 43	1, 9, 16, 27, 52, 69	21, 39, 40, 47	64	
Track target (prey)	1, 8, 21, 62, 67, 71, 72	1, 3, 8, 9, 26, 45, 67	20, 43, 65, 67, 68, 69	3	6, 7, 33, 39	16, 21, 33, 43, 52	1, 5, 7, 20, 62, 66, 68, 69	39, 47, 66	63, 64	19, 45, 48, 49, 67
Recognize owner (hospitality)	1, 8, 9, 17, 21, 33, 43, 67, 71, 72	1, 2, 8, 9, 10, 22, 25, 32, 43, 45, 68	16, 20, 32, 43, 62, 68, 73	3, 57, 62	6	10, 21, 32, 33, 40, 43	1, 5, 7, 16, 20, 27	27, 44, 47, 51, 60, 66	63, 64	9, 19, 42, 45, 49, 67
Search resources		9, 21, 22, 55, 66	3, 9, 16, 24, 40, 65		6, 7, 8, 43	3, 40	16, 24, 25, 52, 62	9, 16, 47	63, 64	36, 42, 45
Search service (bio-symbiosis)	7, 11, 15, 20, 30, 31, 37, 45, 48, 54	74	39, 53, 54, 71		39, 45, 59	11, 31	53		58	
Monitor weather		9, 55, 62, 66	32			4, 7, 32, 51	17, 62	17, 32, 45, 51		

UV: ultraviolet.

inspirations. Because the expected behaviors are abstracted from bio-systems in Step 2, the reformulation of expected behaviors primarily concerns the re-selection of analogous bio-systems. In other words, new analogies should be established. For example, the expected behaviors can be reformulated by considering variations in bio-systems within the same biological family under different survival conditions. Meanwhile, the expected behaviors should be reformulated by considering technological development such as artificial intelligence and machine learning, which will affect the designer's expectations. For example, by means of additive manufacturing, designers can now produce highly complex structures based on inspiration from biological structures (e.g., the honeycomb structure)

3.2.8. Step 8: Reformulate functions based on biological inspirations

Finally, biological inspirations can be leveraged to reformulate functions. First, as indicated by arrow 8(i) in Fig. 1 novel functions can be abstracted from bio-systems and then transferred to the smart product. To be specific, the analogous bio-systems are regarded as peer products of the smart product, and functional recommendations are generated based on the similarity between the bio-systems and the smart product. Second, as illustrated by arrow 8(ii) in Fig. 1, functions can be reformulated based on their coupling relationships. Inspiration can be gained from bio-systems regarding how they manage functional couplings. For example, ants navigate their surroundings using polarized light and smell, and communicate with their peers using smell and touch, with smell playing a key role in exchanging contextual information within a network. Ants have four to five times more odor receptors than other insects [19].

Fig. 2 provides a flowchart of the sequential steps of the biologically inspired smart product design process. The specific design methods and tools that can be used to facilitate each step are also included in the flowchart.

4. Case study

Here, a case study is presented to showcase how to follow the BID-SP framework to develop smart products. The task is to redesign a robot vacuum cleaner, iRobot Roomba 650 (Roomba), to make it more context-aware.

4.1. Step 1: Formulate functions based on customer requirements

Customer requirements were solicited based on online customer reviews collected from Amazon.com. A structured qualitative data analysis process was followed to analyze a total of 50 customer reviews (i.e., ten reviews for each rating on a scale from 1 to 5). A systematic qualitative data analysis process [20] was followed to retrieve design information hidden in these reviews. The process included the five steps of data collection, transcription, segmentation, categorization, and coding. Examples of customer requirements that were relevant to context-awareness included the following:

- The device sometimes picks up pet poop and spreads it all over the floor.
- Users should be notified via APP if the device gets stuck.
- The device gets stuck on black mats, as cliff sensors detect the mat to be a cliff.
- The device fails to mop the room before cleaning.
- Cleaning route seems random… it is difficult to tell which area has been cleaned.

Considering the customer requirements, a set of functions was formulated based on the functional basis (see Table 1), including <recognize concentrated dirty area>, <mark territory>, <recognize

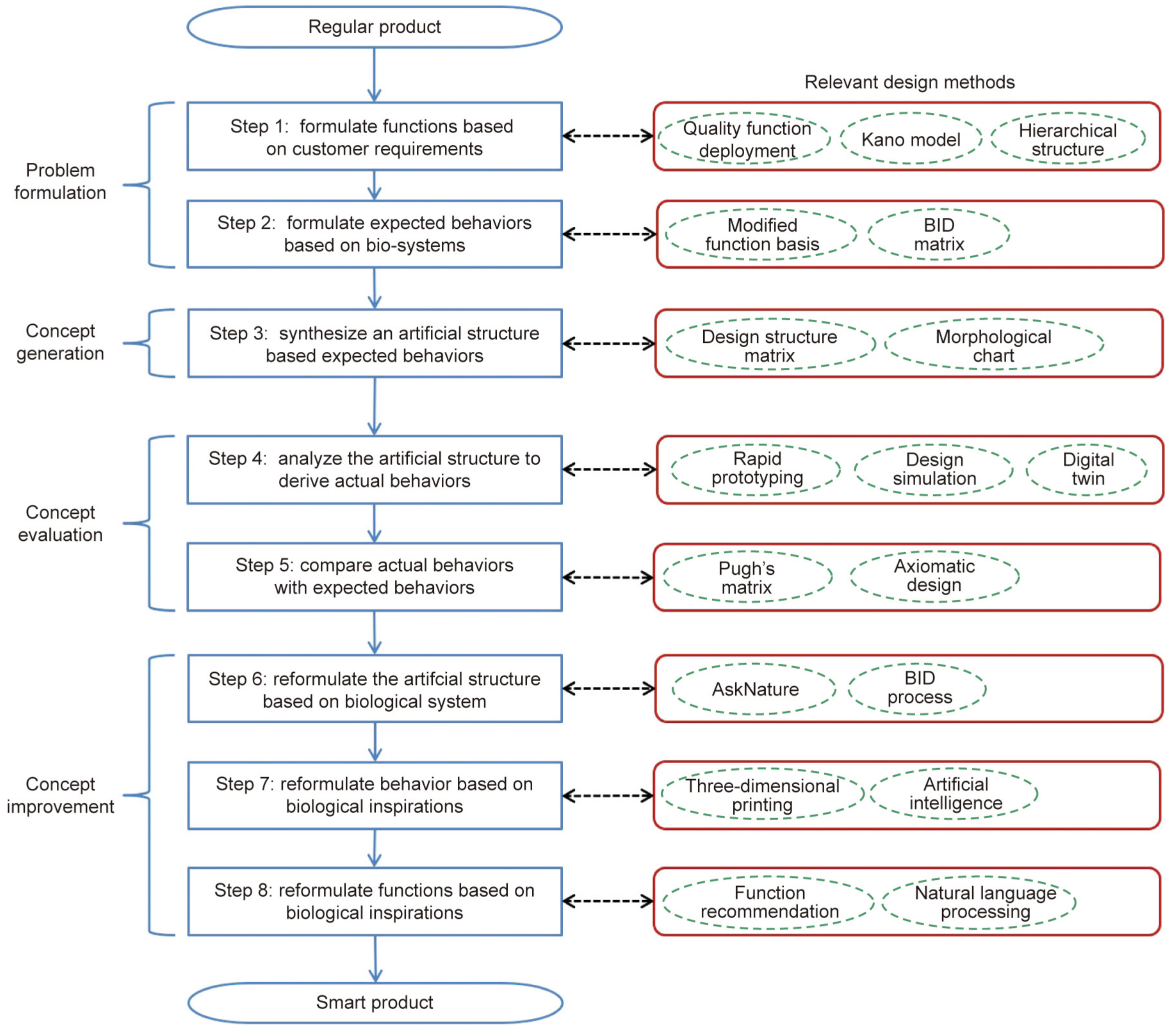

Fig. 2. Flowchart of the biologically inspired smart product design process.

baby/pet>, <recognize trash type>, <recognize trapping>, <plan cleaning route>, <communicate with peer product>, and <seek user intervention>. Fig. 3 illustrates the complete functional hierarchy, with the context-awareness-related functions highlighted.

4.2. Step 2: Formulate expected behaviors based on bio-systems

The functions were mapped to a set of expected behaviors abstracted from bio-systems, as summarized in Table 4 [21,22]. For example, "odor cue" was abstracted from bees that use a pheromone to communicate with peers, and "movement cue" was abstracted from bees that use "dancing language" to convey information about food location. In this case, although both "odor cues" and "movement cues" were abstracted from the same bio-system, they were intended for different functions. On the other hand, the same behavior can be extracted from different bio-systems. For example, spiders, snakes, and honey bees all rely on vibration to recognize moving objects.

4.3. Step 3: Synthesize an artificial structure based on expected behaviors

Based on the expected behaviors, a set of design parameters (DPs) were proposed to fulfill the intended functions. Since multiple DP alternatives are proposed for each function, they can be integrated into different system solutions (artificial structures). The results were organized based on the morphological chart, as illustrated in Table 5.

4.4. Step 4: Analyze the artificial structure to derive actual behaviors

Table 6 lists a selection of artificial components that can be added to a Roomba to enhance its context-awareness. Some actual behaviors are derived from every component.

4.5. Step 5: Compare actual behaviors against expected behaviors

The actual behaviors derived from the artificial component were compared with the expected behaviors derived from the bio-systems. For example, ravens demonstrate strong logical thinking. A raven relies on logic (as opposed to instinct) to solve problems. The artificial component chosen to emulate this behavior was fuzzy logic, which forms a part of the overall control system for the Roomba. Fuzzy logic enables the interpretation of variables along a continuous spectrum (e.g., "slightly warm" and "slightly cool") instead of binary values (i.e., "hot" vs. "cold"). Fuzzy logic enables a robotic device to behave more logically when problem solving. Through fuzzy logic, the Roomba can not only differentiate between a status of "stuck" or "free," but also evaluate to what extent it is stuck based on wheel traction data. As a result, the

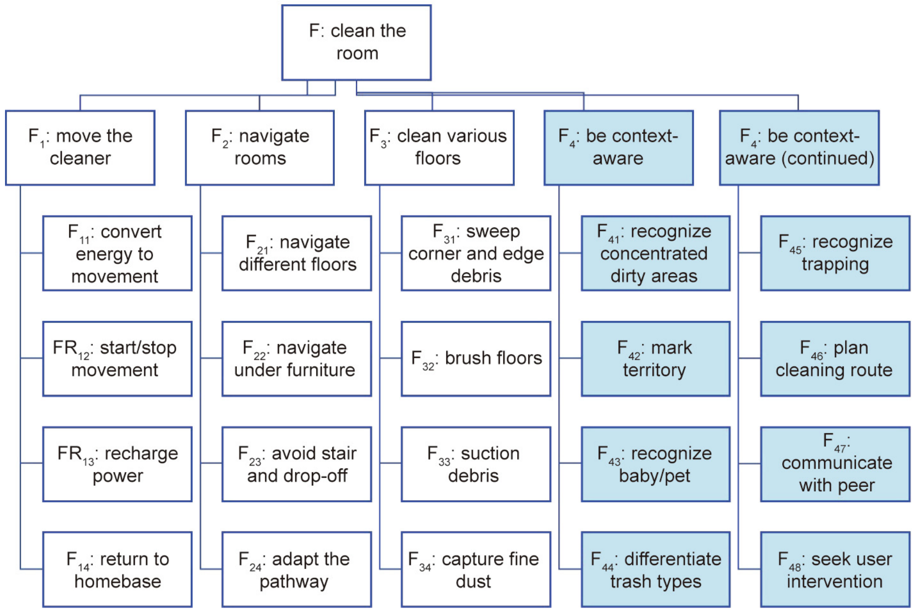

Fig. 3. Functional hierarchy of context-aware robot vacuum cleaner.

Table 4
Function–behavior pairing results.

Function	Expected behavior	Behavior of bio-systems
Recognize a dirty area	Image sharpness	Falcons can "see" prey when flying at high speed, due to sharp images created by a unique retina structure with fewer vessels
	Image coverage	Jump spiders have eight eyes to create 360° image coverage
	Odor cues	Snakes use the tongue to pick up scents and locate the scent source
	Polarized light	Mantis shrimps rely on the torsional rotation of their eyes to maximize the polarization contrast [21]
Mark territory	Odor cues	Wolves use scent to mark territory and the hunting route
	Chemical scent	Spiders release a special chemical scent to warn other spiders
	Acoustic signals	Male green frogs can lower the dominant frequency of calls to mark and defend territory [22]
Recognize trash type	Image sharpness	Falcons can "see" prey when flying at high speed, due to sharp images created by a unique retina structure with fewer vessels
	Odor cues	Octopuses rely on smell to differentiate good food from bad food
Recognize baby or pet	Odor image	Bloodhounds can create an "odor image" in the brain based on the complex combination of various smells
	Vibration	Snakes locate prey through vibration waves
	Touch sense	Octopuses rely on sensitive feelers to distinguish objects
	Echolocation	Bats produce echolocation sound to detect obstacles
Recognize trapping	Touch sense	Bees can use their antennae to gauge the dimensions of an object
	Polarized light	Octopuses use polarized vision to measure the amount of light
	Fuzzy logic	Ravens use logical thinking to assess a trapping situation
Plan cleaning route	Compass bearing	Ants can correct the route based on visual landmarks
	Odor sense	Ants can create a traceable trail by dropping pheromone
	Counting steps	Desert ants calibrate a mental clock according to the motion of the sun and count steps to navigate direction in the featureless desert
Communicate with peers	Vibration	Elephants coordinate actions by making the group rumble
	Odor cues	The queen bee produces different pheromones to characterize situations
	Touch sense	Ants touch each other to share information about food
Seek user intervention	Logical thinking	Ravens employ logic to solve problems, even if it is a problem that does not exist in the natural domain
	Movement cues	Ravens draw other predators such as wolves to food through movement cues, by circling dead or dying prey
	Movement cues	Bees convey an image of the location of food sources through a dance language

Roomba evolves to become smarter regarding when to seek user intervention. For example, if the Roomba detects a large moist area on the hard floor, fuzzy logic enables it to assess the degree of mess and hence make a "smarter" judgment regarding whether to notify the user before proceeding. This smartness will potentially prevent the Roomba from coming into contact with pet feces and spreading it over the floor.

4.6. Step 6: Reformulate the artificial structure based on biological inspirations

The artificial structure was reformulated based on biological inspiration. For example, ravens can not only solve problems logically, but also adapt existing solutions to new problems. This principle inspired the designers to combine fuzzy logic with

Table 5
Morphological chart of DPs.

Function	DP				
	1	2	3	4	5
Recognize dirty area	360° camera	Bio-electronic nose	Master/slave protocol	Fuzzy logic	Image processing
Mark territory	Bio-electronic nose	Flavor-releaser	Ultrasonic sensor	Touch sensor	UV light sensor
Recognize baby/pet	Image sensor	Bio-electronic nose	Ultrasonic sensor	Camera	Vibration sensor
Recognize trash type	Vibration sensor	Odor sensor	Touch sensor	Pressure sensor	Camera
Recognize trapping	Displacement sensors	Case-based reasoning	Vibration sensor	Master/slave protocol	Proximity sensor
Plan cleaning route	Odor sensor	Compass	Touch sensor	LIDRA	Master/slave protocol
Communicate with peers	Vibration sensor	Touch sensor	Odor sensor	Dancing algorithm	Fog computing
Seek user intervention	Smartphone APP	Dancing	Alarm	Augmented reality	Fuzzy logic & case-based reasoning

Table 6
Actual behaviors derived from artificial components.

Component	Actual behavior			
	1	2	3	4
360° camera	Degree	Resolution	Water resistance	Battery life
Bio-electronic nose	Electronic signals	Mass spectrometry	Acoustic wave	Organic polymers
Vibration sensor	Frequency	Piezoelectric effect	Electrical charge	Resonance
Master/slave protocol	Command sending	Command execution	Data transfer	Latency
Proximity sensor	Resolution	Calibration	Feedback	Electromagnetic field
Fog computing	Security	Date storage	Computing power	Latency
Fuzzy logic	Control accuracy	Adaptive adjustment	Rules	Problem type
Case-based reasoning	Case storage	Case access	Case indexing	Case searching

case-based reasoning. Fuzzy logic enables the Roomba to evaluate a problem situation accurately (e.g., to what extent it is stuck) and recognize new problems proactively (e.g., what kind of trapping is occurring). Case-based reasoning enables the Roomba to compare the current problem with historical ones and determine their similarity. The effectiveness of case-based reasoning can be further enhanced by connecting all Roombas to a cloud-based central database that stores all kinds of historical trapping problems in different contexts (i.e., various home environments). In this way, it creates a form of swarm intelligence through shared data. Moreover, the network latency can be minimized by means of fog computing, thus permitting a timely response to any developing situations.

4.7. Step 7: Reformulate the expected behaviors based on biological inspirations

The comparison between expected behaviors and actual behaviors triggered new design ideas. For example, the queen bee produces a special pheromone to communicate with worker bees [23]. She can spread the pheromone by moving around within the hive and leaving traces of the pheromone on the honeycomb. However, this behavior cannot be fully realized by means of WiFi or other networking technologies, as the router itself cannot physically move around; this leads to a signal coverage issue for the Roomba. For example, in large houses, it can be difficult to locate the Roomba if it is trapped in a corner without WiFi coverage. When a beehive is attacked, the queen bee releases a special alarm pheromone to mark the intruder and draw other bees to defend the hive. The pheromone consists of different compounds that allow the bees to pursue, locate, and attack a moving target [24]. The stronger the scent of the pheromone, the more aggressively the bees will attack. Therefore, the abstracted behaviors are "pheromone intensity" and "situational pheromone cues." Accordingly, the expected behavior was therefore reformulated from "situational pheromone cues" to "pheromone intensity" to reflect such a behavioral inconsistency.

4.8. Step 8: Reformulate functions based on biological inspirations

Some new functions were abstracted from analogous biosystems and transferred to the Roomba. For example, the Roomba can be connected to the home security system, e.g., the closed-circuit television (CCTV) camera system, to recognize home intruders. This simple network enables the security system to temporarily "enslave" the Roomba to acquire telemetry from the onboard sensors. The connection can also work in the opposite direction, as the Roomba detects suspicious activities and then sends an activation signal to the CCTV system. By networking with the security system, the Roomba can deploy a greater number of sensors and gain access to a larger database. The Roomba–CCTV network can benefit other functions as well. For example, if the Roomba detects a black rug as a cliff, it can cross-reference the sensor telemetry with camera images of the CCTV system. This artificial behavior is inspired by the biological behavior of ants, where one species of ants can parasitize another species within a dual-species colony for tasks the other species are better suited for.

In summary, the robot vacuum cleaner is made more context-aware through the proposed BID process. First, a set of new functions are assigned to the cleaner, and these functions are all formulated based on the proposed functional basis specifically in regards to context-awareness. Second, for every context-awareness-related function, multiple DP alternatives are proposed according to biological inspiration. Third, the proposed DP alternatives are qualitatively evaluated by comparing their actual behaviors with the expected behaviors of the corresponding bio-systems.

5. Conclusion and future work

This paper presents a structured design BID-SP framework. As its original contribution, this work adapts the FBS ontology for the first time to structure the BID process. Some existing design methods and emerging design tools are incorporated into the BID-SP framework. Furthermore, a systematic design process is prescribed in order to leverage biological inspirations for smart product design, and particularly for the design of context-aware products. Context-awareness is defined from the perspective of product design, and a selection of context-aware bio-systems are analyzed. Integration with BID is beneficial for the FBS ontology. In the conventional FBS process, expected behaviors are directly derived from intangible functions; this is a very challenging design operation, since functions are supposed to be solution-neutral. In the proposed framework, the expected behaviors are derived from tangible bio-systems. Moreover, the three reformulations in FBS are supported well by biological inspirations.

Some limitations should be considered. First, while product smartness is inherently a multifaceted notion, this work focused on only one facet (i.e., context-awareness). Other facets (e.g., service and cognitive engineering) will be addressed in future work. Second, the design is performed based on a selection of context-aware bio-systems chosen by the authors, which could be biased due to design fixation. Third, although the authors suggested some design methods that may be used to facilitate the proposed design process, the specific execution is not elaborated, since this was not the focus of this work. Finally, although a case study is an effective method to describe how to carry out the proposed framework to solve a real-world design problem, it may not be adequate to fully demonstrate the actual performance of the new design concepts.

This work illuminates the promising direction of leveraging biological inspirations for smart product design. The research strategy and framework can be adapted to benefit other facets of product smartness such as adaptability, location-awareness, and network-awareness. Future work will focus on the overlap between context-awareness and network-awareness. Design inspirations will be drawn from bio-systems in terms of how such systems build different kinds of networks and coordinate actions in different ways, when situated in different contexts. Given the descriptive nature of the case study method, we will build a prototype device to illustrate the design concept obtained from this work; based on this device, we will then validate the actual performance of the new context-awareness capabilities through design experiment.

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Compliance with ethics guidelines

Ang Liu, Ivan Teo, Diandi Chen, Stephen Lu, Thorsten Wuest, Zhinan Zhang, and Fei Tao declare that they have no conflict of interest or financial conflicts to disclose.

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