Shipboard Power System Reconfiguration

A Self-Adaptation Exemplar

Luca Sabatucci
ICAR-CNR
Palermo, Italy
luca.sabatucci@icar.cnr.it

Giada De Simone
ICAR-CNR
Palermo, Italy
giada.desimone@icar.cnr.it

Massimo Cossentino
ICAR-CNR
Palermo, Italy
massimo.cossentino@icar.cnr.it

ABSTRACT

The Shipboard Power System (SPS) is the component responsible for granting energy to navigation, communication, and operational systems. The SPS Reconfiguration is the ability to react to electrical failure and to restore critical operations for granting vessel survivability. This work illustrate why SPS Reconfiguration software system may be implemented as a self-adaptive system.

To illustrate this relation we exploit a systematic classification of SPS reconfiguration methods, by highlighting terms and attributes related to self-adaptive systems. In particular, the research method considers four types of self-adaptation systems with different degrees of autonomy and proactivity. The corresponding data analysis highlights a strong correlation between SPS Reconfiguration and Self-Adaptive systems, revealing most of the SPS reconfiguration techniques found in literature often belong to three of the four types of adaptation.

The outcome of the paper is proposing SPS as an interesting benchmark for comparing self-adaptive approaches, also highlighting scenarios, tasks, norms goals and quality aspects with the support of the IEEE specifications.

KEYWORDS

Self-Adaptation Exemplar, Shipboard Power System, Systematic literature review

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1 INTRODUCTION

The Shipboard Power System (SPS) is the component responsible for granting energy to navigation, communication, and operational systems. It consists of various electric and electronic equipment, such as generators, cables, switchboards, circuit breakers, fuses, buses, and many kinds of loads.

Shipboard equipment increasingly demands higher performance from the electric sources in a vessel. Moreover, after the occurrence of failures and their subsequent isolation, there could be correctly working sections that remain without supply. A reliable SPS must be able to supply power even in the case of power variations to loads or critical events such as failures occur. The problem of fast and efficient SPS reconfiguration has been a topic of research for around three decades.

Nowadays, real-time data acquisition, classification, assimilation, and correlation can be almost entirely automated at a reasonable cost, with modern computer technologies. Software-based reconfiguration systems consist of two different layers: the software layer encapsulates the logic for monitoring and controlling the underlying electrical layer (the controlled system).

In a previous work [3], we reported the intuition that some common characteristics exist between the software layer of an SPS and smart IT systems. In [2], we anayzed standards and guidelines driving the SPS reconfiguration procedure, highlighting that different behaviors may appear in different navigation contexts. Moreover, the whole ship may be seen as a cyber-physical system in which the human-machine cooperation is fundamental.

This work proposes a systematic classification of reconfiguration methodologies through the characteristics of self-adaptive systems [7, 8]. The conducted review highlights a strong correlation between SPS Reconfiguration and Self-Adaptive systems, revealing most of the SPS reconfiguration techniques found in literature often belong to three of the four types of adaptation. In the second part of the paper, we describe the main characteristics a self-adaptive SPS reconfiguration system should have, focusing on elements like missions, tasks, norms, goals and quality aspects. The objective is to encourage the use of SPS domain as a benchmark-platform for self-adaptive approaches. Moreover, we retain that self-adaptive approaches may improve the SPS research area providing new stimulus to the current state-of-the-art.

This paper is organized as follows: Section 2 briefly introduces the SPS problem; Section 3 provides details about methods and challenges to face when developing a self-adaptive SPS reconfiguration; finally, some conclusions are drawn in Section 4.

2 SHIPBOARD POWER SYSTEMS

The SPS is the electrical and electronic hearth of a ship, composed of a series of components such as power generators, buses, circuit breakers, heterogeneous loads, and others electric sub-systems appointed to navigation, communication and so on. An example is shown in Figure 1.

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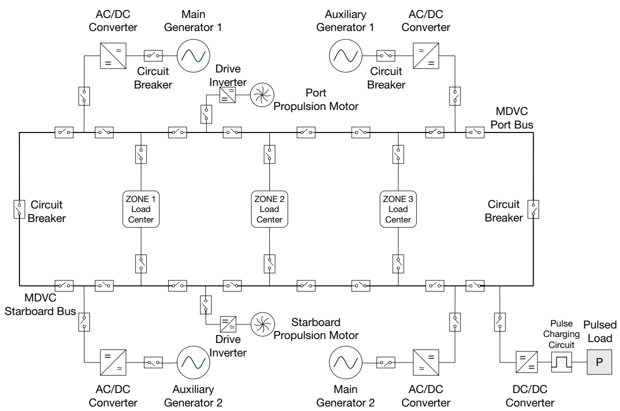

Figure 1: A typical SPS electrical topology.

Reconfiguration is a critical operation requested in unexpected situations such as in the case of severe or major failures. The reconfiguration procedure is driven by the ship power and energy management control, that communicates with all the generators and loads to keep the continuity of service during reconfiguration operations. In this way, the reconfiguration of the electrical layer can isolate failures, restore/transfer power to vital loads, but also more generally it can optimize the management of electrical and electronic equipment to improve energy efficiency.

During normal navigation or after a specific event (such as a weapon hit or a collision), there can be a series of multiple equipment damages. These can affect electrical layer and/or other systems such as the control one.

The strategy that enables restoration of the electrical power system is called *reconfiguration*. The number of steps and the adopted strategies (that can also involve humans) may vary. In particular, in a recent work [3], authors observed in literature exists several software-based reconfiguration techniques enabling smart and timely reconfiguration of the electrical layer due to a fault (or multiple failures).

Smart reconfiguration methodologies need complex coordination between electrical power and protective functions and must deal with several electrical architectures (radial, ring, zonal, ...). Zonal architectures are electrical layers ideally divided into zones. They are frequently used because, even if a single minor fault may spread in systemic failure, circuit breakers are designed for isolating and restoring electric zones [3].

For the sake of space, we refer to [2], that provides a detailed description of a typical SPS reconfiguration strategy. The next section proposes a systematic literature review about reconfiguration procedures from a self-adaptation point of view.

3 SPS AS A BENCHMARK FOR ADAPTATION

This section shows how self-adaptive methodologies may be suitable to address SPS reconfiguration, adding the *quid-pluris* that is missing in current state-of-art on management and control systems, mostly based on stimulus-response approaches.

3.1 A Systematic Literature Review

For reasons of space, we briefly summarize the systematic literature review and the main findings we consider important for identifying SPS reconfiguration as a Self-Adaptive system. For more details about the review, please refer to the technical report [1].

The review follows the guidelines set in [5]: (i) planning, (ii) conducting and (iii) reporting. Four researchers were involved in the review, and it took around six months. The objective is to investigate to which extent engineering an SPS may be considered as a sub-problem of building self-adaptive systems [6, 8]. The main research question:

RQ 1*: Are self-adaptive software systems suitable for the solution of SPS reconfiguration problem?*

is decomposed in two sub-questions:

RQ 1.1*: Does the state-of-the-art highlight common characteristics between self-adaptation systems and software-based strategies for the reconfiguration of a SPS?*

RQ 1.2*: Which kind of adaptation is more suitable for a software controlling reconfiguration of the SPS?*

To answer RQ1.1 a set of features have been identified as relevant for implementing a self-adaptive system from [7, 8]. Conversely, to answer RQ1.2, we referred to the works [12, 13]. A meta-model of the four types [13] reveals the increasing complexity from the type I (the less complex) to the Type IV (the most complex): *Type I* consists in anticipating all the reactions at design-time; *Type II* consists of systems that own many strategies and the selection of the right one is done at run-time; *Type III* consists in systems able of assemblying ad-hoc strategies, according to dynamic goals and quality aspects; *Type IV* consists in systems able of self-inspecting and self-modifying their own code.

We identified relevant databases and selected a large collection of papers by searching with the following keywords: 'shipboard reconfiguration', 'shipboard power failure' and 'shipboard power restoration'.

Due to the qualitative nature of data, the analysis is mainly based on clustering data in categories, to identify possible trends and answering to the research questions. A statistical analysis will also be conducted to check evidence of a direct correlation between *reconfiguration techniques* and the *reconfiguration sub-problems*.

The analysis of the papers reveals a great variety of approaches for SPS reconfiguration. The most used approaches are multi-agent systems (MAS) and meta-heuristic methods. Others, less used, are based on optimisation, machine learning, and deductive reasoning.

Data highlights that all the approaches may be classified as type I to III (answering positively to RQ 1.2); conversely, Type IV (a form of adaptation very complex to achieve) is never adopted. Type III are not very frequent, but they are strictly correlated to the problem of managing multi cascade failures. Centralised feedback loops are mostly used in Type III, while a hierarchical architectures are exclusively used in Type I. Type II is associated to probabilistic, deductive, and linear programming algorithms. Finally, Type III often adopts machine-learning, meta-heuristic, and optimisation algorithms.

Data also highlights that *meta-heuristic* and *multi-agent systems* are equally used for type I, II and III, whereas *probabilistic algorithms* are employed mainly in type II, and *Machine learning* is only used for type III.

The analysis shows there is a correlation between SPS sub-problems (failure, priority, and shedding) and the characteristics of a self-adaptive system (goal/QoS definition, decision making and feedback loop).

Multi failures management is mainly realized by solution in which goals are *hard-coded* into the source code. Dynamic goals are used in about 20-25% of the total and often are correlated to metaheuristic approaches.

The most used *Decision Making* techniques are based on utility functions and rules. A few approaches use most advanced AI techniques with planning and learning.

Decentralised control always are always implemented as multi-agent systems.

According to these findings, we may conclude that a correlation between SPS sub-problems and Self-Adaptation features exists and therefore RQ 1.1 has been positively addressed.

3.2 Self-Adaptive Features of the SPS Domain

SPS reconfiguration problem embraces a series of possible scenarios, goals, and decisions based on functional and non-functional requirements.

Requirements. Functional requirements include prescriptive goals – related to onboard operations that must be granted without any degree of freedom – and flexible goals which also can be satisfied partially, thus granting a minimal degree of functionality.

The main goal of a SPS reconfiguration system is restoring the electrical layer of a ship after the occurrence of failure(s) thus ensuring the survivability of the vessel and/or the crew. However the priority of sub-goals may change according to the operating scenario in which the vessel is. This configure the problem as more complex than a controlled system. Indeed, the strategy must be flexible enough to dealt with goal changing at run-time, for example due to a unanticipated ship's mission changes.

In this application domain, non-functional requirements are various and interrelated, thus complicating very much the kind of actions to be taken. International manuals [9, 10] exist that suggest appropriate norms and regulations for granting the quality of service during power generation, accumulation and distribution to the loads. An example of a QoS metric is the *mean-time-between-service-interruption* (MTBSI) that norm transients during normal system operation (it is not taken into account during exceptional events like battle damage, collisions, fires, or flooding).

Causes of adaptation. The primary cause of adaptation is the enactment of post-failure actions. The kind of failures in an SPS electrical layer may be either single or multiple (further distinguished in contemporaneous or in cascade). The single failure is a frequent condition, for which international norms and guidelines exist. These procedures are not trivially executable in case of multiple failures without considering possible interferences, inconsistencies or even conflicts. Moreover, the kind and the locations of failures are not conveniently classified a priori. It is necessary to define a module for the run-time identification of the failures meanwhile they appear. It may require some reasoning with raw data from sensors and/or the ability of reasoning with uncertainty.

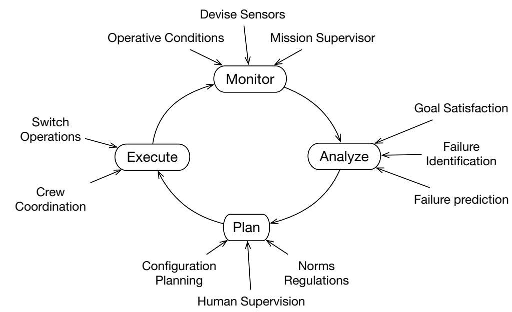

Figure 2: The MAPE loop for a SPS reconfiguration system

Some works in literature also propose some techniques for anticipating possible failures by analyzing electrical components that are more risky [14].

Mechanism for Adaptation. The result of SPS reconfiguration is finding a configuration of circuit breakers (open-closed) that leads power to the desired loads according to a dynamic electrical topology. Despite this may lead thinking this a problem of structural adaptation, it is noted that the synchronous changing of multiple switches may be complicated. For this reason, the order of any opening-closing action of a configuration is of paramount importance for managing a correct electrical transitory (max ampere, voltage...).

The self-adaptation mechanism should be able to front cascade multi-failures, i.e., scenarios in which a new failure occurs during the reconfiguration action due to the previous failure. It also should be able to find many reconfiguration schemas, thus selecting the most appropriate one according to non-functional requirements, QoS, regulations or, in case of need, enacting a solution in which some goals are partially addressed.

The choice of the software architecture has consequences on system robustness and efficiency. A monolithic solution [4] with centralized control has the advantage of reaching the optimal solution very fast, but is highly vulnerable. Many works highlight the importance of deploying a distributed system [11], in which each component owns a degree of autonomy (decentralized control). This has positive consequences on the global robustness, but it could require an organization overhead to reach the optimal configuration. Finally, a hierarchical solution [10] seems an advanced compromise to both robustness and efficiency.

3.3 Designing a Self-Adaptive SPS

This subsection discusses the main elements for building a self-adaptive solution to the SPS reconfiguration problem. The feedback loop has been recognized as the central factor for developing most of the self-adaptive systems. Figure 2 reports a generic MAPE feedback loop [6], specifying which are the activities that realize the SPS reconfiguration. The loop starts with data collection, and then data is analyzed to decide the kind of behavior. Finally, the system must act for the producing the desired behavior.

Monitor Module. The vessel (including the electrical layer) is instrumented with a set of sensors for monitoring some physical variables. The monitor module shall control these sensors to collect raw data with the aim of detecting possible failures.

Other device sensors could be used to get the operative condition of the vessel components (navigation system, communications, ...). Additionally, the self-adaptive system could require additional information about the vessel state concerning the current mission. These could be obtained by interacting with humans devoted to the management of the different devices.

Analyze Module. The system should be able of reasoning on raw data in order to estimate all the relevant vessel conditions (e.g., steady state, electrical failure, dark-ship-start[1], etc.). Also, it should obtain the necessary information to fully characterize and assess system performance. For instance, the analysis should infer the kind and the position of possible electrical failures when they occur. In some cases, reasoning with uncertainty may be necessary because sensors are available, or because of multiple failures at the same time. The analysis of the current electrical status may also be necessary for evaluating the degree of goal satisfaction (even partial), thus to establish when to adapt. The most advanced solutions also include a system for the prediction of failures by analyzing historical series of data. Anticipating a possible failure would be a great benefit in term of isolating/protecting electrical devices.

Planning Module. This component must elaborate a configuration for maximizing the continuity-of-service of vital loads during the reconfiguration operations, avoiding instability or even system collapse. According to the current mission and the kind of maneuver, loads may be dynamically classified into four QoS categories that adopt two system-dependent time thresholds related to the interruption of loads.

Reconfiguration time *t1* is defined as the maximum time to reconfigure the distribution system without causing additional damage. For a system employing conventional switches, *t1* is on the order of two seconds.

Generator start time *t2* is defined as the maximum time to bring the slowest power generation module online. Generator start time is typically on the order of one to five minutes.

The generated electrical configuration should respect a set of international norms and regulations [9, 10] establishing best practices and constraints when prioritizing and optimizing the power flows throughout the ship. For instance, some MVDC components, such as alternating current generators, must be protected against over-voltage.

The design of the planning system should incorporate human factor to enable specialized operators to maintain situational awareness and take appropriate measures during normal and emergency conditions.

Execute. The main operations of the SPS reconfiguration are *connection/disconnection*, *configuration*, and *isolation* of the loads and generators. These actions are performed by controlling the automatic switches placed along electrical buses. Controller distribution and autonomy are fundamental features to allow each block may act independently from the rest of the system.

[1]The dark ship restart is the condition in which all the generators are disconnected, thus the vessel is in a blackout situation: the use of energy storage devices allows the electrical system to restart

The self-adaptive system may also coordinate humans in the solution execution. The employment of crew operations may be fundamental to repair certain kinds of failures. Otherwise, there are situations in which zones of the vessel must be set off-limits for the crew because of safety reasons.

4 CONCLUSIONS

Starting from a systematic review of SPS reconfiguration methods, the paper has proposed to develop this case study as a self-adaptive system. Indeed the analyzed state-of-the-art highlights many common characteristics between self-adaptation and shipboard power reconfiguration. The outcome is to create a synergy between two research areas that – so far – are unrelated. From the one side, SPS could represent an excellent benchmark for the self-adaptation community for comparing their approaches. On the other side, the state-of-the-art in self-adaptive systems may provide new ideas for improving SPS reconfiguration approaches.

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