

Conceptual design of multi-modal products

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Abstract On modern mechatronic products, incorporating multiple modes is a common and effective way of dealing with changes in task, requirements, and environment. Modes are established to enable the system to switch from one configuration state to another. However, using the traditional methodology in engineering design, products are considered and designed with fixed configurations. A systematic method to involve and enable the design of changeable configurations is lacking. This paper focuses on product functional models and investigates the conceptual design of multi-modal products, which are identified by their reconfigurability during the operation stage. The author connects the phenomenon of multiple modes to product reconfigurability, asserts function and technology multiplications as the basis of multiple modes, and then specifies that usability and robustness are the key drivers of incorporating multiple modes. At the end of the paper, the author reconciles the conceptual design procedures to derive the principle solutions specifically for multi-modal products. This research on the dynamic characteristics of

the product functional model introduced by multiple modes complements the current systematic design methodology.

Keywords Mode · Transition · Functional model · Reconfigurable product

1 Introduction

In modern industrial products, product complexity and variety are boosted by the advancements in technology and customers' diverse needs. To handle variant tasks or achieve improved performance demanded by customers, integrated products with multiple functions or technologies are invented to replace a number of specialized products. Integrating a number of specialized products into one artifact has become a common form of innovation. A significant design commonly found on integrated products is that they have multiple modes. A multi-modal product is identified by its reconfigurability during the product's operation stage. Instead of keeping all of its functions and technologies in operation, a multi-modal product activates only a selection of functions and technologies specified by the currently selected mode. The operational reconfiguration can meet customers' diverse needs (Haldaman and Parkinson 2010) and maintain an optimal performance when unpredicted factors arise (Ferguson et al. 2007).

Nevertheless, conceptual design, which aims to specify the principle solution from a design problem (Pahl et al. 2007), remains critical and yet difficult (Nagel et al. 2008b). The changeable and dynamic behaviors introduced by mode transitions contribute to the system complexity. Comparing to simple and specialized products, the system's changeable configuration introduces challenges and potential for achieving a good design that efficiently substitutes for the

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original products. The case study in morphing airfoil design introduced by Schultz et al. (2010) suggested that function structures in their current state were incapable of accurately modeling the functionality of the artifact's shape-changing aspect. For complex systems, a desirable principle solution is not sought by simply accumulating the principle solutions of several separate products, but by unifying them and implementing adequate supervisory control.

However, the theory and methods of designing and analyzing multi-modal systems significantly lag behind state-of-the-art product development, since multiple modes have been widely applied to modern mechatronic products, such as electric home appliances, automobiles, and consumer electronics. The term “*mode*” has not been defined in engineering design. Existent literature about product conceptual design, the entities of task, function, and principle are mainly abstract and have limited elaboration related to changes during the operation stage. Product design methodologies mainly concern the functional and physical construction of the system, while the changeable configurations and behaviors involved with various situations are not clearly demonstrated in the principle solution. The necessity of studies on multiple modes is also observed in comparison with the achievements in the hybrid dynamical systems in cybernetic and control science (van der Schaft and Schumacher 2000; Goebel et al. 2012). For these reasons, the interrelationship between mode, task, function, and principle in the conceptual design should be revised.

This research work focuses on the elaboration of functional models and deriving principle solutions of multi-modal products, exemplified by modern mechatronic products. In this paper, the complexity of multi-modal products is viewed as the result of redesign, through which novel integrated products are invented based on related simple products. The research background includes related topics in reconfigurable products, design methodology, and hybrid dynamical models. The concept of mode is presented in Sect. 3 by focusing on the changeable configurations and their purposes. Thereafter, we establish a three-dimensional paradigm based on three fundamental factors: function, technology, and mode. Section 4 summarizes the key drivers of multi-modal products. Thereafter, we propose methods of conceptual design of multi-modal products. The final section compares the phenomena of function clustering and sharing created by multiple modes with that created by modularity.

2 Background

The collaboration across different disciplines suggests that the dynamic characteristics of multi-modal systems should be investigated using different approaches (Veeke et al.

2006). Numerous examples of artifact-oriented design practice toward multi-modal products were found in the literature. They have represented scientific abstractions of dynamic systems viewed from different angles. Li et al. (1999) developed an automatic design synthesis algorithm that generated solutions of a multiple-state mechanical device. However, the method used for mechanism abstraction was not sufficient for design tasks in an overall system scale. An attempt at computer-aided design of multiple-state mechatronic devices described a modeling framework to support conceptual design using state transition diagrams (Xu et al. 2005). A methodology of inventing new reconfigurable products is introduced with three transformation principles and 20 transformation facilitators (Singh et al. 2009).

On the front end of product design, the changes of requirements and circumstances promote reconfigurability. Reconfigurable systems are defined as systems designed to maintain a high level of performance through real-time change in their configuration when operating conditions or requirements change in a predictable or unpredictable way (Ferguson and Lewis 2006). System reconfigurability has been studied as the leverage for two applications. The first application is to create, evolve, or upgrade a product at lower cost by modification (Siddiqi et al. 2006; Cormier et al. 2009). Adaptable design was introduced by Gu et al. (2004) and further developed by many researchers (Li et al. 2008; Fletcher et al. 2009; Zhang et al. 2014). Their works originated from the idea of replacing multiple products with one adaptable product with a set of add-on accessories or attachments. The other application which includes multi-modal products is to handle multiple tasks and requirements and enhance functionality by changing or transforming the product configuration during the operation stage (Siddiqi and de Weck 2008; Singh et al. 2009; Haldaman and Parkinson 2010). In general, the research works in reconfigurable system design are case-oriented and solution-oriented. They are not well connected to the design theory, especially because they lack a function modeling process.

The viewpoints of product evolution and redesign suggest that the design of multi-modal products is dependent on the status of product development. The practice of redesign is implemented as reverse engineering (Otto and Wood 1998). From a holistic view in design theory, Cross (2008) proposed that design is implemented when there is a stock of previous design ideas on which to draw. Otto and Wood (2001) categorized redesign into original, adaptive, and variant design, which are classified according to the effort required. It is even arguable that “all design is redesign.” Pahl et al. (2007) advised that the starting points for new products include new product functions, other working principles, new embodiments, and rearrangements

of system structure. These four aspects indicate the areas where product innovations can be achieved.

In the ontology of engineering design, the elaboration and analysis of a system functional model is a major activity in conceptual design, which leads to an outcome of a principle solution (Otto and Wood 2001; Ulrich and Eppinger 2003; Pahl et al. 2007). In the search for an appropriate principle solution, black box models and system boundaries have been widely used to explain the interactions with the environment by means of function (Stone and Wood 2000; Otto and Wood 2001; Veeke et al. 2006; Nagel et al. 2011). Function structure derived by decomposing an overall function into numerous sub-functions has been a common repertoire in conceptual design. To formalize the representations in function-based design, Stone and Wood, followed by Hirtz et al., developed a functional basis, which provides a formal function representation to support functional modeling (Stone and Wood 2000; Hirtz et al. 2002). Moreover, the functional basis and representation were expanded across multiple engineering domains for modeling of mechatronic products and even control systems (Chen et al. 2002; Rajan et al. 2003; Jayaram and Chen 2003; Nagel et al. 2008a). As a fusion across the mechanical and control domains, the consideration of function modeling leads to complex interrelations between functions. Therefore, the design procedures were proposed with high fidelity (Chen et al. 2002; Jayaram and Chen 2003).

The methodology in function modeling provides a sufficient knowledge basis for the conceptual design of changeable configurations. Nevertheless, there is a lack of a unified framework for modeling the reconfigurability. The considerations regarding transitions in engineering design are found to be coherent to either logics (Buur 1990; Pahl et al. 2007; Ullman 2010) or the functional basis such as to couple, actuate, stop, and so on (Hirtz et al. 2002; Chen et al. 2002). More fundamentally, the gap is found at the differentiation between configuration changes and flow changes. In cybernetics, state is used to quantify the current status and behavior in an already-designed configuration, such as position, velocity, temperature, and voltage. By contrast during the design process, since the design solution is not resolved, the configuration and the flow are both dynamic. This confusion is perceived when Umeda and Tomiyama (1995) propose state as a sum of the changeable configuration and the so-called state in their function–behavior–state paradigm. The function modeling methodology needs to enable modeling of reconfigurability.

Buur (1990) involved state transitions and function modeling in his mechatronics design methodology by using finite state models. This approach inspires the combination of the knowledge in design theory and cybernetics. In the cybernetic community, a multi-modal system is abstracted

as a combination of continuous and discrete processes (Alur et al. 1993). The former is represented by a set of differential equations, while the latter indicates discrete events or transitions (Guckenheimer and Johnson 1995). Methodologies and mathematic models have been systematically studied by Mostermann and Biswas (2000) and Goebel et al. (2012). In addition, the study of variable-structure systems was done by van der Schaft and Schumacher (2000). These research works suggest establishing a modeling framework, which includes all the configuration states and transitions in between.

In summary, many modern products have multiple modes. The science of engineering design provides comprehensive guidance in developing a physical product from a functional perspective. However, the existent design theory lacks effective methods for modeling and designing changeable configurations. The concept of mode is left underdefined in the ontology of engineering design. The research works in reconfigurable products have studied the necessity and best practices in designing multi-modal products. The frameworks that integrate multiple modes and transitions can be borrowed from the cybernetic community. In this paper, we strive to combine the knowledge in these disciplines and revise the existing conceptual design methodology.

3 Modes in conceptual design

Mode is a switchable system configuration state made for a specific purpose. A multi-modal product's changeable configuration switches between a number of configuration states during the operation stage. Thus, the product achieves varied purposes with different configuration states.

In this section, our investigation of multi-modal products will focus on changeable configurations and the purposes of changes. In Sects. 3.2 and 3.3, we select various examples, in which the manipulation of functions, technologies, and modes will be interpreted with various product design concepts.

3.1 Switchable system configurations

When multiple modes are involved, the system dynamics are not limited to the material, energy, and signal flows, but also include the system's configuration that defines the flows. In design literature, where a system's infinite possible configurations are focused, changeable configurations have also been mentioned as states (Umeda and Tomiyama 1995; Singh et al. 2009) that actually indicate *configuration states*. A configuration state is one of the system's infinite achievable states due to its configuration changes. If a

system is configured to a certain configuration state that is suitable to operate for a specific purpose, the designer may adopt this configuration state as a mode. Hence, a system’s modes are a subset of its configuration states.

Figure 1 shows the functional model of a dual-mode solar lamp. Basically, there exist three achievable configuration states. However, among these three configuration states, only two are suitable for achieving some practical purposes. As a result, the lamp converts and stores electric energy in the day mode and then converts the stored energy to light in the night mode.

In the solar light example, despite the electric energy flow constantly changing, the configuration changes only when the mode is switched. In this sense, a configuration change caused by mode switching is a discrete event, rather than a continuous process like a flow. Simply speaking, a mode keeps an asset static while letting the flows change. This asset remains static unless a transition occurs. Basically, the asset includes both a functional model and all the detailed information that conduct the flows. However, depending on the system scale in which the design task is undertaken, this asset is described either functionally or mathematically.

In an overall system scale, in which decoupled subsystems are architected together to form a complex system, elaborating functional models for each configuration state is an effective means to overview the system. It is more efficient to describe the asset with a functional model. The design of a solar light is regarded in this system scale. In an elementary system scale, in which a simple structure with complex and coupled physical behaviors may embody multiple functions, a functional model is no longer

sufficient to assist the design work (Schultz et al. 2010). In such cases, the design is done by studying the physical behaviors and parameterizing the configuration. A mode is thus more effectively described as a physical system with resolved parameters and variables.

3.1.1 Modes in overall system scale

The design of modes in an overall system scale is carried out by function modeling. To have an overview of the functional models that appear in all the modes, we propose a *transitional functional model* as a scheme that shows how the system configuration changes between modes. Each mode is a configuration state established to serve the user for a specific purpose.

As an example in mechatronics products, a multi-functional sport watch is a combination of a normal digital watch and two extra functions for sport enthusiasts, as shown in Fig. 2. Moreover, this product also has a multi-modal property, enabling the user to activate and deactivate the heart rate measuring and positioning functions during training. From the designer’s point of view, the intent of establishing two working modes reveals itself in two steps. First, the designer decides to design a sport watch, which helps the users for the purposes of both sport training and other daily uses. Secondly, considering the added functions in the training mode shall not be activated all the time, the watch requires a transition that activates and deactivates the two additional functions. With these two considerations, two configuration states of the dual-mode sport watch are elaborated in Fig. 3. Under the clock mode, the watch only activates its minimum time displaying function. When the user switches it from clock mode to training mode, the watch initiates a prescribed transition, which activates the heart rate measuring and positioning functions, and then starts displaying the real-time data on its screen.

3.1.2 Modes in elementary system scale

In an elementary system scale, function modeling is not always involved in the design of modes. This is mainly

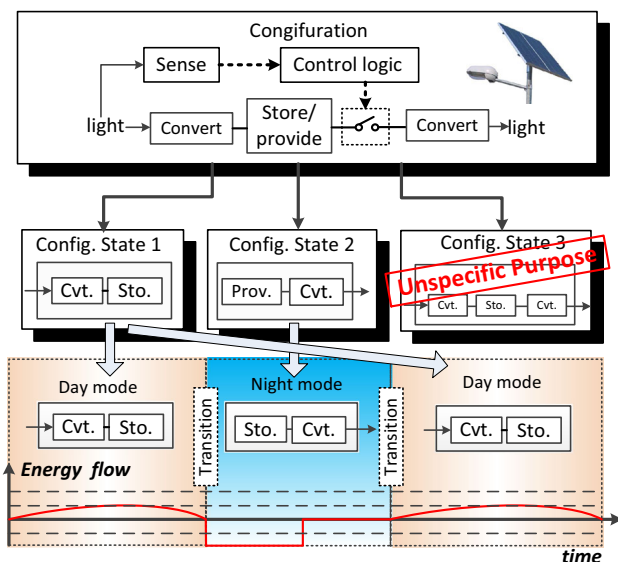


Fig. 1 Configuration states, modes, and the energy flow of a solar light

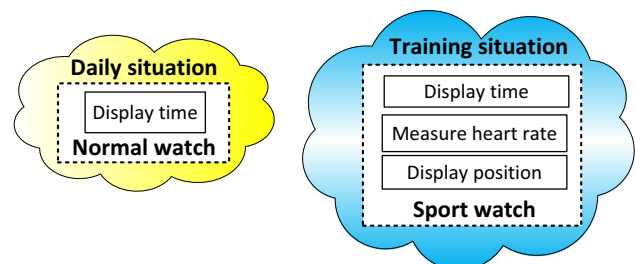
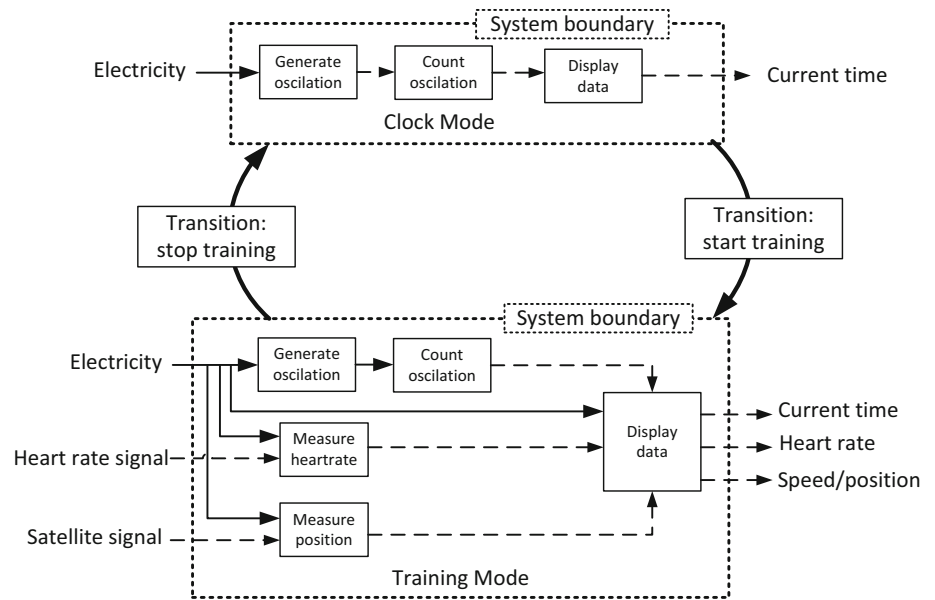


Fig. 2 Overall functions of a normal watch and a sport watch

Fig. 3 Transitional functional model of a dual-mode sport watch



because the design in elementary system scale is very often assigned to a specific physical phenomenon; thus, the variation between configuration states is no longer at different functional models, but different design variables. For example, the takeoff, cruise, and landing mode of an aeroplane’s flap share the same functional model; however, the modes constrain the flap’s position variable to different values. The limitations to functional models are also attributed to the lack of quantification of the flows. Schultz et al. (2010) attempted to develop a functional model that accurately describes the functional model of an airfoil that passively changes its shape at different airspeeds. The difficulty was that the configuration states share the same functional model, but different flows of airspeed. Thus, in dealing with complex behaviors of aeroelasticity, using a functional model is not as straightforward as using physical laws.

The design of modes in an elementary system scale aims to match a system’s natural behaviors to different purposes. Ferguson et al. (2007) proposed the necessity of integrating cyber infrastructure with reconfigurable systems. Development of an effective reconfigurable system requires the understanding of dynamic behaviors (Ferguson and Lewis 2006). In most engineering domains, the natural behaviors of physical objects are interpreted by mathematic equations with designated *state variables* and *design variables*. In cybernetics, flows are quantified with state variables, which are defined as “the smallest set of variables such that the knowledge of these variables together with the knowledge of the input completely determines the behavior of the system for any time” (Ogata 2002). Design variables are a set of data kept static in each mode, however, may change from one mode to another. They are very often derived

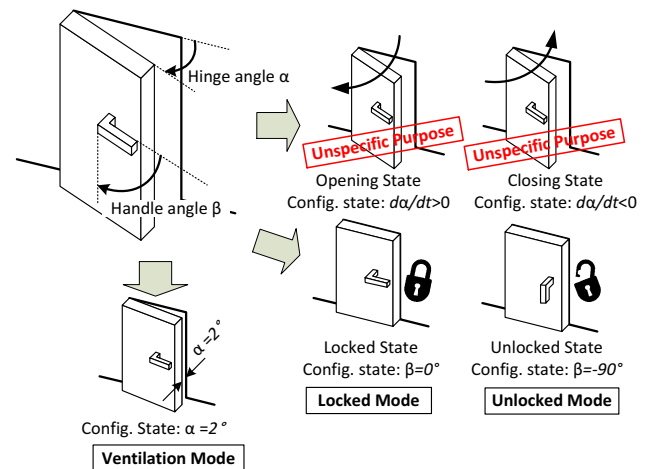


Fig. 4 Configuration states and modes of a simple door

from optimizations, calculations (Ferguson and Lewis 2006), or experiments in specific domains.

Figure 4 refers to the simple door example presented by Li et al. (1999). The door has two movable parts: the door hinge and the handle. The hinge velocities and positions together with the handle position are the state variables that describe the configuration state. Thus, four of the door’s configuration states are shown, such as opening, closing, locked, and unlocked state. But a mode is established only when a certain configuration state can achieve a specific purpose, such as to prevent people from entering. Hence, the locked mode and unlocked mode are designed by configuring the handle to different states. If necessary, the designer may design a ventilation mode by constraining the hinge angle to a small angle. Mathematic equations that describe classic Newtonian mechanics can be used by the

designers to analyze the complex behaviors of the flows of forces, velocities, and positions.

3.2 Toward multiple functions and technologies

The word “mode” is defined as “a particular functioning arrangement or condition” (Merriam-Webster 2014) and “a particular way in which a machine or piece of equipment can operate” (Pearson Education Limited 2014). These two definitions intrinsically convey *what* the artifact accomplishes and *how* it accomplishes it. Connecting *what* and *how* to engineering design, we assert that modes facilitate the multiplication of functions and technologies. Multi-modal designs are hence categorized as *functional multi-modal design* and *technological multi-modal design*. Functions and technologies are also the fundamental purpose that modes are incorporated in a product.

The division of function and technology is a time-independent, dichotomy about the system boundary, shown in Fig. 5. Outside the system boundary, the environment interacts with the artifact by means of its external inputs and outputs, whose relationship is defined as function (Pahl et al. 2007). Inside the system boundary, we assign the term technology as the sum of decomposed functions and their principle solutions that achieve an overall function. Technology multiplication is identified by the multiple paths between its input and output. The division of function and technology also agrees with the environment-centric and device-centric viewpoints of function studied by Chandrasekaran and Josephson (2000). The environment-centric viewpoint emphasizes the artifact’s desired effect on the outside, namely the function. The device-centric viewpoint focuses on the internal structure and configuration, namely the technology.

Functional multi-modal design and technological multi-modal design stand for the increase in reconfigurability in two directions. They not only explain the purpose of multiple modes, but also help the designer to navigate in expanding a product family.

Two examples of functional and technological multi-modal design are shown in Fig. 5. The sport watch example reveals functional multi-modal design, since modes are prescribed as different configurations toward multiple functions. Technological multi-modal design can be also implemented in the same fashion, in which the variant or redundant technologies are specified by modes. A hybrid electric vehicle is a good example of technological multi-modal design, in which using a fuel engine and using an electric motor are switchable technologies.

On the basis of the decoupled function, technology, and mode, we construct a three-dimensional paradigm to quantify design concepts and their reconfigurability with the scales of function, technology, and mode, shown as the Cartesian frame in Fig. 5. On each of the three dimensions, a scale is used for quantifying the corresponding entities. Set at the origin of the frame, a simple product represents the primary artifact, on which multiplications of functions, technologies, and modes are to be performed. In practical cases, the design of an integrated product is initiated on a conventional product with a basic function and technology. After the multiplication, the design concept of an integrated product is evaluated in three aspects and positioned in this three-dimensional space.

Figure 5 positions a number of design advancements found on a variety of watches in the proposed three-dimensional paradigm. The watches are abstracted into functional models and fit their positions. A simple digital watch with a unique function of displaying time is positioned at the origin. As defined previously, the function multiplication, demonstrated by path F1, leads to the design concept of a pure multi-functional watch, exhibiting no mode transition in its operation. The idea of switching the watch between two modes is suggested by path M1, finally resulting in the functional multi-modal concept. Hence, the concept of a functional multi-modal sport watch is broken into a two-step path F1–M1. Similarly, the technology multiplication is exhibited by path P2, leading to the design concept of combined digital and analog time

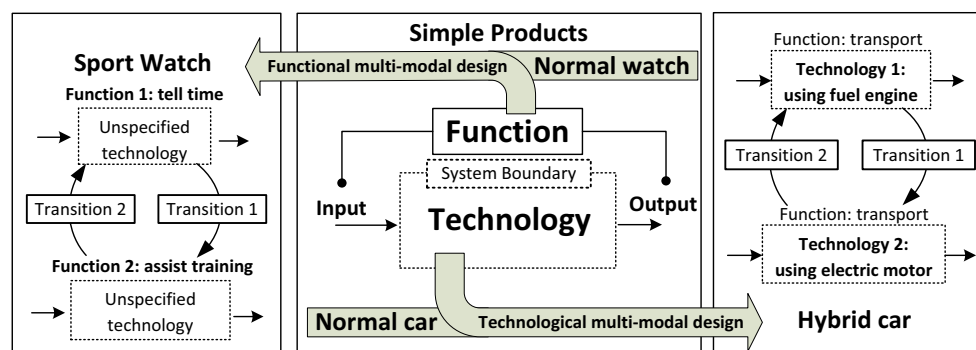


Fig. 5 Function and technology stand for the external and internal system descriptions

display. An inventive, yet imaginary, product is suggested by path M2, which suggests a switchable means of time display. Hence, incorporating multiple modes becomes a means of facilitating multiple and switchable technologies.

3.3 Examples of multi-modal products

Figure 6 provides an in-depth case study of Garmin™ 920XT, a recently released multisport watch (Garmin Forerunner920xt 2014). The watch is designed to provide triathlon enthusiasts a package of training assistance in swimming, biking, and running activities with a variety of measurements, data logging, and upload functions. In overall system level, the three training modes and the normal watch mode facilitate multiple overall functions of assisting three training activities and displaying time. The four overall functions facilitated by four modes represent a functional multi-modal design. Further, at the sub-system level, the

overall functions of assisting training and displaying time are broken down into switchable sub-system functions.

The validity of the function–technology–mode paradigm is not limited in the overall system level, but also in sub-system levels. On this level, divergences appear that for one sub-function the system is equipped with multiple technologies, such as using either GPS or GLONASS signals for the positioning sub-function. Therefore, at the sub-system level, the design for a specified function exhibits technological multi-modal design (Fig. 7).

In addition to the sport watch and a few other examples mentioned in this paper, we summarized examples of multi-modal products from the cited reference. Table 1 categorizes these examples into functional and technological multi-modal products, according to the multiplications in the overall system level. These examples cover the domain of mechanical, electric, mechatronic, and electronic products.

Fig. 6 Variety of watch concepts in the proposed function–technology–mode paradigm

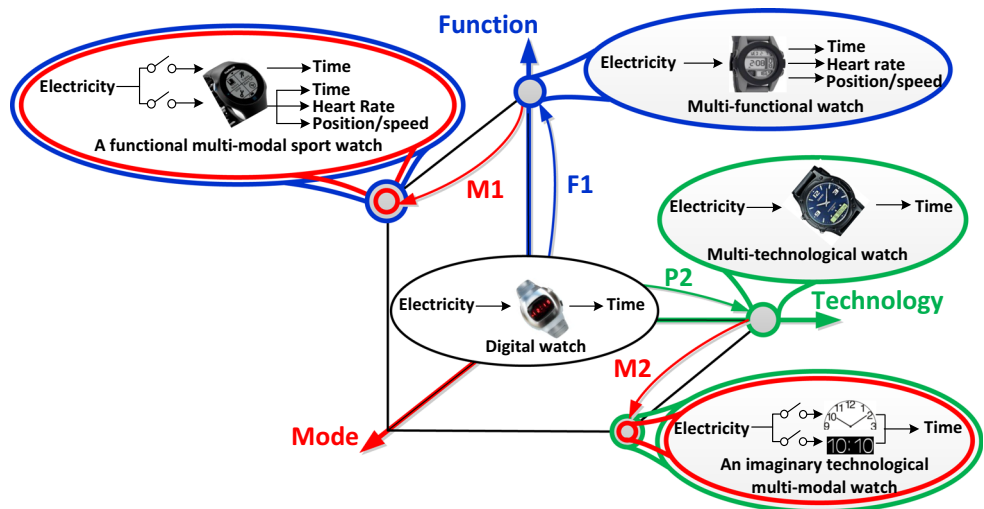


Fig. 7 Mode and function breakdown of Garmin™ 920XT multisport watch

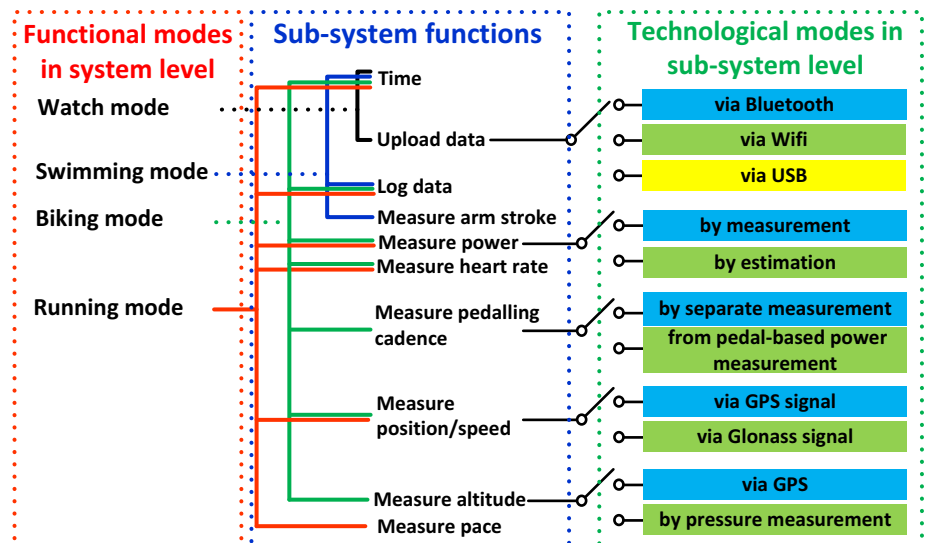


Table 1 Examples of multi-modal products

Examples of multi-modal products	Observed multiple functions	Observed multiple technologies	Domain
A bicycle lock that also serves as a carrier rack (Gu et al. 2004)	To lock the bike or carry items		Mechanical
A morphing airfoil capable of high- and low-speed flight (Schultz et al. 2010)		To produce lift at low speed or high speed	Mechanical
A mountain bike front suspension with climb, trail, and descend modes (Fox bike suspension 2014)		To suspend the chassis with stiff, medium, or mild damping setups	Mechanical
An automobile's transmission with manual and automatic modes		To shift gears automatically or manually	Mechanical
A vibratory feeder that can serve as both a linear and spiral feeders (Zhang et al. 2014)		To vibrate with linear or spiral functional unit	Mechanical
A washing machine that can do washing and spinning separately	To wash or spin clothes		Mechatronic
A washing machine that does laundry in normal, quick-wash, and economic modes		To wash clothes with different motion, temperature, timing, and so on	Mechatronic
A pickup-SUV-convertible concept car (Li et al. 2008)		To transport with open or closed storage compartment	Mechatronic
A hybrid vehicle with fuel and electric drives (Xu et al. 2005)		To transport with fuel, electric, or combined drive	Mechatronic
An LM555 timer configured to generate time delays or oscillation signal (Texas instruments 2014)	To produce time delay or oscillation		Electronic

4 The key drivers of multiple modes

For a complete product provided to the users, functionality is a technical issue and refers solely to the product (McNamara and Kirakowski 2006). As Fig. 8 shows, redesigning a product by function and technology multiplications basically leads to multiple functions and improved performance. Functionality is demonstrated by the product's provision of the needed functions and sufficient performance. Combining multiple functions and technologies into one product introduces reuse of system resources among modes.

After investigating the concept of mode in its configuration and purpose, the key drivers of incorporating multiple modes remain an unsolved question. What are the significances of combining modes with expanded functions and technologies? Inevitably, when multiple functions and technologies incorporate multiple modes, the integrated products lower total cost and further benefit environmental friendliness. The increased efficiency in reusing system resources can also be perceived. However, these improvements exist in numerous design initiatives. To this extent, the significance of having multiple modes does not differentiate itself from well-designed products. We propose that usability and robustness are the key drivers and major significance when multiple modes are implemented. When the abundance of functions and technologies is

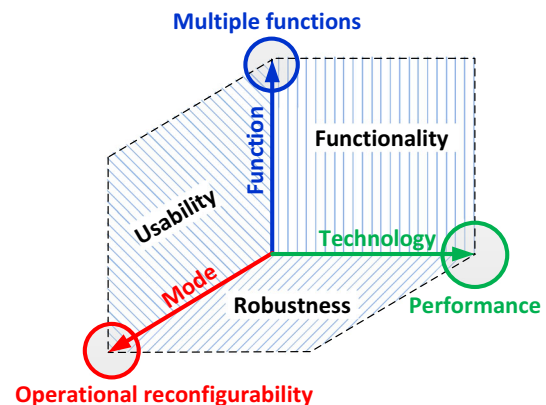


Fig. 8 Key drivers of redesigning products toward multiple functions, technologies, and modes

managed under multiple modes, the multiple modes present *operational reconfigurability*. The operational reconfigurability is demonstrated by the ability to switch between different configuration states during the operation stage.

4.1 Robustness

Robustness is achieved by selecting appropriate technologies during the operation stage. To deal with the changes of environment, task specification, and user preference, multiple technologies embodied by different system

configurations are incorporated to achieve the performance requirements. Ferguson et al. (2007) defined robustness performance flexibility as “the system changes dictated to maintain an optimal performance, or maintain a required level of functionality, in response to unpredicted factors.”

Zhang et al. (2014) defined and quantified robustness as the capability of a product to resist the influence of uncertainties on product performance. A design configuration can achieve higher robustness when it incorporates more operation configurations that have high probabilities. In other words, high robustness indicates the collection of most-needed, high-performance technologies. This approach suggests that the robustness achieved by adopting multiple system configuration states will not only provide a backup means of working, but also increase resilience to the changes and uncertainties.

4.2 Usability

Usability is the characteristic of the interaction between the user and the product (McNamara and Kirakowski 2006). Both functionality and usability include usefulness of the functions. However, usability demands effectiveness, efficiency, and satisfaction when the goals specified by the users are achieved (ISO 1998). Hence, the reconfigurability of multiple modes offers a bridge from functionality to usability.

A well-designed multi-modal product should be able to conduct mode transitions with minimal human effort. The step between functionality and usability is at the quality of tackling different situations facilitated by multiple modes, as shown in Fig. 8. Specifically, regarding the changeable configurations, the usability on a multi-modal product to a large extent depends on the elaboration of control logic and the switches, which interprets the different tasks into configuration states. The efficient and effective organization of the system configuration states by successfully achieving both mechanical and software engineering will ultimately provide convenience to the users. Nielsen (1994) and Hornbæk (2006) have provided a framework for the study and measurement of usability.

Basically, the users’ needs are not explicitly expressed as functions interpreted by engineers such as displaying time, measuring heart rate, and positioning, but simply and ambiguously as a fantasy of wearable training assistance. In the sport watch example, the purpose of training assistance is literally interpreted as training mode. Functionality is demonstrated by the accessibility of current time, heart rate, and position. However, manually activating each of the functions would require trivial effort. Therefore, the prescribed activation of these three functions represents usability. Hence, the information of time, heart rate, and position is automatically provided on the display after the

training mode is activated. When the user no longer needs training assistance, usability is represented by a unique time displaying function. As one of the key features of mode, usability is primarily demonstrated by the effortless and effective user operations during mode transitions.

5 The design of multiple modes

In Sect. 3, we established transitional functional models for multi-modal products. Modes have been resolved as configuration states that serve specific purposes. However, the overall system described by a number of functional models is still dependent on time. In this section, we strive to settle the time-dependent description into an explicit and time-independent functional model by incorporating switches and control logic. The idea is to derive the principle solution via a reconfigurable functional model, both governed by control logic. The framework of conceptual design that involves and enables changeable configurations is an essential complement to engineering design in overall system scale. However, we are not able to derive a methodology for the design of modes in an elementary system scale, since these tasks are highly dependent on the knowledge in particular domains. Therefore, this section continues the design of modes in an overall system scale.

5.1 Reconfigurable functional model

Figure 9 resembles a generalized transformation from a transitional functional model to a reconfigurable functional model for a functional multi-modal system. The multiple functions are indirectly organized by the mode selection as a system input. The selection is interpreted by the control logic, which abstracts modes into the actuation of switches. Similarly, a generalized transformation for a technological multi-modal product is illustrated by Fig. 10. The switchable paths between the input and output are also organized by switches and control logic. Apropos to these conditions, the switches stand for a variety of digital and analog manipulations that enable the control logic to undertake reconfiguration.

The two schemes derived in Figs. 9 and 10 are proposed as a *reconfigurable functional model*. It has a twofold significance for the existing design methodology:

- It determines a time-dependent system description that facilitates further design process.
- It specifies the later domain-specific design process by separating mechanical and control design.

The example of the sport watch has only two modes that organize three overall functions. Nevertheless, in complex products, where configurations reside in a large number of

Fig. 9 Deriving a reconfigurable functional model for a functional multi-modal product

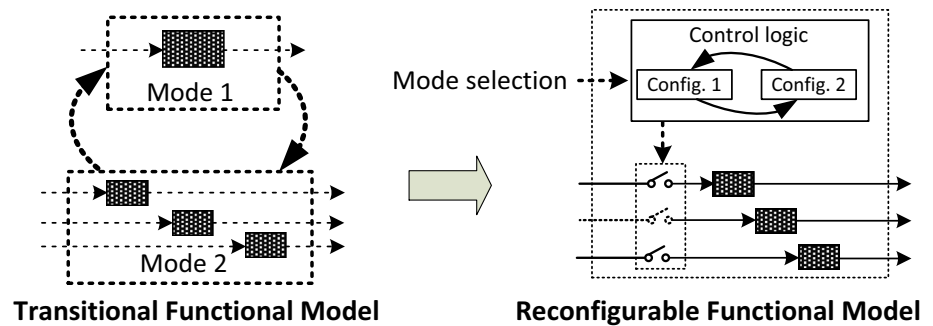
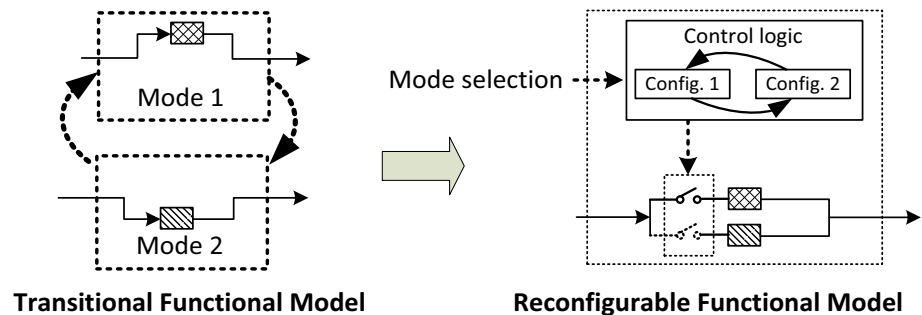


Fig. 10 Deriving a reconfigurable functional model for a technological multi-modal product



functional models, listing all the possible configuration states would be an inefficient way to describe the system and predict its behaviors. Yet, the transitional functional model needs to be consolidated to further facilitate the design process. Therefore, the form of the time-dependent functional model in Figs. 9 and 10 is essential for deriving the principle solution.

A reconfigurable functional model is the main feature of a multi-modal product. Compared to the verb-object function descriptions for manipulating material, signal, and energy flows formalized by Stone and Wood (2000) and Hirtz et al. (2002), multiple modes manipulate the functions rather than the flows. Therefore, reconfigurable functional models require a level of hierarchy above the functions that the conventional functional models include. Buur (1990) adopted a set of secondary functions to undertake mode transitions, but the variety of the secondary functions tends to excessively complicate function models and diverge from the functional basis. For simplicity, we point out only two manipulations that enable the switch between configuration states:

- *Activation/deactivation*: what the needed sub-functions are.
- *Connections*: how the sub-functions are connected.

In order to resolve the two manipulations above, we propose two methods for establishing functional models specifically for multi-modal products, shown as merging

method and clustering method in Fig. 11. The merging and clustering methods represent two views of the complexity introduced by multiple modes. The former corresponds to our perspective of integrating multiple products into one artifact. The latter aims to expand the product functionality and promote flexibility on the basis of abundant system resource, which allows the system resources to be further exploited by alternative configuration states.

Despite the differences, both of the methods are introduced as amendments to the systematic design methodology created by Pahl et al. (2007). For this reason, the terminology *function structure* will be used instead of functional model in the presentation of the two methods. The techniques in function modeling of reconfigurable mechatronic products are based on the implementations undertaken in the past two decades. The sub-functions can be selected on a functional basis, which formalizes various functions into a standardized format (Stone and Wood 2000; Hirtz et al. 2002). To elaborate the control logic, the procedures may adopt the functional basis formalized by Rajan et al. (2003) and Nagel et al. (2008a). The research in hybrid systems and control has been studied by the cybernetic community (Guckenheimer and Johnson 1995; Mostermann and Biswas 2000; van der Schaft and Schumacher 2000; Goebel et al. 2012). As a fusion across the mechanical and control domains, the methodology in function modeling mechatronic products refers to Chen et al. (2002) and Jayaram and Chen (2003)

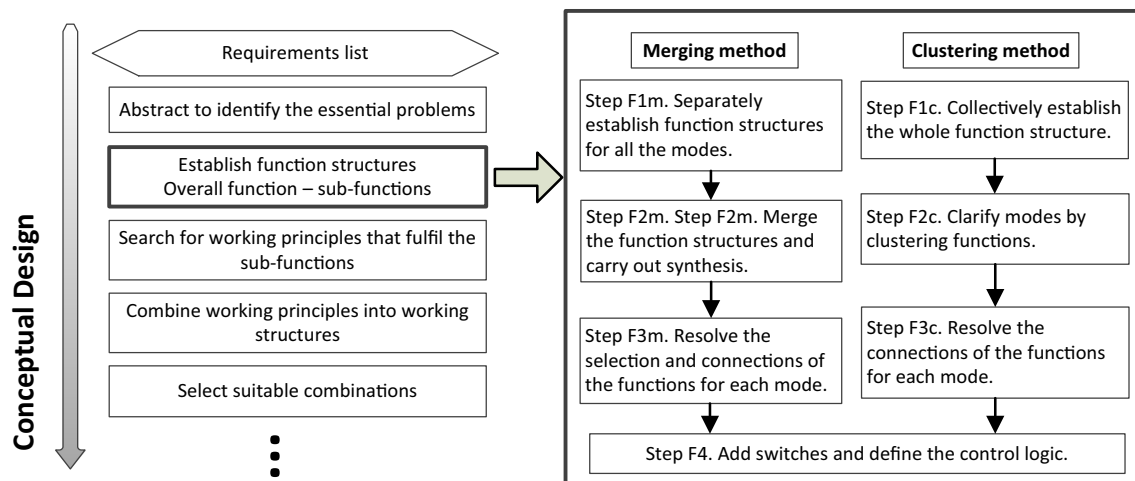


Fig. 11 Merging and clustering methods for elaborating function structures

5.1.1 Merging method

The merging method provokes functional synthesis when multiple modes are established for achieving an “all in one” effect. The synthesis step aims to avoid the redundancy and conflict induced by integration. The final goal is to let the new product efficiently inherit the functions or technologies from the original products.

The four steps in the merging method for establishing a function structure are shown in Fig. 12 with an example of an imaginary watch in Fig. 5. To emphasize the overall topology of the function structure, the functions are not broken into a functional basis. The technological multi-modal watch combines and switches digital and analog technologies for the unique overall function of displaying time. Two separate products, a digital watch and an analog watch, represent two switchable modes. Therefore, in establishing the function structure for the integrated product, decomposing each mode into sub-functions is performed in Step F1m. This step involves elaborating function structures for the original products separately. After this step, the designer discovers two identical functions that generate oscillations, shown in the dashed box. Therefore, in the next step, the two functions are merged. Generally, in Step F2m, the merging and synthesis among the function structures shall not be limited to the identical functions, but provide a comprehensive investigation of the potential commonalities among the modes. A detailed commonality screening method is introduced by Hofstetter and Crawley (2013). Step F3m resolves the activation/deactivation and connection manipulations at each transition. The designer restructures the configuration states according to his/her experience and physical laws. Next, in Step F4, switches and the roughly defined control logic are added to activate and redirect the unique sub-functions. The

roughly defined control logic indicates the system configurations defined by the transitional functional model, notwithstanding the detailed algorithm and software toward specific sub-systems.

By now, the reconfigurable functional model reaches maturity by reconstructing the function structure for all the modes while allowing the reuse of functions. The four proposed steps promote synthesis among the functions across modes. Step F2m and F3m are critical in determining the quality of the final principle solution in terms of cost, weight, and size.

5.1.2 Clustering method

The clustering method is a practical method for establishing modes based on the abundance of system resources. When a system or product has great redundancy in functions or technologies, the organization of system resources provides tremendous potential in expanding the product functionality. A significant example is the development of smart phone applications in recent years. The mobile phone manufacturers reserve the access of on-board devices to the software developers, enabling the phone to transform into a highly flexible product. Under the software’s regime, a mobile phone reveals various configuration states for multiple functions and technologies.

Back to our sport watch example, the two modes can be regarded as two clusters of functions. (This is not to deny the viewpoint of the merging method, from which the watch is regarded as a synthesis of a normal watch and a training assisting device.) As shown in Fig. 13, in Step F1c, the designer realizes three necessary functions for the purpose of assisting training. The whole function structure is then elaborated. In Step F2c, isolating the time

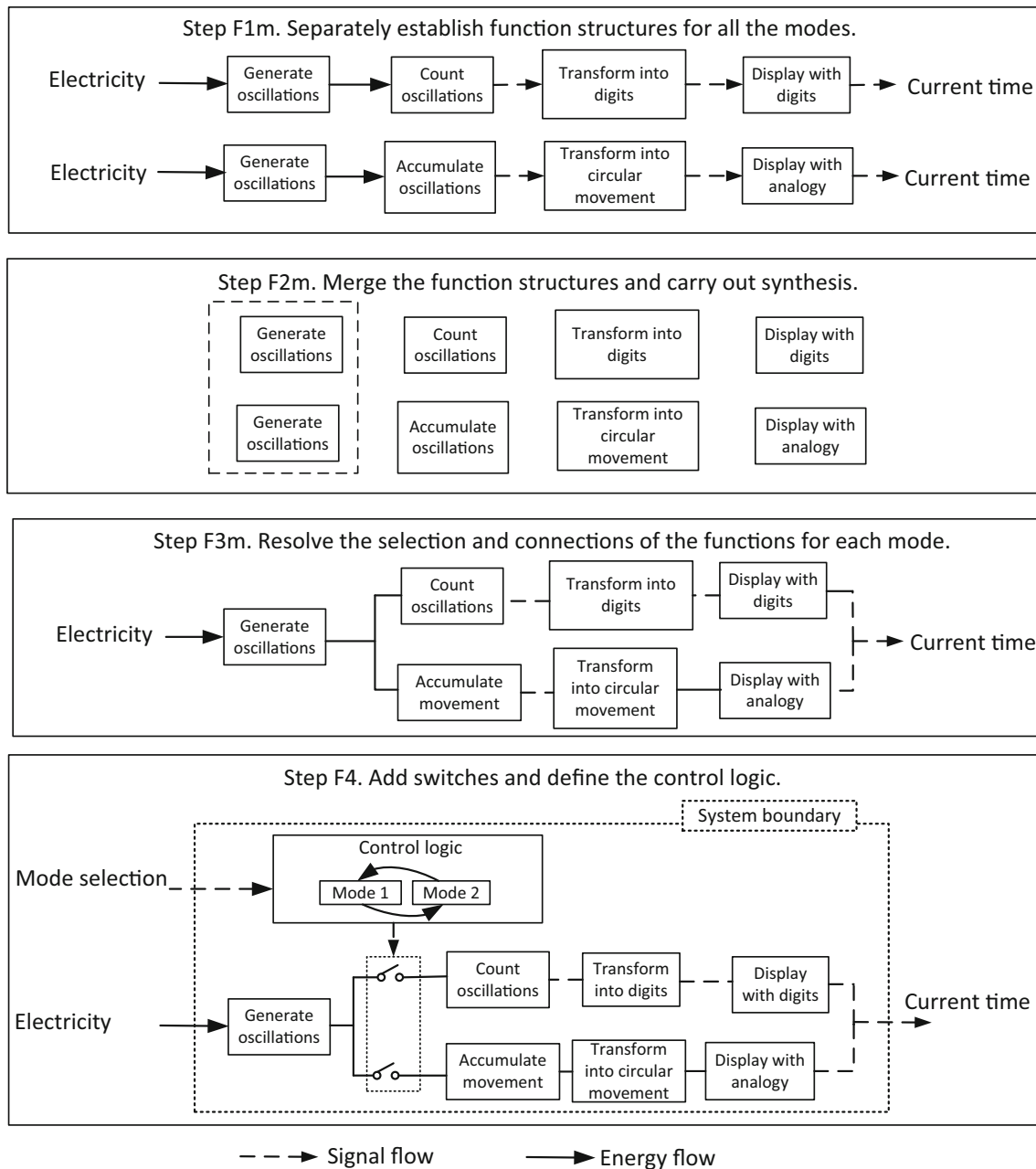


Fig. 12 Deriving the reconfigurable functional model for an imaginary technological multi-modal watch

displaying function indicates the typical purpose of a normal watch, so that the user may also use it as a normal watch. The divergence of the two configuration states creates two clusters of functions. Generally speaking, modes are selected among all the permutations of configuration states. Step F3c facilitates the function clustering by establishing connections between functions. In this step, the designer shall also anticipate all kinds of circumstances in which the user may configure the system. At last, the step of adding switches and defining the control logic is identical to Step 4 in the merging method.

5.2 Principle solution

The specification of each principle facilitating function reuse and the general control logic shall be resolved in the principle solution. The consequence of multiple modes to the principle solution exists in the following aspects:

- The principle of a reused function must be sufficient for all the modes.
- The principle may need active adjustments to facilitate each mode.

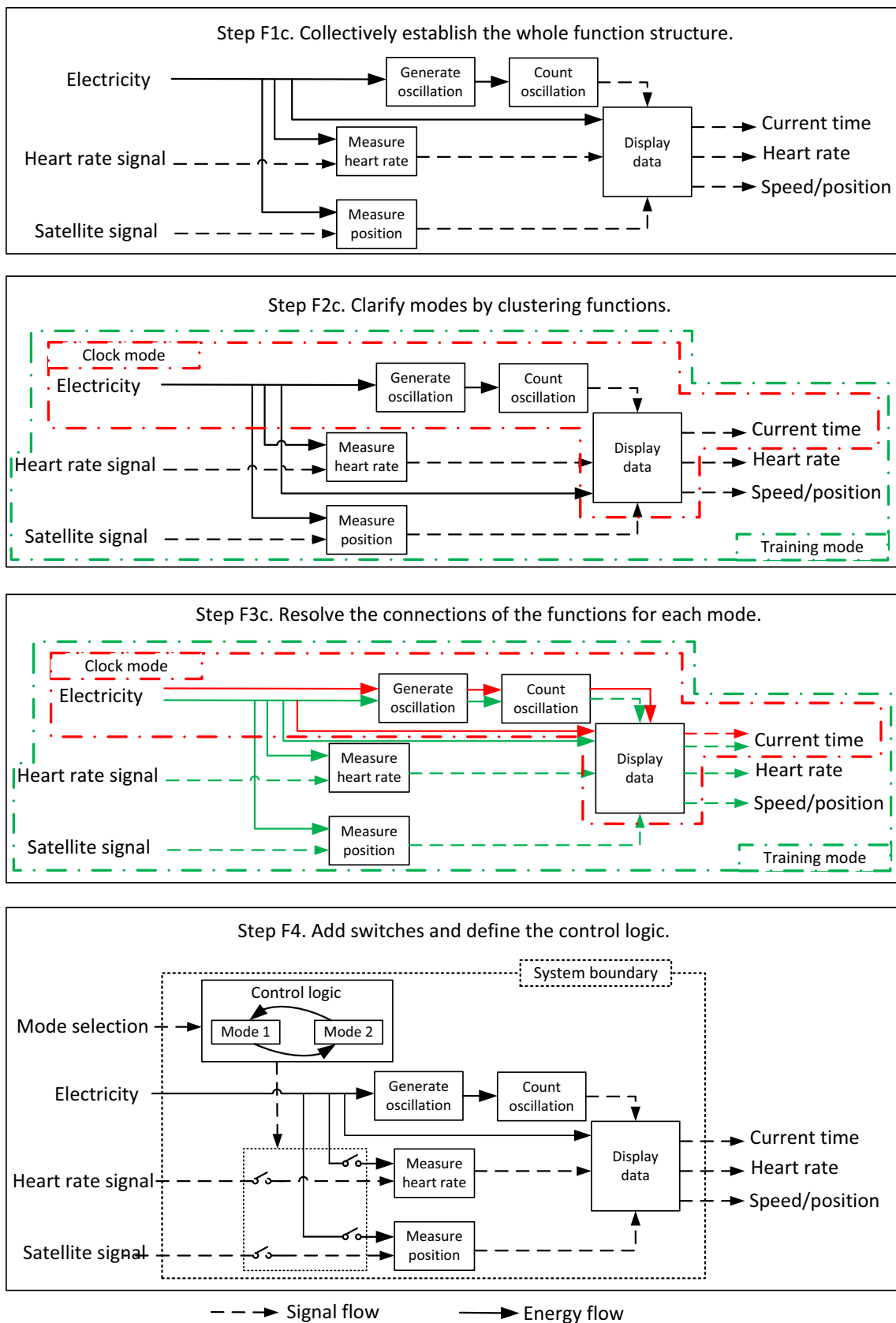


Fig. 13 Deriving the reconfigurable functional model for a functional multi-modal sport watch

Together with the activation/deactivation and connection manipulations, adjustments should also be conducted at transitions. We propose three steps P1, P2, and P3 in Fig. 14 as the amendments to the procedure of firming up principle solution variants for multi-modal products.

In Step P1, the technical specification of each principle shall satisfy all the modes. In addition, the designer shall reserve access to adjusting these principles for varied configuration states. In the sport watch example shown in Fig. 15, the sub-function of displaying data is shared by both modes. Being the principle to this sub-function, the digital display must be specified to display all the information provided by the oscillation counter, heart rate sensor, and positioning sensor. Moreover, it is necessary to conduct an adjustment on the digital display, so that the information about heart rate and position is activated in accordance with the actuation of the switches. The adjustment is expressed as the arrow between the controller and digital display in Fig. 15. Step P2 inherits all the necessary activities in generating principle solution variants initially introduced by Pahl et al. (2007). Step P2 finally derives the working principles for each sub-function inherited from the function structure shown in Fig. 13. At last, Step P3 suggests transferring the switch actuations and adjustments collectively to the control system design, specifying the interface to control and software design.

In a broader view of mechatronic products, the design of sensing, feedback/forward control, and actuation may include sophisticated electronic and software design of many automated devices.

5.3 Temporal function clustering and function sharing

Since each mode indicates a cluster of functions, a multi-modal product exhibits a temporal clustering of system functions. Temporal clustering is proposed relative to the physical clustering of functions. Based on the sport watch example, these two ways of clustering are illustrated in Fig. 16 in forms of different mappings between sub-systems, functions, modes, and time. The temporal function clustering is illustrated by the mappings from modes to their functions. The physical function clustering, which provokes the phenomenon of modularity, is revealed by the mapping between the functional model and the physical model. Modularity reveals in this figure as either one-to-one or one-to-multiple mappings from subsystems in the physical model to functions in the functional model (Ulrich and Eppinger 2003).

A significant feature of temporal function clustering is the function overlap in the functional model. The overlapped functions exist as reused functions on a multi-modal

Fig. 14 Amending steps for deriving principle solutions of multi-modal products

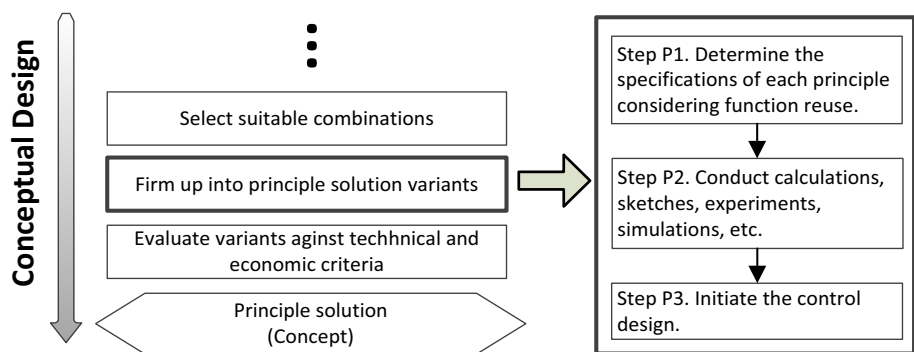
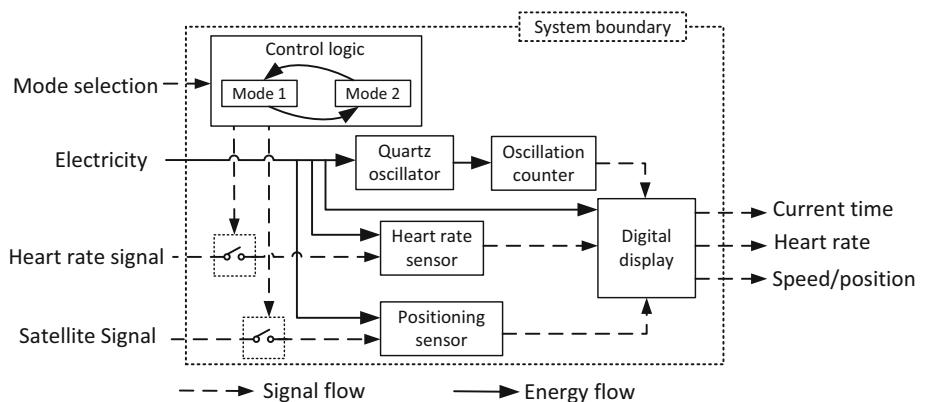


Fig. 15 Principle solution of a sport watch



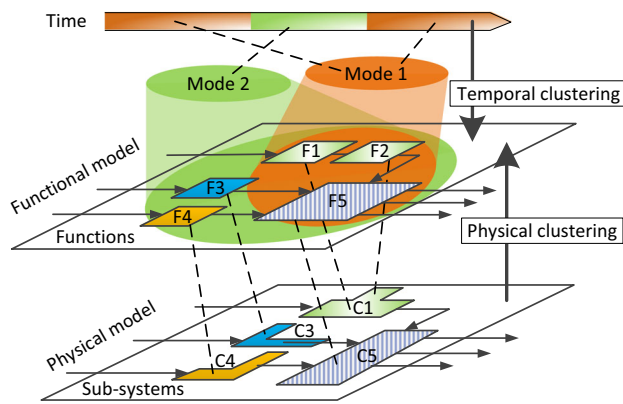


Fig. 16 Temporal and physical function clustering

product. However, the physical clustering does not allow an individual function to be overlapped by two sub-systems, as no single function in a functional model is mapped to multiple sub-systems in Fig. 16.

On a multi-modal product, the overlap in temporal function clustering provokes the phenomenon of function sharing, which was initially defined as a mapping from more than one element in a schematic description to a single element in a physical description by Ulrich and Seering (1992). Function sharing exploits the secondary function of one physical object. In Fig. 16, the description of function sharing matches the mapping from sub-system C1 to functions F1 and F2. In this sense, the original concept of function sharing indicates sub-system C1 shared by functions F1 and F2. The temporal function sharing discovered on multi-modal products indicates the shared/reused functions F1, F2, and F5 by both Mode 1 and Mode 2.

6 Conclusion

Although having multiple modes has been a common phenomenon in modern products, the term “mode” has been rarely mentioned in systematic engineering design. In this research work, we attempted to discover the concept of mode and how the designer elaborates modes in the conceptual design process. The attempt aims to reconcile the conceptual design considering the reconfigurability induced by multiple modes and their transitions.

We clarified mode as a switchable system configuration state made for a specific purpose of either an additional function or technology. Thus, the complexity of a large variety of products can be measured in the proposed function–technology–mode paradigm. Next, the key drivers of inventing multi-modal products were discovered to be not limited to the efficiency achieved by reuse, but also projected from the purposes of functions and technologies

to the improved product usability and robustness. The nature of mode is further observed as a temporal clustering of functions, which enables temporal function sharing. Regarding the conceptual design process of multi-modal products, we provided two methods for deriving the function structure, merging and clustering, together with three additional steps for deriving principle solutions.

After our first attempt in defining mode for a broad range of multi-modal products, areas that need to be explored remain. First, the conduction of transitions was confined to switches and control logic, which leaves the adjustment ambiguously defined. This indicates that mode is not discussed with respect to the fidelity of sub-systems. Secondly, human operation is only limited to mode selection, notwithstanding the complex configuration undertaken by human machine interactions. In other words, the border between mode selection and human operation is not clearly defined. In addition, due to the topic of conceptual design, our future work will also focus on the influence of multiple modes on embodiment and detailed design, especially in product architecture.

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