A REVISION OF PRODUCT ARCHITECTURE DESIGN FOR MULTI-MODAL PRODUCTS

Liu, Cong (1,2); Hildre, Hans Petter (2); Zhang, Houxiang (2); Rølvåg, Terje (1)
1: Norwegian University of Science and Technology, Norway; 2: Aalesund University College, Norway

Abstract

Integrating a number of products into an all-in-one artefact is a common form of innovation. The integrated products can finally meet diverse customers' needs, adapt to changes in the task or environment, or improve performance. Very often, the expansion of functionality achieved by the integrated products is accomplished with multiple modes, which enable the product to operate in various configuration states. This paper investigates the phenomena and significance of having multiple modes in regard to product family design and platform-based product development. As a revision of product architecture, the authors claim that modes indicate different clusters of functions and modules at different times. More intrinsically, the modes are seen as a product or system divided by time. Multi-modal products promote innovative and efficient design by actively reallocating system resources. As an example, the design of a dual-mode swimming climbing underwater robot is examined to verify the assertions.

Keywords: Product Architecture, Design theory, Mechatronics, Mode, Reconfigurable design

Contact:
Cong Liu
Aalesund University College
Faculty of Maritime Technology and Operations
Norway
lico@hials.no

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1 INTRODUCTION

The complexity of modern mechatronic products has been observed from two categories of product innovations. The first is integration, which promotes the expansion of functionality by merging multiple products into one artefact(Siddiqi and de Weck 2008). The resulting all-in-one products are responses to the increase of demanded functionality. Examples of this sort of innovation are combined washing-drying machines, multifunctional drink machines, and hybrid electric vehicles. The other category is reconfiguration, which aims to exploit new functions and improve performances by means of new organizations of system resources. This initiative is applicable for products that are already complex, especially programmable devices. A typical example is the smartphone, which can function as numerous devices by reconfiguring its on-board hardware using various software applications.

A common mechanism of operation in these complex products is the use of multiple modes. A multimodal product is identified by its reconfigurability during the product's operation. When a change in task or environment occurs, they system actively reallocates its resources by shifting to another mode instead of keeping the system resources in a fixed configuration. The reconfigurability found in multimodal products enables the product to meet diverse customers' needs(Haldaman and Parkinson 2010) and maintain optimal performance when unpredicted factors occur(Ferguson et al. 2007).

An evident drawback to these complex systems is the increased difficulty and cost of their development. Yet market competition forces companies to reduce development time. To leverage complexity and limited development time, one of the most significant strategies in product architecture design is modularity. Based on modularity, product platforms are created when new products are developed with a common set of knowledge, processes, and standards(Ulrich and Eppinger 2003, Jiao et al. 2007). Therefore, investigating the interactions between modularity and system reconfigurability is an indispensable step in multimodal product research.

The necessity of research in architecting multimodal systems is also observed in two aspects. First, the awareness and design theory of multimodal systems significantly lag behind the state of the art of product development, since adopting multiple modes has long been a common design among modern mechatronic products, such as electric home appliances, automobiles, and consumer electronics. In existing design methodologies, products are considered and architected for fixed configurations. A systematic method to involve and enable the design of changeable configurations is lacking. Second, the science of control and cybernetics has developed sufficient theory and methods to describe reconfigurable systems. Engineering design theory may undergo considerable development if it can refer to and incorporate the knowledge developed in these fields.

This paper studies the product architecture of multimodal products. Our focus is on how the physical modules implement the functions in a given reconfigurable functional model. Specifically, we will investigate how modes exist in modular architecture and the significance of having multiple modes in architecting a product. Two examples of mechatronic product design are examined with regard to the proposed assertions: the architecture of a hybrid vehicle power train is scrutinized during the discussion, and at the end, the modular design of an innovative swimming-climbing underwater vehicle is presented.

2 BACKGROUND

The research works that touch most nearly upon the topic of multimodal products address reconfigurable systems. Reconfigurable systems can reversibly achieve distinct physical configurations (or states) through alteration of system form or function in order to achieve a desired outcome within acceptable reconfiguration time and cost(Siddiqi et al. 2006). Modeling and conceptual design of this kind of system were further studied(Siddiqi and de Weck 2008). Form-focused studies on transformation promoted innovative product ideas(Singh et al. 2007, Singh et al. 2009). Ferguson et al. summarized and defined reconfigurable systems and suggested a few research questions, including their influence on systematic design processes, effective leveraging of product family design, and the integration of cyberinfrastructure. These three questions illuminate the critical research fields that our research is built upon.

The systematic design methodology is a step-by-step approach that guides designers from particular design tasks to final successful products. 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). At the end of the conceptual design phase, the basic technological working principles have been established. In systematic design methodology, the design of reconfigurability is constrained, since considerations regarding transitions in engineering design are found to be coherent to either logic (Pahl et al. 2007, Ullman 2010) or the function basis, such as to couple, actuate, stop, and so on(Hirtz et al. 2002, Chen et al. 2002).

After the conceptual design, product architecture is the scheme by which the functions are arranged into physical components and how they interact(Ulrich and Eppinger 2003). Simply speaking, the ultimate goal of product architecture is to enable a set of physical objects to fulfil the functions as expected. In fundamental cases, mapping from a function to a physical component is described as decomposing the function until it matches a design in the catalogue(Umeda et al. 1990). In the context of modularity and product platform, the search for a physical building block that fulfils a particular function is very often conducted by referring to the company's product platforms. Companies benefit from leveraging new product development by using proven solutions in terms of economy, reduced development time, complexity, and risks(Meyer and Utterback 1993, Kimura et al. 2001, Simpson 2003, Jiao et al. 2007, Nanda et al. 2007, Ki Moon et al. 2009). By developing and evolving new products in this way, similar products share a common product platform and yet possess specific features or functionality in a product family(Meyer and Lehnerd 1997).

Jiao et al. categorized product family into scalable and configurational product family design(Jiao et al. 2007). The architecting process illustrated above, in which new products are created by adding, substituting, or removing one or more functional modules, conforms to the configurational product family design. In this category of design, the mapping from functional elements to physical building blocks has been intensively focused. Based on the phenomenon of function sharing, which suggests implementing multiple functions in one physical component or module(Ulrich and Seering 1992), a variety of methods have been developed to derive optimal solutions for modularization, including the Modular Function Deployment (MFD) by Ericsson & Erixon(Ericsson and Erixon 1999), Design Structure Matrix (DSM)(Hölttä-Otto and de Weck 2007, Eppinger and Browning 2012), and heuristics for grouping functions for each module(Stone et al. 2000).

In cybernetic and control sciences, multimodal systems have been intensively studied under the topic of hybrid dynamical systems. In this community, a multimodal 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, a study of variable-structure systems was done by van der Schaft and Schumacher(2000).

3 WHAT IS MODE?

Mode is a switchable configuration state that a system is configured for a specific purpose. Modality is the quality of operating a system in multiple modes. Ferguson et al.(2007) emphasizes that reconfigurability should enable the system configuration to be changed repeatedly and reversibly. In the functional level of a multimodal product, the change of a configuration is observed at the different configuration states. However in physical level, the product has only one resolved physical configuration that is constructed with the same group of subordinate components.

In the context of platform-based products and modular product architecture, we assume all products are physically architected with modules, despite some other necessary trivial components and parts. The term "module" is valid for all the building blocks that physically construct a system, including the trivial components, and parts. The term "subsystem" is used to mention the hierarchy between a system and its subordinate systems.

In this section, the product architecture of multimodal products is revised by observing the correspondence between functions and modules.

3.1 Reconfigurable functional model

The drive train of a hybrid electric vehicle is a typical example of a multimodal system. In the upper diagram in Figure 1, each mode is explicitly shown in a separate functional model. Basically, a hybrid drive train can produce torque using a single power train or both together. The three schemes are incorporated in Modes 1, 2, and 4. In addition, considering the potential of using the bidirectional conversion between torque and electricity, Mode 3 is elaborated to utilize the mechanical energy generated when the engine is idling(Ehsani et al. 2009). The four modes separately correspond to four switchable functional configuration states.

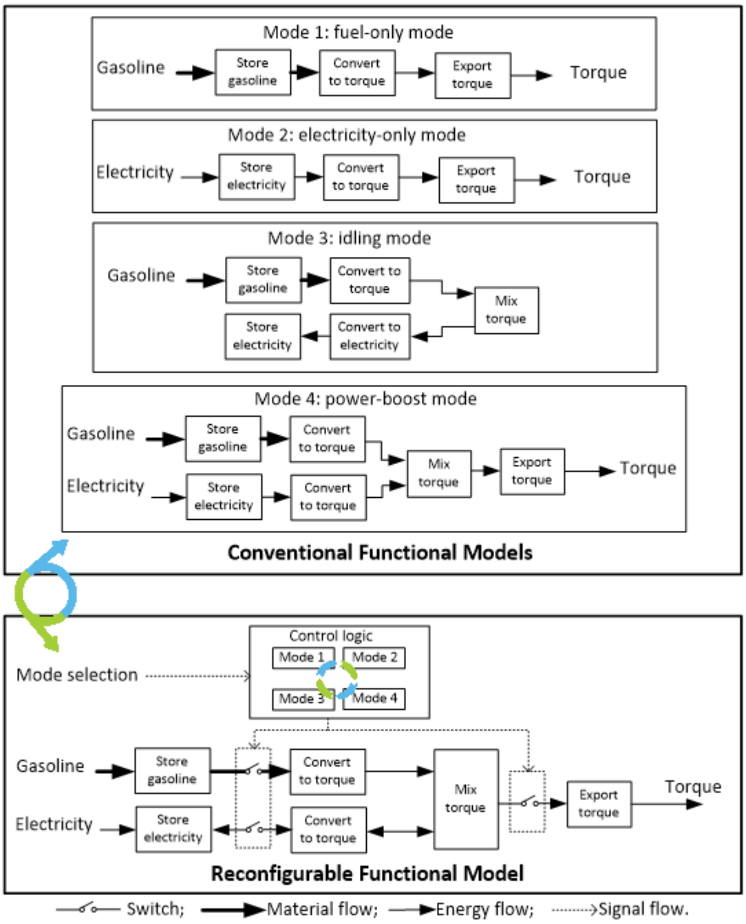

Figure 1. The reconfigurable functional model that operates in four modes

When designing a system with multiple configuration states, it is necessary to consolidate all functional models into one time-independent functional model that can support the product architecture design. The *reconfigurable functional model* of a typical hybrid drive train is shown in the lower diagram of Figure 1. This form of functional model assembles all necessary functions so that it can change itself into any of the four functional models. Each functional model resembles a unique configuration state.

Mode transitions are facilitated by the control logic, which interprets the mode selection signal into actuations of the switches. In a reconfigurable functional model, switches and control logic aim to conceptually manipulate the functional model. In reality, control logic and switch signs are abstractions of a variety of digital and analogue manipulations that enable the control logic to change the functional model.

3.2 Clusters of functions and modules

After the reconfigurable functional model is derived, the functions of a product need to be allocated to physical modules. Product architecture design usually occurs during the system-level design phase, after the basic technological working principles have been established but before the design of components and subsystems has begun(Ulrich 1995).

Figure 2 shows the correspondence between the reconfigurable functional model and the product architecture of the hybrid drive train, where functions and physical modules exist in the functional and physical levels, respectively. As the continuation of the conceptual design presented in Section 3.1, functions are embodied by the corresponding modules, such as the electric motor, fuel system, planetary gear unit, and so on.

A mode specifies a cluster of functions and modules in both levels. In the functional level in Figure 2, the four modes of the reconfigurable functional model are indicated by different shading. Each shaded cluster indicates one of the functional models given in Figure 1. In the physical level, modality also results in similar clusters of modules.

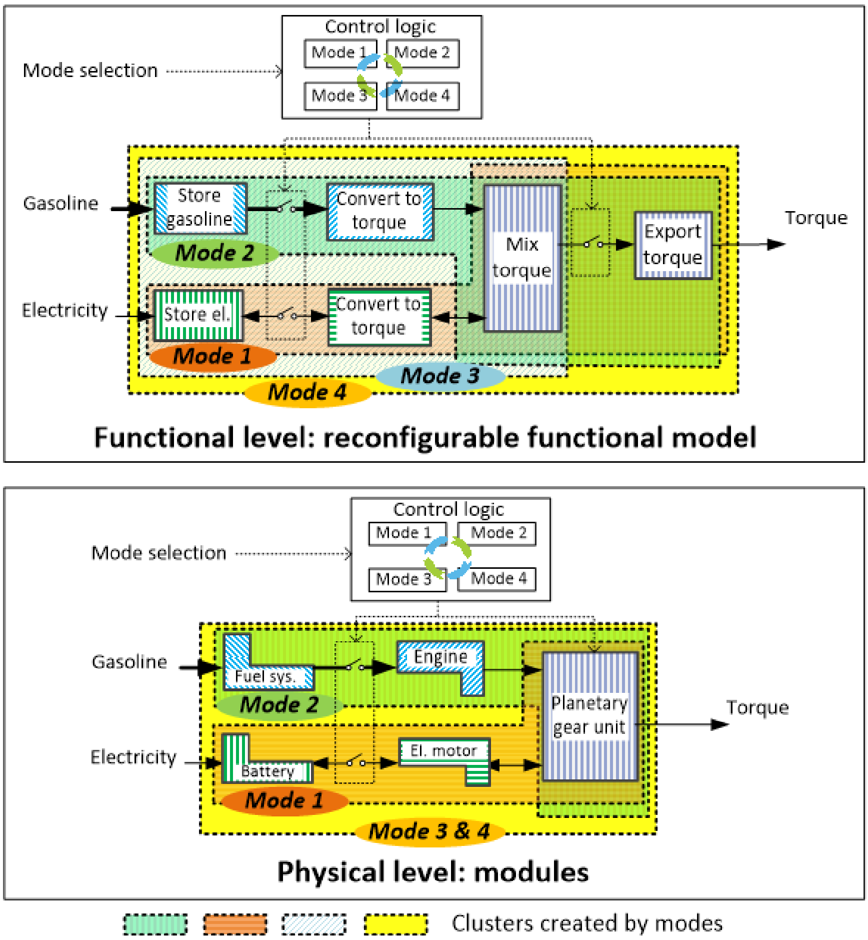

Figure 2. Product architecture of a hybrid drive train

The clusters caused by modality provoke a comparison with modularity, which also applies a function-clustering methodology in its design. Basically, modularity is the mapping between functions and modules(Ulrich and Eppinger 2003), illustrated in figure 2 through the identical texture of the "Store electricity" and "Battery" blocks in the functional and physical levels. By contrast, modality exists as different clusters of entities in both of these levels. In addition, we summarize two critical features of modality to delineate it from modularity in product architecture.

- **Temporal clustering.** Generally, modality presents a system divided in time. As the column of modes in Figure 3 shows, the whole operation time is compartmented by the modes. In contrast, modularity divides the system into physical modules in space.
- **Completeness.** A mode promotes the completeness of the whole process in a product. In Figure 2, each mode describes a full process from the input to the output in both functional and physical levels. In contrast to this completeness, a module covers only a section of the process in the two levels. Among the modules in Figure 3, not a single one is found to conduct a whole process.

Combining the above two features of modality, a multimodal product's physical configuration indicates the sum of its modules in space. These modules must be organized in different clusters to form different configuration states at different times. The configuration states, corresponding to the system modes, may have overlap on some of the modules. The overlapped planetary gear unit module in Figure 2 plays a critical role in accomplishing the four modes.

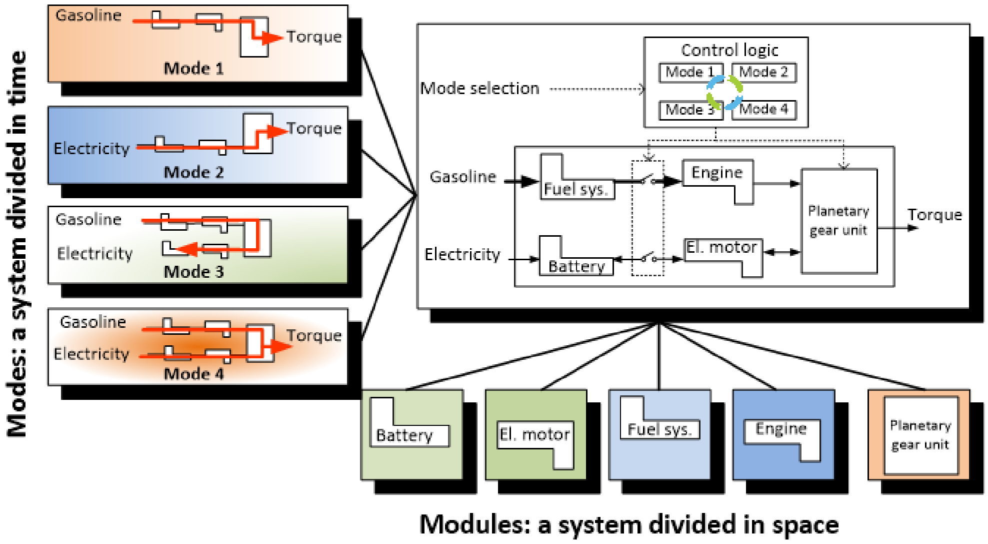

Figure 3. The physical configuration of a hybrid drive train divided in time and space

3.3 Reuse resulted from modality

In product architecture, in which substantial modules are focused, the significance of modality lies in the temporary reuse of modules. To differ from the reuse in modularity, we point out two features of the reuse achieved by modality.

- **Individual product.** The reuse of modality enables individual modules to contribute different configuration states of a product. In modularity, reuse may occur to the identical modules for a product family.
- **Operation time.** The term "temporary" means that the reuse is observed during the product's operation time in a relatively short time frame. The modules reused by different modes do not include recycling a module in its life cycle.

For example, the planetary gear unit module on a hybrid drive train is reused by all four modes at different times, shown in Figure 2. This temporary module reuse is actually efficient and flexible reallocation of system resources. More fundamentally, module reuse is caused by the commonalities among modes. To identify the commonalities among modes, a comprehensive commonality screening method has been introduced by Hofstetter and Crawley(2013).

In architecting multimodal products, the results of module reuse are found in both positive and negative sides. From the viewpoint of design outcome, reused modules promote simplicity by reducing the number of modules. Novelties, performance, and robustness are gained by implementing transformation(Singh et al. 2009) and reconfiguration(Haldaman and Parkinson 2010). In design practice, however, elaborating reused modules is a major challenge in designing multimodal products, especially when the modes have different requirements on a reused module. Haldaman and Parkinson mention that a reconfigurable system considers the worst-case scenario for each configuration(2010). This suggests the necessity of searching for or developing solutions when existing modules cannot satisfy the requirements of the reused modules.

4 CASE STUDY: A SWIMMING-CLIMBING UNDERWATER VEHICLE

A design task was presented to create a novel underwater vehicle prototype for locomotion on and around complex steel surfaces, such as the bow area on a ship hull. The robot should be able to transit between swimming and climbing modes by attaching itself to and detaching itself from the surface(Liu et al. 2013). In this section, the design work is introduced as a student laboratory project, in which the assertions from Section 3 will be examined.

4.1 Conceptual design

Figure 4 lists the major functions in each mode. The swimming mode needs one linear movement along the x-axis and three angular movements about x-, y-, and z-axes. In the climbing mode, the surface locomotion needs to be similar to that of a wheeled vehicle, which reserves a linear movement for propulsion in the z-axis and an angular movement about the x-axis for steering. The transitions between the two modes are naturally recognized by the attachment to and detachment from the surface.

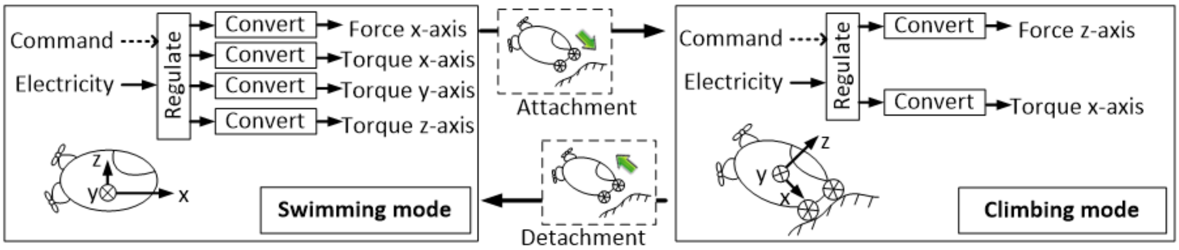

Figure 4. The major functions of the two-mode underwater vehicle

From the viewpoint of increasing module reuse, the design concept should utilize common actuators in both modes as much as possible. The final *Searazor* concept (shown in figure 5) was selected, which adopts only two coaxial wheels to minimize contact area on the ship hull. As the name *Searazor* describes, the standing position during locomotion on a curved surface is like that of a razor moving around a chin. The two-wheeled attachment enables the vehicle to fit high-curvature surfaces better than existing four-wheeled platforms. In the climbing mode, the vehicle is suspended and steered by two magnetic wheels. Surface locomotion is accomplished with synchronic and differential wheel motions. The drawback of the two-wheeled attachment is that the vehicle must balance its slender body from the back end with the vectored thrusters. The balancing torque is implemented by dynamically changing the orientation of the thrusters, governed by a feedback control system. In swimming mode, the vehicle is propelled and maneuvered by the two vectored thrusters. Torques and forces are achieved by regulating the thruster intensities and orientations according to the reconfigurable functional model in Figure 6.

Between the two modes, surface attachment is automatically engaged by the permanent magnetic wheels. The detachment transition is accomplished by aligning the thrusters in the backward direction and using them to pull the vehicle against the magnetic force.

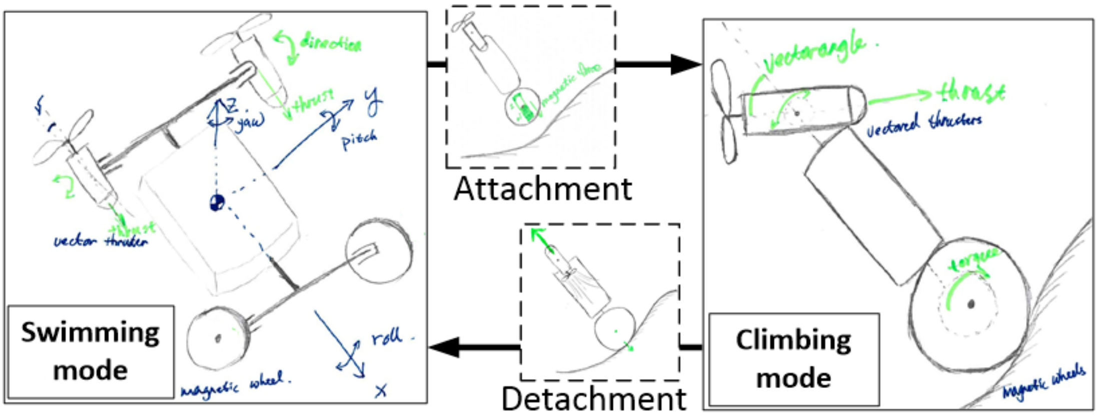

Figure 5. The concept of the Searazor swimming-climbing underwater vehicle

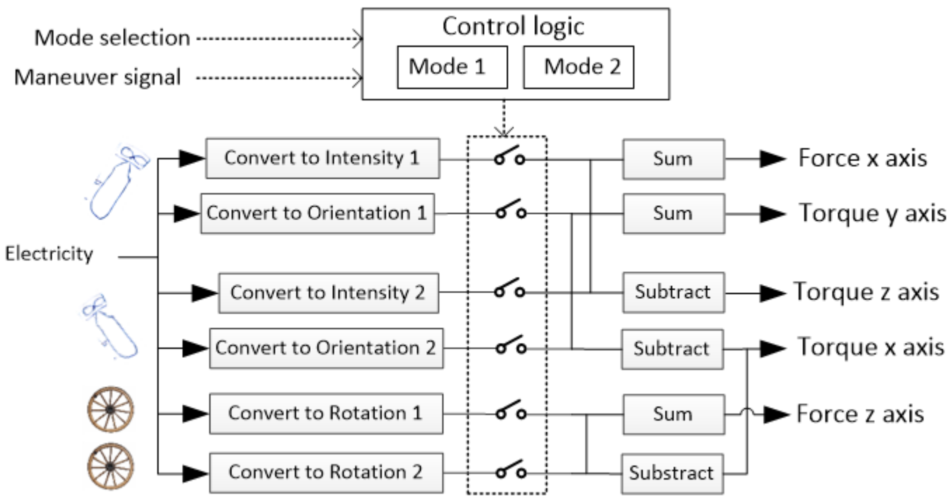

Figure 6. The reconfigurable functional model of the Searazor prototype

4.2 Modular architecture design

The product architecture design begins with the reconfigurable functional model derived in the conceptual design phase. In Figure 6, the six functions of converting electricity to forces indicate six independent actuations, which are categorized into three types of rotational actuations: the high-speed actuation on the thrusters, the high-precision actuation on the thrusters' bases, and the high-torque actuation on the wheels. To achieve a modular architecture, these three types of actuations were assigned to three types of modules, named thruster, pivot, and wheel drive modules, respectively.

In Figure 7, modularity design is observed by the one-to-one mapping from functions to modules (except the vehicle body, whose natural behaviors are described as the functions in yellow). For example, the function of converting electricity to Rotation 1 corresponds to Wheel drive module 1.

The swimming and climbing modes are expressed in the green and light-blue shades. Both of the swimming and climbing modes describe a complete process during different operation times. In the physical level, the overlapping area between the two clusters of modules indicates the reuse of thruster and pivot modules by both modes. The efficiency achieved by reusing the modules is perceived when compared to having extra modules used solely for balancing the vehicle in the climbing mode.

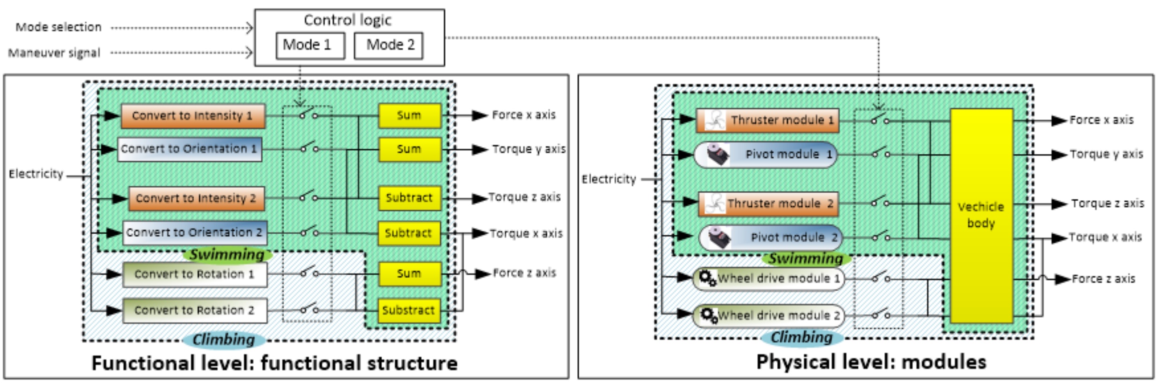

Figure 7. The modular architecture of the Searazor prototype

As a result of module reuse, the design of the four modules and the vehicle body must satisfy the requirements from all modes and transitions. For example, in the swimming mode, the range of thruster rotation is between −90° and 90°. However, the detachment transition requires full thrust to overcome the magnetic force of the wheels. Therefore, the pivot module must be able to flip the thrust to 180°. The design of the pivot module must cover both ranges. The challenge of designing multimodal products is perceived when the design of the swimming-climbing underwater vehicle must take the worst cases in each occasion into account.

The detailed design of the pivot and wheel drive modules incorporated PVC water pipes, as shown in Figure 8a. The PVC pipes provided reliable sealing, a wide range of dimensions, and standardized interfaces. The thruster modules were modified from bilge pump cartridges by adding a propeller and a clamp, shown in Figure 8b. Figure 8c shows the total mechanical assembly of the prototype.

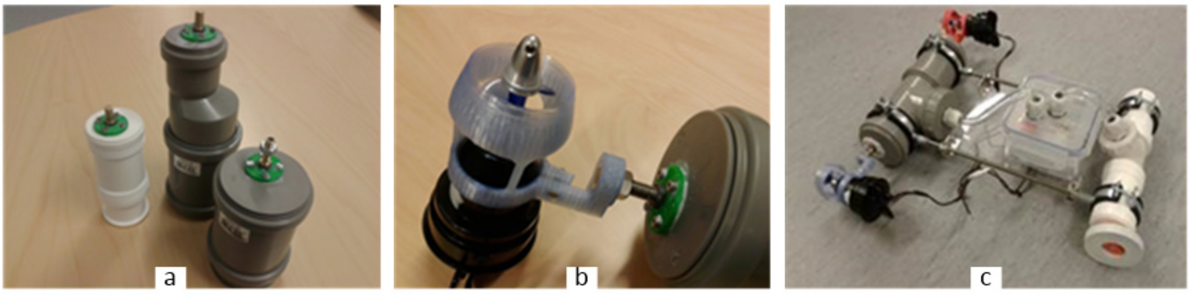

Figure 8. The modular design of the Searazor prototype

5 CONCLUSION

In this paper, we investigated the definition of mode with regard to product architecture. Mode was defined as both a functional and physical configuration of a product. Multiple modes on one product create clusters of functions and modules. The significance of modality is that modules can be reused at different times, so that innovative designs can be achieved through efficient reallocation of system resources. Investigations were made into modularity, in order to better integrate our assertions with modern product-family design. At the end, the assertions were examined through an exploration of the design of the *Searazor* prototype.

Generally, this paper has not dealt with how to organize modules to achieve multiple modes. In the near future, the method of constructing multimodal products with multimodal modules will be a focus of our research focuses.

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