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Multi-physics simulation for product-service performance assessment

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Abstract

Complex cyber-physical systems need particular attention both for physical architecture but also for service integration. In order to exploit the system but also to aid in controlling and driving it, one solution consists in elaborating functional models and to put them on board. During the lifecycle of the system, any person in charge of one given task or service has the possibility to get some help in driving the system and also to get some feedback with respect to reference models. The aim of the keynote is to present a global modeling approach and to illustrate the application of the propositions with ship building and controlling systems, both for the need of technical and functional people on board and also for the services dedicated to passengers.

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Keywords: cyber-physical systems; product-service performance assessment; modeling and simulation

1. Introduction

Cyber-Physical Systems (CPSs) are open systems composed of cyber and physical parts. Their sensing and their manipulation extend both the physical and the digital universe. CPSs build up a purposeful contextual model of their environment, by sensing their environment for state information and usually enriching this information through additional internet queries, to further increase their control, their effectiveness and their impact. CPSs have a number of distinct characteristics and implementation principles, described in [1].

CPSs independently and individually adapt their behaviors, whereas coupled adaption may actually be needed for convergence and stability.

The concepts that underlie CPSs [1] fit a wide class of generic systems to which also smart products, intelligent systems and complex adaptive systems belong. Over the past decades, products increasingly became equipped with connectivity and embedded computational capabilities. Through sensing, on-board intelligence and connectivity, products have been endowed with information acquisition capabilities, negotiation capabilities, and limited forms of decision making abilities. Due to their intensive contextual interaction (sensing and manipulation), smart products can also be approached at system level, i.e. as CPSs. A system of systems with a framing architecture and interoperability can make individual CPSs contribute to a joint overall service production..

The reductionist principle, breaking down desired functionality in piecewise contributing functional parts that can be synthesized into a solution, has long been seen a correct engineering approach. With growing interaction complexity, however, systems start to exhibit emergent behavior. In an environment with limited sources, synergic implementation and operations require that sources depletion rates permit for sustainable operations. Furthermore, accumulated environment manipulations shall not have impact going beyond the adaptive capacities of the eco-system, so as to prevent it from being destroyed or extinguished. Synergy seems an internal system characteristic, having an external counterpart across systems: applying synergy principles to technical and societal system aspects is an often-suggested approach to deliver ecologically sustainable cyber-physical systems.

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In order to phase such challenges in designing robust and adaptive systems, it is necessary to model and simulate during the early design stages of the CPSs any behavior and performance aspect. Design models, methods, tools organizations and environments are to be adapted to new needs for CPSs. These new needs mainly concern (1) formal modeling and dynamic analysis of CPSs, because of continuous change of these hybrid systems (continuous and discrete functions), (2) performance analysis and assessment of CPSs, permanent comparison between model-based and experimental evaluation, (3) verification, validation, certification, robustness assessment of CPSs, (4) safety control in order to minimize the risk of failure and possible “dramatic” consequences, (5) security for information processing and networks.

So, new challenges have to be faced in order to provide new design tools and environments enabling sustainability assessment and control before and during the lifecycle of a CPS. At the design stage, both the cyber and physical parts of the CPS have to be defined, modeled and integrated, mainly based on CPS performances and services.

This paper presents an example of product-service system design and performance analysis in the field of shipbuilding.

2. Ship as an IPSS

A ship may be viewed as a complex CPS. Indeed, it is composed of a huge number of components which interactions are not obvious [2]. Its behavior can be predicted using multi-physics models integrating potentially multiple control loops. Without any support in how to drive it, performance of the global driving may not be optimal, even if subsystems are locally optimized. Couplings between sub-systems are really hard to understand without any help, especially as there are several operators or crew members that are responsible for these sub-systems.

Moreover, the International Maritime Organization (IMO) defines mandatory regulation on energy efficiency and greenhouse gas emissions. The IMO Marine Environment Protection Committee (MEPC) also defines a Ship Energy Efficiency Management Plan (SEEMP) to guide ship-owners in managing the energy efficiency of their fleet [3]. Without any onboard services supporting SEEMP, the ship owners cannot satisfy IMO requirements based on the four following steps: planning, implementation, monitoring and self-evaluation and improvement.

2.1. Generic ship definition and modeling

The work was mainly focused on cruise liners, but most concepts can be applied to any kind of ship [4]. This is because most of the ships are based on the same sub-systems as shown by Fig. 1. The main purpose of a ship is to transport a shipment (goods, humans) on water. The propulsion system and the hull are the major elements to carry out this mission.

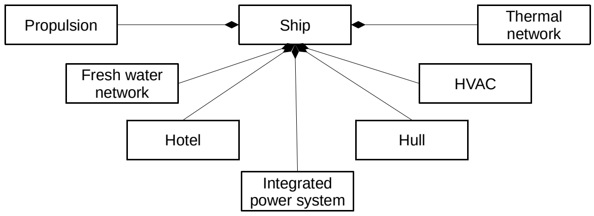

Fig. 1 UML Class diagram of a generic ship architecture.

However, to ensure the wellbeing of the shipment [5] and of the crew, several sub-systems are needed like hotel equipment (rooms, restaurants or mess, etc.) or a heating and ventilating air conditioning system (HVAC).

Most recent ships are based on an all-electric architecture where an integrated power system (IPS) which is mainly based on diesel generators or on steam turbines, provides electrical power to other sub-systems [6]. For instance, the propulsion engines consume a major part of the electrical power. Other electrical power consumers are numerous like any ventilators or pumps, lights, etc.

Even if electrical power is the main energy onboard, a thermal network may be used to cool down (e.g. diesel engines) or warm up (e.g. boilers) some equipment. A fresh water production system is often integrated on ships to produce distillated water for machinery and also for hotel use.

All these systems interact with others as shown on Fig. 2. For instance, the fresh water network requires heat from the thermal network (e.g. for boilers), but also electricity (e.g. for pumps or for osmosis machines) and it provides fresh water for the hotel (e.g. for showers or swimming pools). The IPS is linked to all others due to ships’ architecture. In the case of diesel-based (or steam turbine) propulsion, the role of IPS is less important and alternators may be directly connected to propulsion engines.

2.2. Onboard services for driving support

Recent ships integrate onboard decision support systems to help the crew to efficiently operate this complex system. When ship owners buy a new ship, they buy services at the same time for the ship operation like mainly routing systems [7]. Such services use weather and current data to define the best route to go from one place to another [8, 9].

In the same way, dedicated control is applied to the IPS using a power management system (PMS) [10]. This service provides advanced supervision and automatic control of diesel-generators. It also integrates automatic power unballasting to avoid too fast increase of load, i.e. risks of blackout. Most PMS are based on load dependent start tables [11] which correspond to thresholds for possible configurations used for activating or deactivating diesel-generators. These thresholds are defined to limit the risk of blackout, while optimizing diesel-generators running point closest to their best efficiency (around 85 percent of maximum current rate).

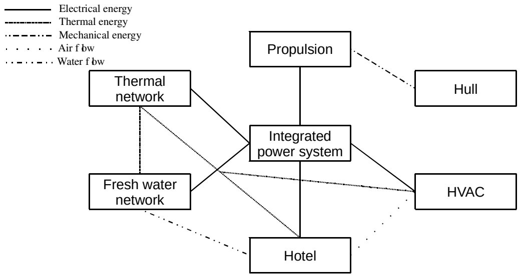

Fig. 2 Simplified flow diagram between main sub-systems in an all-electric ship.

In the same way, there is an automatic control of the chiller compressor in the HVAC subsystem. It works almost in the same manner as PMS allocating the load to available compressors to optimize their efficiency around their best running point.

Some recent research works are done to provide new services to support green driving of ships due to recent environmental laws on marine transport emissions and energetic efficiency. Routing systems and PMS limit the ecological impact of IPS and propulsion, but there is no support for most other energy consumers. Only supervision can be done. It requires integrating new sensors on a ship, which can be very expensive or simply impossible on some equipment. In this case, the crew and operators are not guided to improve themselves in the way of driving the ship. Complex coupling between subsystems can be undertaken since it is often different people who manage subsystems.

Thus, multi-physics modeling and simulation is the next step to provide new support in driving a ship.

2.3. Performance assessments through multi-physics simulation

Current onboard services are mainly dedicated to automatic control of some security equipment or to the supervision of real-time behavior of the ship. Based on a holistic modeling of a ship as previously presented, it is possible to assess performance indicators and predict them based on scenarios.

With relevant models, it is also posible to build multi-physics holistic ship models which can evaluate greenhouse gas emissions and fuel consumption, which are the main key performance indicators (KPIs) that ship-owners or the ship captain will consider optimizing [12]. THE IMO MEPC also defines several indicators like the Energy Efficiency Operational Indicator (EEOI) in CO2 tons per nautical mile [13]:

$$EEOI = \frac{\sum FC_j \times C_{Fj}}{m_{ship} \times D} \qquad (1)$$

where j is the fuel type, FC_j is the mass of fuel consumed, C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j, m_{ship} is the gross tonnage and D is the distance.

Other KPIs may also be evaluated on ship subsystems by exploiting couplings that are taken into account through the holistic model of the ship. It allows operators to better understand subsystems they are responsible for and makes it possible to highlight influence relations that cannot be taken in consideration without a global view of the ship.

For instance, we can identify the levers relating to such KPI and guide crews to improve their performance by using optimization routines. For instance, the fresh water production should be regulated depending on the cost of required energy. Some tanks are used to store the fresh water and it can be used to delay the production when it is cheaper or greener to produce it. In many ships, free steam is produced through waste heat recovery boilers fixed on tailpipes of diesel engines. This steam can be used to produce fresh water instead of using fired boilers to produce heat directly from fuel. Obviously the free steam production is more important as the IPS has a highest load. Without model support, the operator responsible for fresh water production is not able to know the real-time water production price, allowing him to reduce the fresh water production cost.

3. Application to cruise liners

3.1. Modeling validation and requirements

The modeling task of a complex multi-physics system is not easy and requires data measures to calibrate models. To avoid too much effort in modeling a new ship, a generic library of multi-physics models implemented in Modelica language is used [14, 15, 16]. This library helps a lot for the definition of new ships by using pre-defined architecture models.

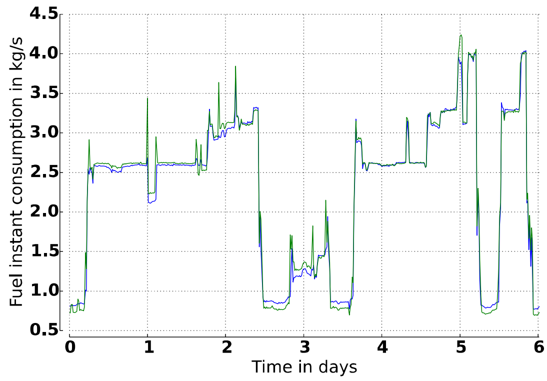

Fig. 3 Fuel consumption (in kg/s) comparison between measured data (blue line) and computed ones (green line) for a one week cruise.

This work was validated for a recent cruise liner based on many sensor data used to calibrate models. The main architecture of the model corresponds to Fig. 2. Ships without any sensors may be difficult to simulate accurately even if most models will observe the tendency of the real ship behavior.

Fig. 3 shows the comparison of measured data in green and computed ones in blue for the fuel consumption indicator. The model indicates a measurement differential of less than 1%. However, not all indicators are so accurate, but they do not impact a lot the fuel consumption computations.

3.2. Modeling results

Fig. 3 represents the real-time fuel consumption for a one-week cruise. A port stop can easily be identified as the fuel consumption falls less than 1 kg/s.

The highest fuel consumption is met just before and after a port stop due to maneuver phases. Since the ship is completely electric, the direct corresponding data between fuel consumption and electrical power supplied to all onboard equipment can be obtained as shown in Fig. 4. This figure shows that the efficiency is mainly the same for all running points: it follows a line. Most of the changes of variations are met in low power production modes. Indeed, in this case, the electrical power variability has a bigger impact on the IPS load, therefore on loads of diesel engines in use. On the given cruise of about 2600 knots, an EEOI of about 45.4 was computed, which shows this efficiency balanced by the gross tonnage of the ship as defined by equation (1).

It is also possible to identify where the electrical power is used as shown in Fig. 5. The total power produced in black is mainly used by the propulsion (in green) and less than 20 % is used for hotel and HVAC sub-systems. Some other minor consumers are not represented in this figure to keep it clear.

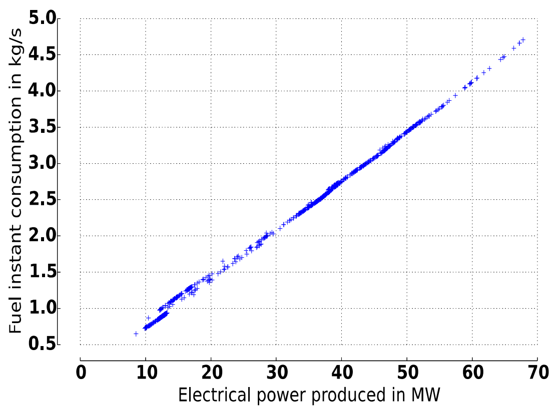

Fig. 4 Fuel consumption (in kg/s) in function of electrical power production (in MW).

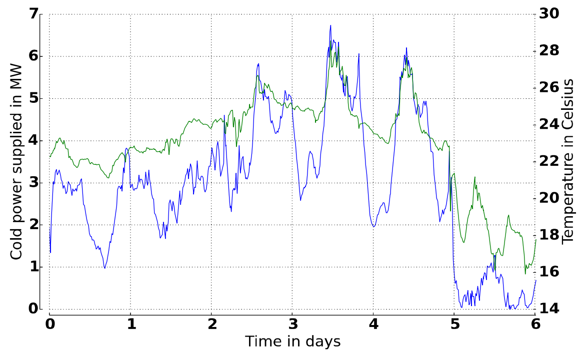

Fig. 5 Impact of the atmosphere temperature (green line on right axis in °C) on HVAC cold power production (blue line on left axis in MW).

The blue line in Fig. 6 as shown represents the amount of cold power supplied by HVAC to cool down insufflated air and the green line reflects the external temperature. Logically, the cold power decreases with external temperature. Other similar indicators are computed in the model and can be presented to operators to help make decisions. In the case of the HVAC along with the weather forecast, this electrical need has to be considered to smooth the production of IPS by postponing some electrical needs. For instance, at night the external temperature falls and consequently reduces the need for the HVAC electrical power usage. If fresh water stocks allow it, the fresh water production can be done preferably at night. Indeed, osmosis machines and pumps for boilers would still require electrical power.

4. Conclusion

Contained in this paper is an example of how multi-physics simulation can help building decision support systems for ship driving. Indeed, such complex CPS cannot be used efficiently without additional services. Multi-physics simulation brings a better insight of the CPS behavior understanding and it can be used to test and validate driving scenarios. The major difficulty is to validate models, because it requires abundant data to tune them so that they are accurate enough to compute realistic indicator values. One other difficulty is also the validity of sensor data, which is not always easy to prove or re-calibrate.

Some future work may need to be investigated for such product-service system to define new services for failure diagnostic and predictive maintenance. Simulation models may be used to compare significant changes in measured data. Moreover, Modelica is an acausal modeling language, which helps in changing inputs and outputs of models quite easily. Inversing models is not so obvious for numerical computations, but this trail may be interesting to follow in order to give more insight in the understanding of performance degradations.

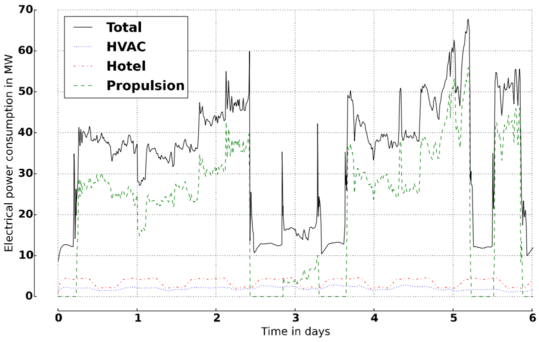

Fig. 6 Repartition of total electrical power in MW (black line), HVAC (blue line), Hotel (red line) and Propulsion (green line).

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