Expressing Functionality Using Design Patterns, a Real-World Example

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Digital Engineering is a transformative strategy that leverages an integrated model-based approach to improve communication, decision making, design understanding, and acquisition efficiency of system development. As modern systems are derived from pre-existing systems, harvesting tacit knowledge from existing systems in a useful, model-based way will reduce the experiential learning and cognition required for new system development, contributing to a Digital Engineering transformation. This study enables such a technique by demonstrating the use of architectural theory in expressing tacit knowledge from existing systems and presenting that knowledge according to the model-based view offered by the Functional Architecture of Systems methodology. By validating the functional information expressed by the design pattern, this work solidifies design patterns as a critical component of a technical architecture and proposes a functional architecture viewpoint for describing mined knowledge in a usable, model-based, way suitable for archival in a modern knowledge management system.

I. Introduction

Digital Engineering is a strategy for transforming the engineering discipline by incorporating technology innovations into an integrated model-based approach [1]. Building on the success of model based systems engineering [2], the strategy seeks to improve decision making, enhance communication, increase understanding and flexibility in design, increase confidence in the developed capability, and increase efficiency of the acquisition process [1]. This study enables such a strategy by making expert knowledge from existing systems available in a model based format for use during formulation phase decision making. Previously dependent on experiential learning [3], decisions made during the formulation phase of the project lifecyle can lead to irrecoverable cost and schedule growth [4] [5]. By incorporating expert knowledge early in the project development lifecycle, decision making is improved and the cognitive load on the performing engineer reduced [6]. This work contributes to a growing body of research in design patterns [7] [8] by validating functionality expressed during the pattern mining process using the Functional

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Architecture of Systems methodology [9]. Using a model based systems engineering tool, the views offered by the FAS method are considered and an architectural viewpoint proposed.

The experimental subject for this research is a sequential development activity aimed at reducing the risk of catastrophic failure propagation in a multi-cell lithium ion battery for use in human spaceflight. Unmitigated, heat generated during thermal runaway of a single cell is transferred to exemplar cells or an external system leading to failure propagation and increased risk of system, user, and environmental damage [10]. Beginning with a proven design [11], the development experiment used a design-build-test approach to incrementally develop expert knowledge in battery and electrochecmical cell failure, mechanisms of failure energy generation and transport, and construction methods and materials that interrupt and manage those energy flows without disrupting the nominal energy storage and delivery, volume, and mass constraints imposed on the battery. The sequential development reused, modified, or replaced prior solutions based on observed performance, new material findings, and volumetric, mass, or external heat transfer challenges presented with each new design. Although energy density and external thermal transport requirements were increasingly restrictive with each subsequent development, the result was a steady increase in design performance and continual reductions in development time and cost. Deployed in low earth orbit in human spaceflight application [12], the experimental system provides a basis for a study in mining expert (tacit) knowledge using architectural theory.

Enterprise Architecture [13], the NASA Systems Engineering handbook [14], and ISO/IEC/IEEE 42010 [15] provide context for this work. Enterprise Architecture provides an ontology for a discussion of architecture [16] by providing a classification schema that organizes system views according to stakeholder perspective and interrogative [13]. This study of expert knowledge considers the architect (system), engineering (design), and technician (solution) stakeholder perspectives of the Enterprise Architecture ontology. The NASA Systems Engineering Handbook [14] and practical guidance in systems modeling [17] define a need for developing a logical expression of system design during the concept development and initial system modeling phases, respectively. The logical expression describes what it is to be something [14] and represents the what (or data) interrogative of the Enterprise Architecture ontology [13]. The intersection of perspective and interrogative is a view of the system, and the conventions for construction, interpretation, and use of the view is defined as a viewpoint [15]. Operating within this context, this study demonstrates the utility of pattern theory in logically describing expert design knowledge from a physical system according to an architectural viewpoint. Capturing this information in a Model Based Systems Engineering tool enables the resuse of this knowledge as part of the digitial engineering transformation.

This work applies the architectural theory of patterns to the experimental system to generate a design pattern in the form of a network diagram. The Functional Architecture of Systems [9] methodology is applied to the experiemental system and the resulting views are presented as SysML [18] model fragments according to the validated methodology. The resulting views are discussed in context of the design pattern and a functional architecture viewpoint is proposed. The remainder of the paper is organized as follows. Section II introduces the architectural theory of patterns and the experimental subject. Section III describes the pattern mining methodology, and Section IV presents the Functional Architecture of Systems methodology. Section V discusses the resulting views and viewpoints and Section VI concludes this writing.

II. Background

A. Archtitecture

Architecture is both a study of history and preparation for the future as modern systems share an essential purpose, to resolve debate (or failure modes) of older systems [19] [20]. Architecture describes the aesthetics of an observed system including such abstract notions as proportion, function, and behavior. Architectural theory is the method of describing the observed aesthetic [19]. Alexander's Pattern and Pattern Language is one such a methodology [21]. A pattern is a heuristic, or mental shortcut, responsible for human cognition [22], learning [23] [24], and problem solving [25]. In the context of Alexander's architectural theory, a pattern is a three-part rule for expressing a relation between a specific context, a problem, and a solution, and a Pattern Language is a network of related patterns [21]. By combining structural hierarchy and Gestalt Theory [26], Alexander developed a methodology for expressing the invisible parts of a system [27]. Intended as a means of describing the perceived organization and environmental adaptation of human dwellings, villages, towns, and cities [28] [29] [30], the architectural theory of patterns contributed to the development of object oriented programming [31], is a validated means of describing [6] and possibly communicating [30] system architecture, and has been identified as a critical component of a Reference Architecture [16].

A Reference Architecture consists of a technical architecture, a business architecture, and a customer context [16]. Technical architecture describes the technology solution in the form of a design pattern [16]. As a design pattern

addresses multiple perspectives of the Enterprise Architecture ontology [13] [8], describing the architectural perspective requires selecting a view [15]. A view is defined as a way of looking at the components and relationships of an architecture [32] from the perspective of specific system concerns [15]. The view is framed by a viewpoint that defines the conventions for generating the view [15]. The software domain has defined a number of architectural views including context, function, information, concurrency, development, deployment, and operations [33]. The function and information views are pertinent to a study of technical architecture [14], and the Functional Architecture of Systems (FAS) is a methodology for generating such a view using SysML [9]. Instead of using patterns, the FAS method analyzes use case activities to identify the functional hierarchy in a system, and expresses this structure as a function tree that describes the call nature of function to subfunction and subfunction to the physical domain [9]. As the FAS methodology is a validated method of describing functional architecture, the technique provides a basis for validating functionality expressed by pattern mining and offers a potential viewpoint for describing functionality in a technical architecture.

B. Experimental System

The development of three energy storage devices provide the experimental basis of this work. Each of the three devices uses a commercial lithium ion technology to convert electrical to chemical energy for storage and use during Extravehicular Activity as a part of NASA's human spaceflight program. Designed to accommodate different energy, mass, and volume constraints, the three batteries share a common format of electrochemical cell, a common cell packaging schema that enables ground replacement, and each mitigates the risk of single cell thermal runaway from propagating to other cells in the design or leading to flame or spark release to the external system. Thermal runaway occurs when an internal short circuit results in rapid heat accumulation due to uncontrolled discharge of stored energy resulting in the thermolytic decomposition of cell construction materials and the generation of both cell body heat and combustion products, or ejecta, released to the internal envrionment of the battery [34] [35]. With no prior experience in mitigating thermal runaway, the battery development was performed in a design-build-test process that enabled incremental knowledge development and growth. The sequential nature of the development activity resulted in continual refinement and adaptation of the geometry, materials, and energy management methods used in construction to deliver increasingly energy dense and higher performance batteries at increasing lower development cost and schedule. Each of the three batteries developed by this experiment are deployed in low earth orbit in human spaceflight application.

The design approach for the three batteries was derived from a heritage battery with nearly a decade of successful on-orbit performance [11]. Designed to enable ground refurbishment, a structural capture plate secures the terminal ends of each cylindrical electrochemcial cell, forming a rigid module with a known separation distance between cells secured within the module. The module included current collection elements that connect cell terminals in parallel and provide an interface for serialization by the internal electrical harness. The harness and module are shrouded by a metallic housing that provides external system interfaces, structural support for the module during transport, handling, and use, and ventilation features to enable pressure exchange with the surrounding environment. Propagation tolerance was achieved by managing heat flux between separated cells and preventing current inrush from cells electrically connected in parallel from increasing body heat of the failed cell. Heat flux was managed through a combination of insulating and conducting materials located within the interstitial module volume. A fusible element between cell terminal and electrical bus prevented parallel connected cells from discharging electrical energy into the failed cell, reducing heat accumulation in exemplar cells and reducing the energy input into the failed cell. Preventing flame and spark release from the battery housing required accomodating the intrinsic cell vent mechanism, creating an ejecta flow path through the unoccupied housing volume, and incorporating thermally conductive, flame arresting screens in the housing vent. Orienting the cell vent mechanism away from the housing vent maximized flow path length and encouraged contact and heat exchange between ejected materials and structural surfaces surrounding unoccupied regions in the battery, reducing flow stream energy and dispersing thermal energy within the battery. Incorporating thermally conductive screens of differing mesh size in the housing vent quenched spark and flame and prevented release of large particles entrained in the flow stream to the external system. The images of Figure 1 represent the heritage battery design and show the replaceable module secured in the structural housing to form a functioning lithium ion battery.

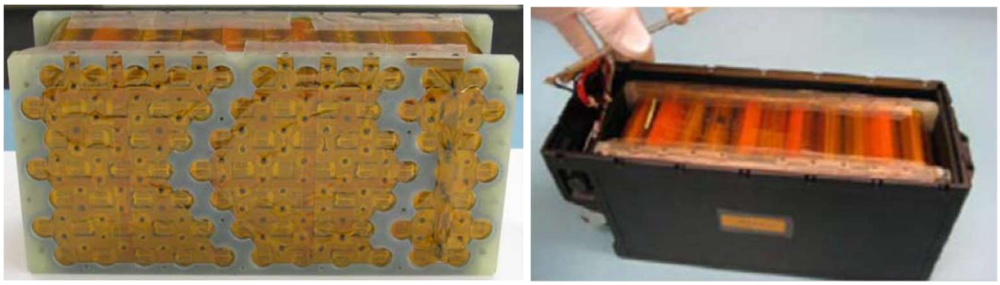


Figure 1 – Battery Module (left) installed in Metallic Structural Housing (right) [11]

III. Mining a Design Pattern

Pattern mining is the process of identifying expert knowledge used in problem-solving. Leitner [11] and Iba [12] proposed frameworks for the pattern-mining process that differ based on pre-existing knowledge. Iba's method incorporates the conversational interview as a means of accessing expert knowledge [36], while Leitner's method assumes the solution designer is applying the framework [37]. The example in this chapter relies on pre-existing knowledge and uses the approach from Leitner [37].

Pattern mining allows for tacit knowledge to be expressed as the logical balance of interacting forces achieved by an observed system. The three step process begins with a list of pattern candidates, progresses through candidate refinement, and ends with a holistic description of the observed design. Using the method of Leitner [37], intrinsic design knowledge provides an initial list of pattern candidates. Each candidate is assigned a hierarchial category based on three stakeholder perspectives of the Enterprise Architecture ontology [13], architecture, design, and solution. The second step of the mining process is performed in a digitial engineering application and begins by graphically arranging the candidates according to assigned level in the hierarchy, and connecting related candidates using straight, non-directional lines to create a network diagram. Candidate refinement begins by arranging and redefining solution and design candidates to prevent both the crossing of relationship lines and connections between candidates at the same hierarchial level. During this phase, the practitioner will begin to identify logical aspects of the design by redefining design and solution candidates using increasingly abstract descriptions. The final phase of refinement begins with the identification of highly related design candidates. Resolving highly related design candidates requires refining architectural candidates based on the functional performance achived by highly related design candidates, and describing this functionality using action words. At this point in the exercise, the pattern mining practitioner will have developed a conceptual abstraction of the design in the form of a three-tier network diagram. The pattern for the three batteries of this experimental study is shown in Figure 2 [7].

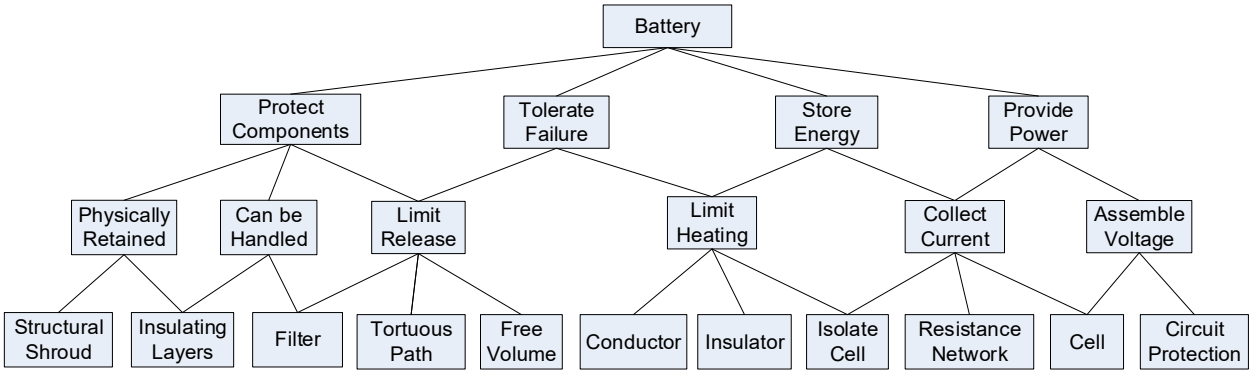


Figure 2 - Design Pattern for the Experimental System

The design pattern of Figure 2 provides a logical description of the battery and expresses tacit knowledge in the form of the relationships between architecture, design, and solution. For example, the relationships between the conductor, insulator, and isolate cell solutions are balanced by limit heating design to provide both store energy and tolerate failure functionality to the battery. The objective of the experimental development was accomplished by incorporating a new functionality (tolerate failure), the associated design (limit heat and limit release), and four new (tortuous path, free volume, conductor, and insulator) and two modified (isolate cell and filter) solutions in the heritage

battery design. Although informative, practicality of the design pattern is improved with the aid of Model Based Systems Engineering application as shown in referenced works for mining [7] and development [8] of the design pattern.

IV. Expressing Architecture Using the FAS Method

The Functional Architecture of Systems (FAS) methodology identifies functionality by analyzing and grouping use case activities into functional elements, organizing these elements into a function tree, and describing the resulting functional decomposition using SysML diagrams [9]. Figure 3 describes the use cases performed by the experimental system releative to the external system which includes powered loads, charging system, user, and environment. Each activity of the use case refines functional requirements by owned behavior as indicated by the rake icon. The functionality expressed by the design pattern is reflected in the use cases of Figure 3. In this figure, the functions store energy and provide power of the pattern in Figure 2 are combined into the single activity, provide stored energy, as discussed in a following section. The use case of Figure 3 includes the functional requirements that refine the defined activities and shows that the relationship between activities performed by the battery relative to the external system.

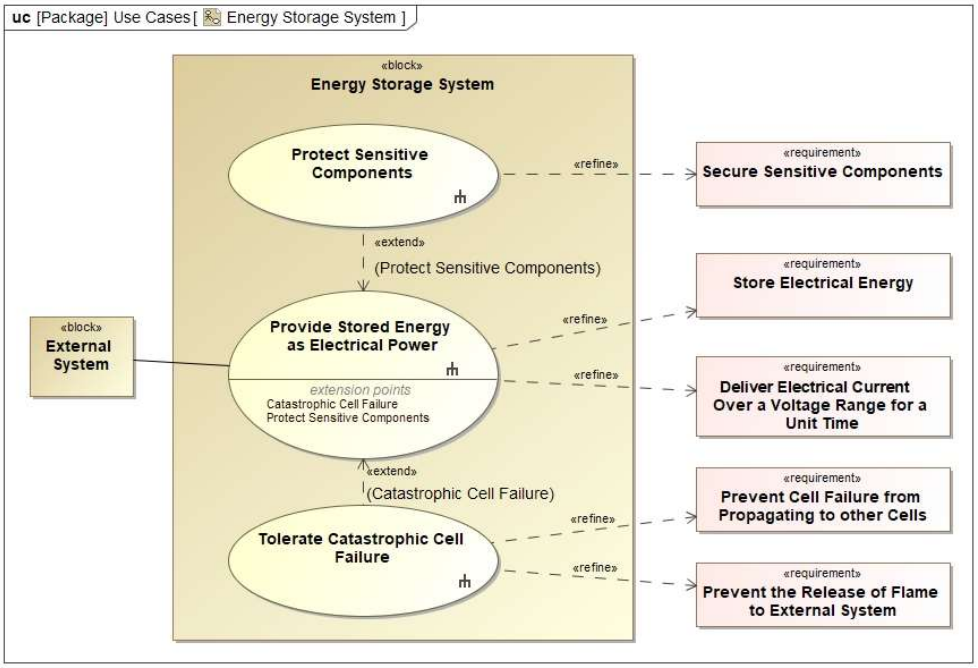


Figure 3 – The Use Case for the Energy Storage System

The behaviors owned by each activity are represented by activity diagrams. The diagram of Figure 4 shows the behaviors owned by the protect sensitive components activity include managing live loads imposed on the battery and protecting external surfaces from excessive heating or polarization. Similarly, Figure 5 shows the power delivery behavior is performed during periods of external demand by the parallel before series configuration of electrochemical cells as limited by the circuit protection elements of the phyiscal design. These two activities reflect nominal operating performance for both the heritage and modern design. The activity diagram of Figure 6 shows the tolerate catastrophic failure activity behaves during periods of cell failure by isolating the failed cell from the parallel bus network, limiting heat transferred to exemplar cells, and reducing ejecta energy before releasing products expelled from the cell from the battery housing. The latter activity of Figure 6 represents the novel contribution to the heritage design.

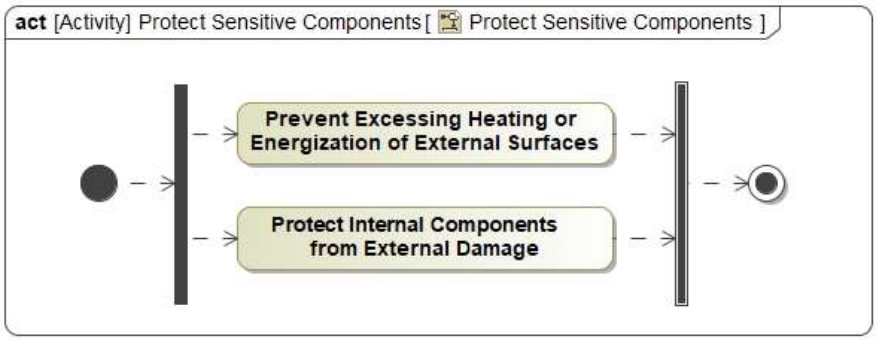


Figure 4 - Behavior of the Protect Components Activity

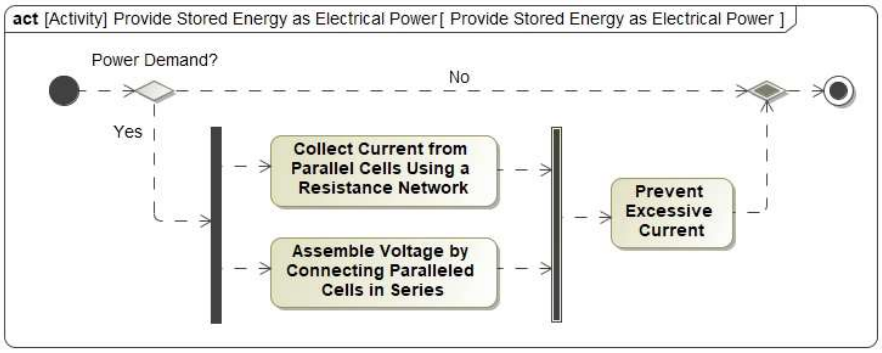


Figure 5 - Behavior of the Provide Stored Eenrgy as Electrical Power Activity

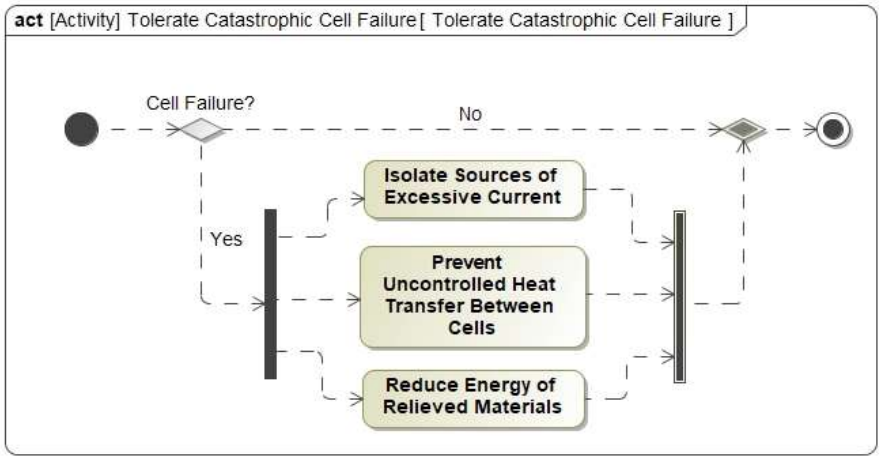


Figure 6 - Behavior of the Tolerate Catastrophic Failure Activity

The FAS methodology translates activity to the physical domain using a function tree [9]. Modeled in SysML as a block definition diagram, the function tree uses stereotypes and composition relationships to provide a static view of the context in which the physical system performs the functionality described in the behavioral views of the system.

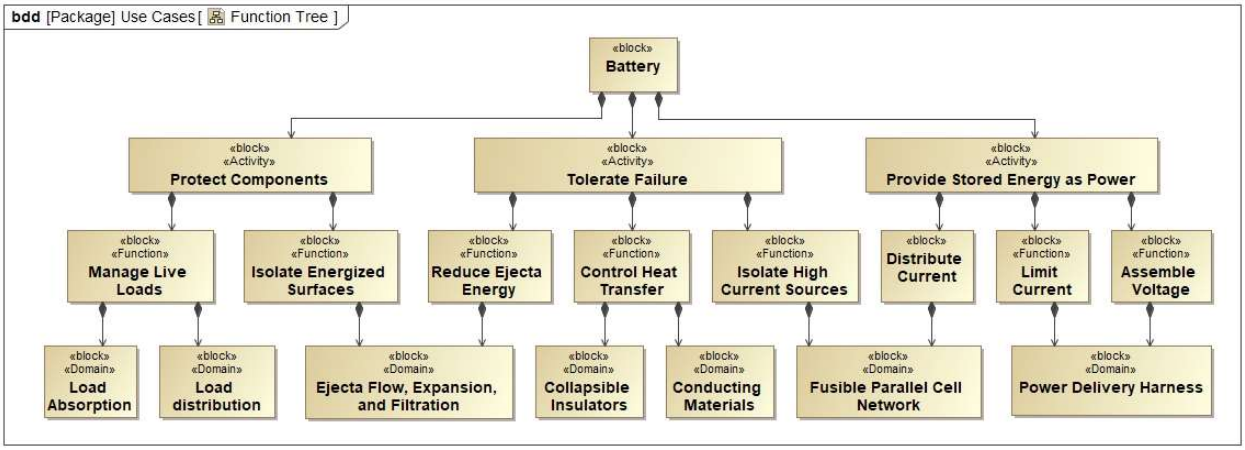


Figure 7 - Function Tree Expressed by the Design Pattern Methodology

The function tree of Figure 7 provides an activity based view of the architecture expressed by the design pattern by relating behavioral performance to a phyiscal expression of the experimental system. In accordance with the FAS methodology, the composition relationships describe the call nature for the functional behavior of the system [9]. The function tree provides additional architectural context by relating activities to discrete functions, however allocating these functions to the physical domain requires consolidating design and solution elements expressed in the pattern mining activity into logical physical descriptions. For example, the behavioral view of the provide power activity in Figure 5 provides a specificity not offered in the design pattern of Figure 2, and reconciling this specificity required combining the circuit protection solution with the assembly voltage design into a single physical element, power delivery harness.

The FAS methodology provides a viewpoint for expressing object and information flows between functions as a SysML internal block diagram. By incorporating a higher level containment structure that includes the battery as a system and the external system as components of a system of systems, and incorporating energy and information flow ports, Figure 8 is generated. In this figure, battery is redefined as system and an external system block not shown in the containment diagram of Figure 7 are necessary to close the information and flow loops and comply with the diagrams of the FAS methodology [9].

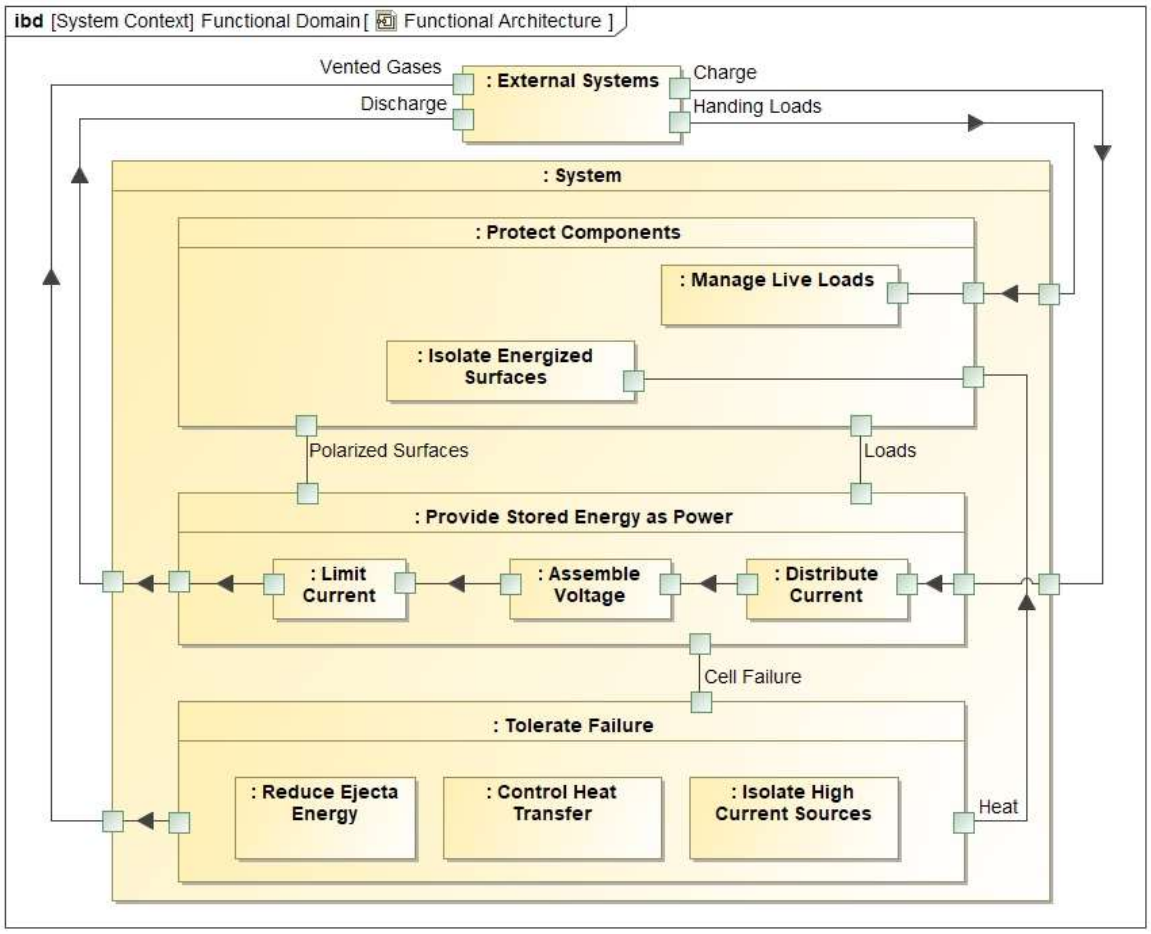


Figure 8 - Functional Architecture for the Energy Storage System

In Figure 8, the activities expressed by the behavioral descriptions are shown as part properties of the system, and the functions as part properties of the activities. The internal block diagram maintains a consolidated view of the provide and store energy functions of the design pattern in Figure 2 based on the use case diagram of Figure 3. While the design pattern separates the two functions of the electrochemical cell based on discrete relationships to differing design elements, providing this level of separation in the architectural view obfuscated the functional expression. Since both share the same polarized surface and cell failure information, the simplifcation of the use case diagram of Figure 3 was left unperturbed architectural expression of Figure 8. By incorporating energy and information flow between functions performed by the system and the external system, the viewpoint offers additional insight into the architecture expressed by the design pattern. For example, the heat transfer between cell failure and separate energized surfaces illustrates a critical aspect of the design pattern that was not expressed in the activity diagrams of Figure 4 and Figure 6.

V. Discussion

The relevance of design patterns in the context of the Functional Architecture of Systems methodology has been demonstrated. By analyzing the experimental system according to the FAS methodology, the behavioral views described by the use case and activity diagrams resulted in a common functional expression, reinforcing pattern mining as a validated and viable means of expressing the functional hierarchy of an observed system. The principle difference between the two methods is the point of origin. While the FAS method begins with behavioral views of the system, pattern mining begins with expert knowledge of the physical system giving rise to an more holistic expression of the relationships between function and design. Specifically, the functional expression derived by the pattern mining process results from physical observation, whereas the FAS method emphasizes a functional decomposition derived from observed behavior, and decomposing this behavior beyond functionality and into a physical expression

obsfucates design detail, reducing the cognitive value of the decomposition. Additionally, the accuracy of the FAS method is dependent on accurate behavioral defintion. For example, if the handling and usability functions were not identified in the use case activities, then the associated functions would not appear in the functional expression. In comparison, pattern mining exposes salient functions based on relationships resolved within the observed system and therefore offers a superior method of identifying functions in existing systems. Additionally, by beginning with a physical description and expressing both the implementation and design views of the Enterprise Architecture ontology, design patterns provide a comprehensive logical expression supplanting the need for the functional to phyiscal domain recommended by the FAS methodology. When using the FAS viewpoint to express architecture, users are advised to incorporate a higher level system of systems block that contains both the experimental and external system in the function tree to improve congruency with the internal view of the functional architecture viewpoint. An example of the recommended function tree is shown in Figure 9 for the experimental system. By avoiding the decomposition of function into the physical domain, the composition relationships of the function tree represent wholly owned behaviors, and by including the external system, the transition to the internal view of Figure 8 is improved.

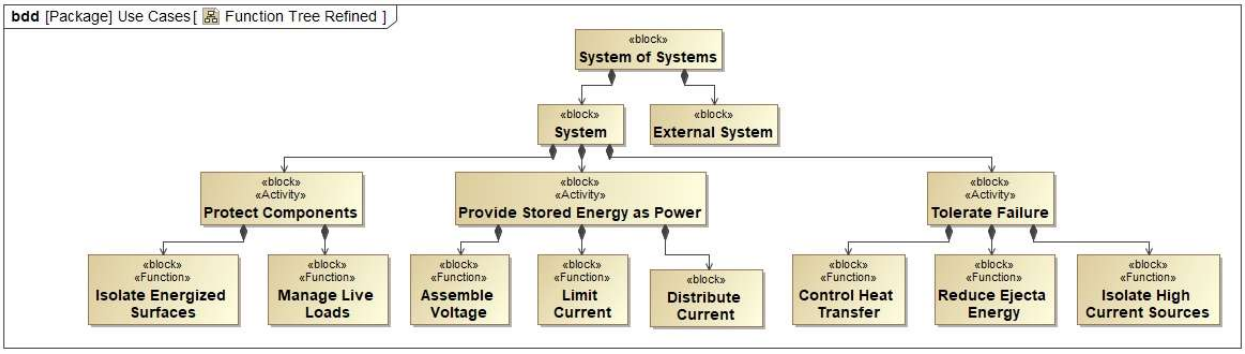


Figure 9 – Refined Function Tree for the Experimental System

The achitectural view provided by the FAS methodology offers three benefits to pattern users, an established viewpoint for expressing functionality, improved cognition when compared to that of the design pattern, and a foundation for developing a pattern language. User cognition of mined data is improved by clarifying information implict to the design pattern in the form of energy and information flows acting within the behavioral composition. By incorporating a the external system in the structural diagrams, the pattern user is encouraged to perform the pattern mining process on those systems to further refine interactions and fulfill the tenant of Alexander's Pattern Language that in order to be functionally complete, a pattern must include relationships to other patterns [21]. Therefore, the modified form of the FAS function tree shown in Figure 9 and the system of systems internal block diagram of Figure 8 are offered as viewpoints for describing the functional architecture expressed in a design pattern.

VI. Conclusion

This research activity has touched on two underlying tenants of patterns; patterns are not completed designs, and a complete pattern must include relationships to other patterns [6] [21]. When describing complex systems using patterns, there reaches a point in the documentation process where additional detail reduces the value of the abstraction, signifying that no further data should be added [6]. This point was reached and discussed during the refin.ement of the behavioral views expressed by the pattern and when developing the function tree per the FAS methodology. By combining two functions relevant to design, but shared by a single physical component, the behavioral view was simplified and the functional view improved by simplying the information and energy flow between interacting functional activities. Additionally, by modifying the function tree to remove the function to phyiscal domain and incorporate the composition of the experimental and external system as a system of systems, the associated architectural view is readily constructed and design information preserved without modifiying SysML language convention [9]. The black and white box views of functional architecture offered by the refined function tree block definition diagram and the associated system of system internal block diagram are offered as a functional architecture viewpoint for describing design pattern information in a technical architecture.

Patterns represent tacit knowledge [6], are a critical component of a technical architecture [16], and are emerging as an enabler of a digital engineering transformation. This work illustrates the value of pattern mining as an architectural expression technique for an existing system and demonstrates the model based acquisition of mined knowledge. By archiving the resulting model, or model fragments, for a range of demonstrated systems in a knowledge

management repository, the pattern user can access a rich inventory of expert knowledge for tailoring and applying in new system development activities. Leveraging existing knowledge when developing future systems will always reduce the cognitive load and improve concept phase decision making of the performing engineer, improving the crucial concept development phase of the project lifecycle. By enabling the accleration and accuracy of concept phase activities, patterns will be cemented as critical component of a digitial engineering strategy and an enabler of a modern knowledge management system [38].

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