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MODELING OF NAVAL PROPULSION SYSTEMS – APPROACH BASED ON HYBRID SYSTEMS

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Abstract. *This paper introduces a model for a naval propulsion system adopting a hybrid system approach. The aim is encompassing discrete events characteristics as well as the continuous variables behavior in a comprehensive model. Considering specifically the case of submarine´s propulsion system, it was used a top-down methodology to derive Petri net based models to describe the system behavior and its main components and equipment.*

Keywords: naval propulsion, submarine, hybrid system, Petri net.

1. INTRODUCTION

There has been an effort of Brazilian government in developing technologies related to naval projects in the last years (Brasil, 2013). In fact, development of naval projects – especially those related to submarines – is a complex and a time-consuming task, involving an engineering team with many professionals that have different skills and expertise. Some authors reckon that project submarines are certainly a complex task (Chalfant, 2015) (Cooper *et al*., 2017), given these include several knowledge areas, such as: electrical, mechanical, marine, control and automation engineering to design each part of a submarine. Consequently, to be able to design an entire submarine, engineers should work in strong cooperation, discussing the project among them and coordinating their future steps, to ensure that the submarine design is being done with consistency. Regarding this kind of approach, Langland *et al*. (2015) describes how to address this matter over a multidisciplinary environment, where different disciplines are thought together in order to achieve results that fulfill client’s requirements. This approach relies on building models for each discipline at same multiple requirements from other areas are evaluated (Chalfant *et al*., 2017).

Building a model of a system for it simulation and analysis is a approach that allows one to verify and to analyze behaviors, values and make decisions based on results obtained from different scenarios (Chung, 2004). Considering, that submarine design involves a lot of specialists and requires project consistency, develop a model for it is a condition necessary to verify premises adopted as well as to ensure that expected performances are being achieved. Nevertheless, before building a model, the developers must observe which are the goals and parts that are going to be modeled. In case of submarine design at early stage, the design team is looking for translate client requirements into a feasible submarine. To achieve this, they should estimate parameters of submarine’ size and weight, thermal and electrical needs and several other subjects (Pereira, 2016). Considering the Brazilian Navy objectives, development of models for submarine components can improve design approaches and can aid during verification of the project itself.

This is particularly relevant for propulsion system and electrical system, given they are responsible – in a conventional submarine – for power generation, for power storage and for propelling the submarine (Pereira, 2016). However, a traditional approach of continuous variables will not encompass all behavior of these two systems, because their operation relies on human commands that made decisions based on external actors or, abrupt and unexpected events. Similarly, using a model that uses only discrete events will not address the systems properly, as continuous variables also may trigger events. Therefore, an approach that deals with both continuous variable and discrete events is required; hence hybrid systems approach (Villani *et al*., 2007), can be used to model these systems.

In this paper, it is discussed a model for a conventional submarine based on hybrid systems approach, considering its expected operation and performances. The main goal is to build a model that represent the propulsion and electrical systems to be used by a design team to improve its project. In the following sections, a review of naval propulsion is presented, as well as details regarding the modeling methodology, and the resulting submarine´s propulsion system model (at conceptual level).

2. NAVAL PROPULSION SYSTEMS

Geertsma *et al*. (2017) points out that there are several technologies and combined solutions for naval propulsion systems. Such as, using a prime mover directly attached to shaft line, or an electrical propulsion motor (EPM) instead of a prime mover. The power generation can be done by diesel or gas generators or for some small ships using solar panels. The power storage might be performed by traditional lead-acid batteries or fuel cells. The decisions of which combination of technologies will be adopted are left for designers that take into account client objectives for the ship. A review about different types of naval propulsion and their common application is discussed in Geertsma *et al*. (2017).

Accordingly, to Pereira (2016) for a conventional submarine the usual propulsion adopted is the one known as “full electric”, because all mechanical power deliver to the submarine’s propeller is provided by an EPM, the electrical power is generated by a diesel generator and this energy stored in batteries. Despite existing other types of propulsion arrangements, the ones that combine prime movers along EPM or that employ only prime movers are not usually used in undersea vehicles. When submerged, submarines do not operate on an environment with oxygen available, then the use of systems that rely on fresh air are discarded. Figure 1 depicts an overview from electrical network point of view of a “full-electric” propulsion system in a conventional submarine, where portside and starboard are represented in red and green colors, respectively. In addition, it is noteworthy to remark that Fig.1 presents the hotel load (HL) per side which is comprised of all electrical loads aboard except the EPM, this aid along modelling because the load profile of HL is a consequence of submarine speed and current depth.

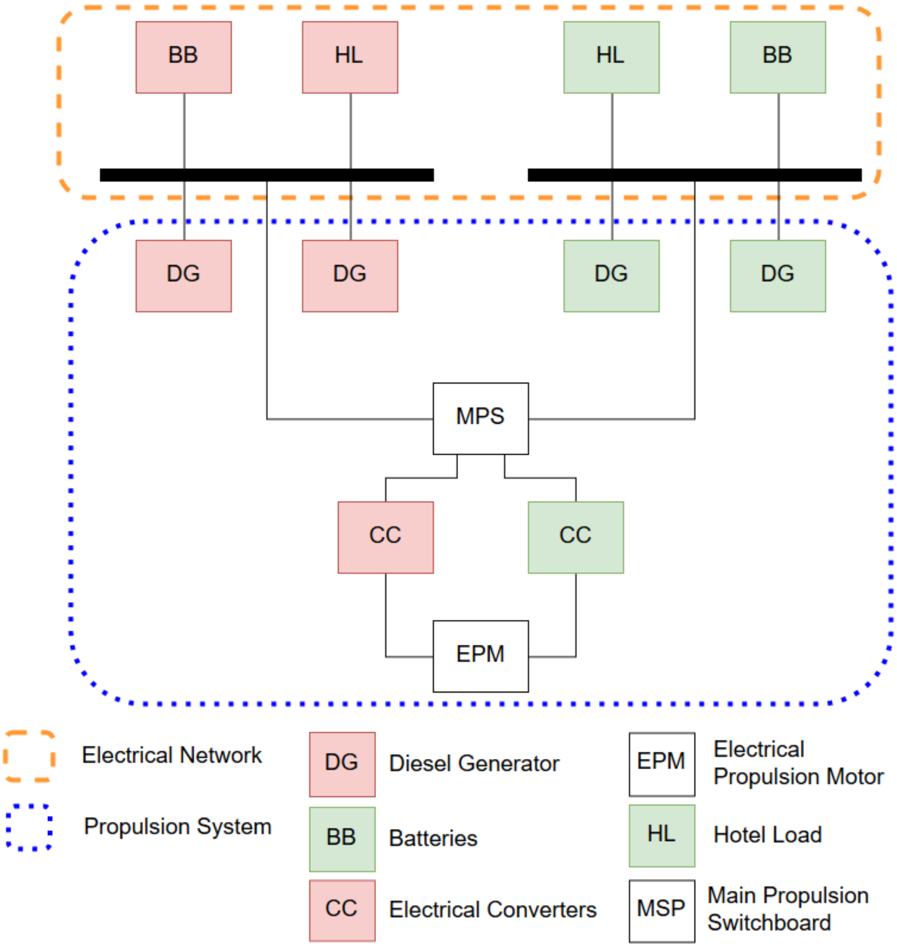

Figure 1. “Full-electric” propulsion for a conventional submarine based on Geertsma *et al*. (2017) and Pereira (2016).

3. MODELING METHODOLOGY

The model of a submarine propulsion system must consider that it has continuous interactions among different equipment, such as electrical power between generators, storage facilities and consumers, and mechanical power from EPM to shaft line that is used to propel the submarine. In addition, there are discrete events in submarine operation, as human decisions over the system that requires propulsion to modify its current set points or to address a specific situation as submerging or emerging. Given those scenarios, it is possible to either develop distinct models for continuous variables and for discrete events systems; however, analysis about electrical power demand and long-term power consumption associated with events that triggers different propulsion operating points are not easily assessed, because they contain both kinds of systems within. Hence, it is considered a hybrid systems approach to be able to analyze these interactions.

Villani (2004) proposes a methodology for modeling hybrid systems using “differential predicate transition Petri nets” and “oriented object paradigm” (OO-DPT nets). This way, it is possible to describe the system as a set of parts – i.e. objects – at the same time the interactions among these parts. The procedure is as follows:

1. Modelling the flows of material
2. Specification of the use cases
3. Specification of classes and objects
4. Building the activity diagrams
5. Building the sequence and collaboration diagrams
6. Building the OO-DPT net of the classes and the class diagrams
7. Verification of consistency between models

This methodology was used in several types of systems (Garcia *et al.*, 2008) (Villani, 2004) (Villani *et al.*, 2007), but its application in the case of submarine’s propulsion systems is not trivial and the revision of some points is necessary.

4. MODEL

Having in mind the goal, that the model will be used by submarine designers to enhance their work, this modeling should follow the guidelines adopted by them in order to represent the ideas and concepts chosen. The first step, according to methodology presented in previous section, is to define the flows of materials, which in the case of submarine are the power that flows along the network – from batteries to loads during autonomous operation, and from diesel generators to batteries and loads during recharging operation – in addition, there is the propulsion actuators that change their behavior accordingly to current operation set by operator and external continuous parameters, such as fuel level and ship speed that vary over time.

Based on those, a conceptual level model based on Production Flow Schema (PFS) (Miyagi, 1996) technique was conceived in view of these particularities as well as operational behavior expected from submarine. PFS is a technique derived from Petri net, proper for modeling systems and processes at high level of abstraction. Figure 2 illustrates the main activities performed by submarine when navigating on open sea. It is important to remark that this model does not consider neither submarine startup nor its shutdown operations which varies and depends on the resources and facilities of each port.

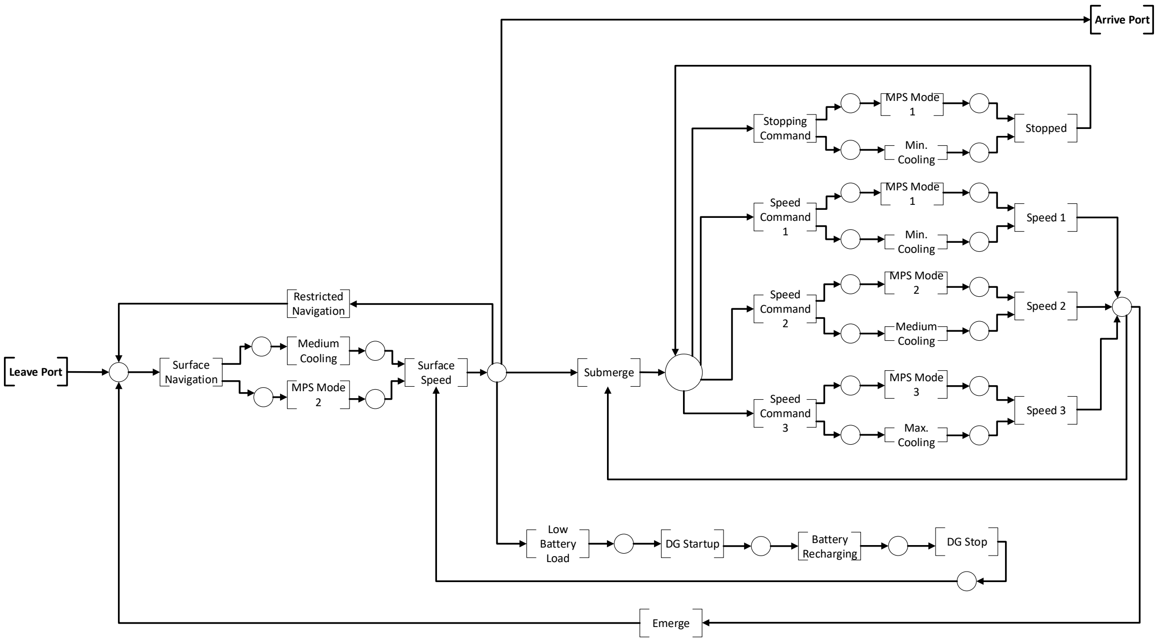

Figure 2. PFS model at conceptual level of submarine navigation

Accordingly, to the model in PFS presented in Fig. 2, it is possible to further steps of methodology, describing use cases of the system, in order to identify scenarios that might be explored by the user. Considering the premises for a submarine operation and model in PFS, Fig. 3 presents the use cases for propulsion and electrical network operator as well as for their supervisor. Each one of them has a set of possible interactions expected with the submarine systems, the propulsion operator is able to select a speed order, accordingly, to current depth of the submarine (surface or submerged) while electrical operator can request emersion (if submerged) to recharge batteries. Supervisor can command immersion or emersion based on current situation of the submarine.

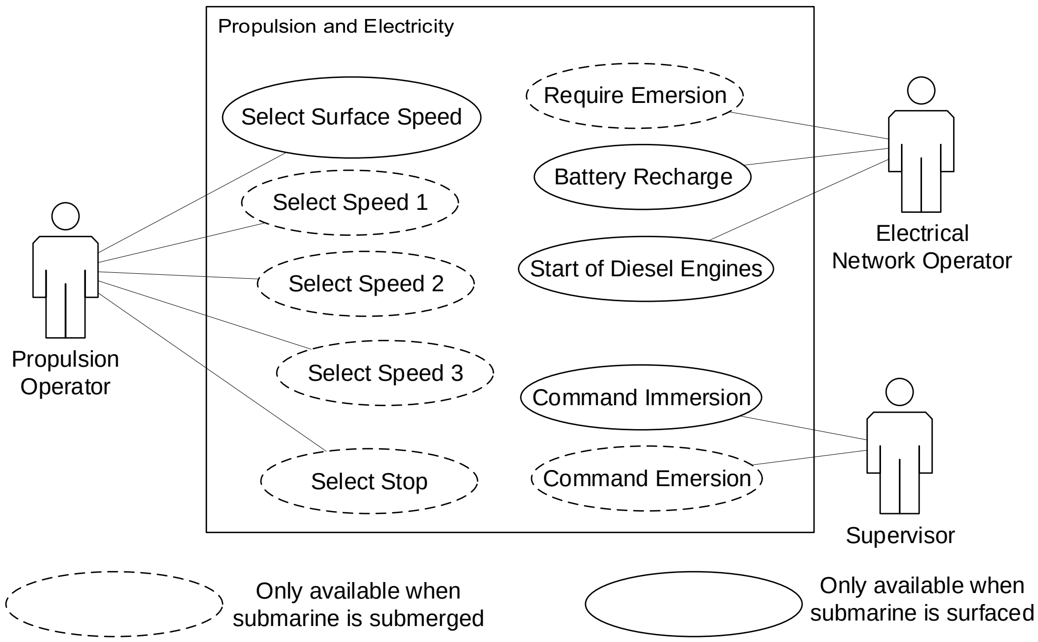

Figure 3. Use cases for activity [Navigation] on UML.

The use cases associated with PFS model provides means to understand how the propulsion and electrical systems of submarine are commanded and which sequence they should attend. And based on them, it is possible to continue the modelling of submarine to step 3: "Specification of classes and objects", using the three rules for decomposition of classes described by (Villani, 2004) it is possible to specify: (i) objects that have only discrete interactions; (ii) objects with discrete and continuous interactions with other objects, however the continuous variables are shared for a limited time frame; and (iii) objects that have discrete and continuous interactions with other objects, however without a limited time frame. With those considerations, there are 13 classes identified: C_1 – *Orders;* C_2 – *Supervisory System*; C_3 – *User Interface*; C_4 – *Interface of Propulsion Block*; C_5 – *Propulsion Block*; C_6 – *Interface of Hotel Load*; C_7 – *Hotel Load*; C_8 – *Interface of Diesel Generator*; C_9 – *Diesel Generator*; C_{10} – *Interface of Propulsion Switchboard*; C_{11} – *Propulsion Switchboard*; C_{12} – *EPM's Converter*; C_{13} – *Battery*. The classes C_1, C_2 and C_3 are identified with aid of PFS model and user case diagram, whilst the other classes are identified when considering the propulsion and electrical systems architecture. In addition, it is important to remark that objects from class C_{12} do not have interface class because this C_{12} and C_2 normally exchange data among themselves. Also, C_{13} do not have any kind of discrete interaction with no other class, only continuous ones (power supply), in this case all interactions are time restricted, sometimes batteries are being recharge whilst in other they are discharging (supplying power for the submarine), only theirs parameters are monitored.

The next step involves building the activity diagram for submarine, to achieve this goal, one should consider the way the submarine operates – as described in PFS model – and the classes identified. This way, it is possible to understand how each component may behave within propulsion and electrical systems operation. Figure 4 presents two diagrams, one in the left for surface operation and one in the right for submerged operation. It is important to highlight that this distinction comes from use cases, where the operators have different choices based on submarine depth (submerged or surfaced).

The main points of diagrams in Fig. 4 are related to requirement for battery recharging and stop condition for the model, in order to represent how a full mission could be addressed by this model. The values for voltage levels are arbitrarily chosen in this representation, however one should specify it accordingly to energy storage criteria and other operational parameters adopted for the model. Considering the purpose of the submarine, scenarios or conditions these values – maximum mission time or battery level for recharging – are susceptible to modifications.

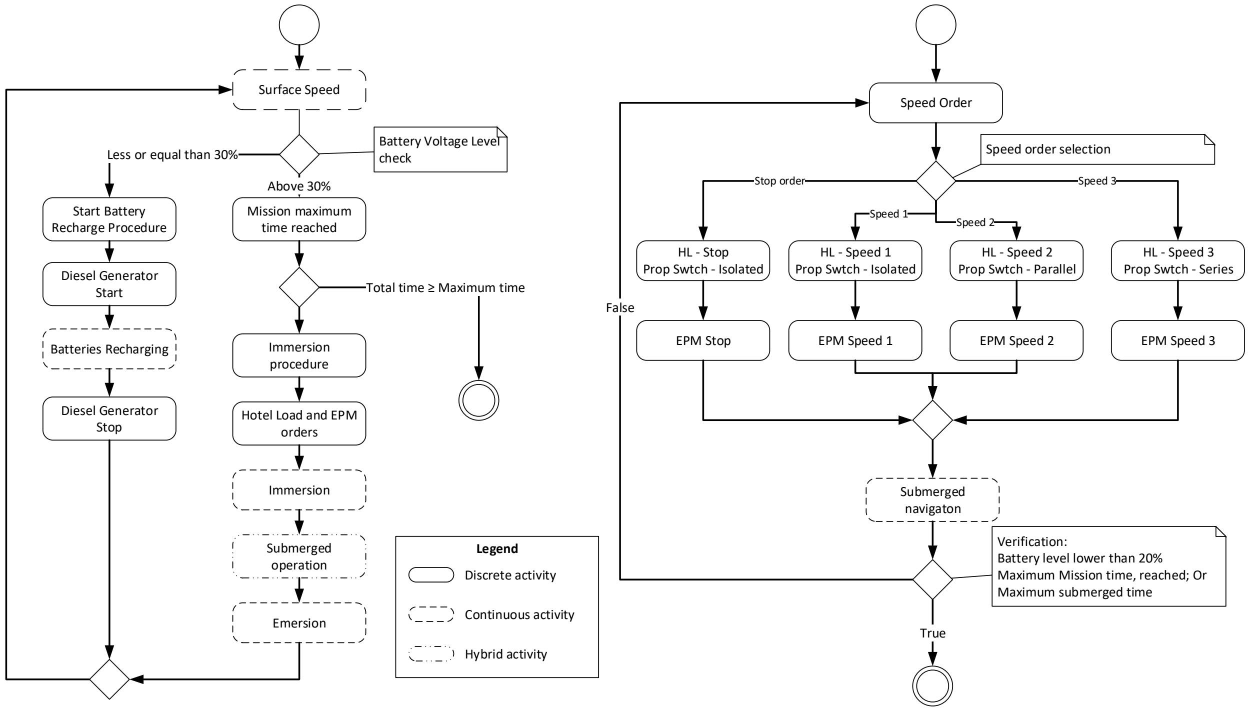

Figure 4. Activity diagram for surface and submerged operation.

Albeit, it is noteworthy to point out that that considering the activity diagram and classes identified, the sequence diagram can be designed. Hence, the classes previously identified are associated with the activity diagram, linking the classes – that stand for a more conceptual level of model design – to actual propulsion and electrical systems. The sequence diagram aims to detail how each object interacts with another one, thus providing a way to identify methods within each class enhancing the description made up to this point. Figure 5 and Table 1 presents the sequence diagram that represents speed orders from the user, battery recharging, immersion and emersion have slight differences in sequence activities whereas the speed order regardless submarine current depth follow same procedures.

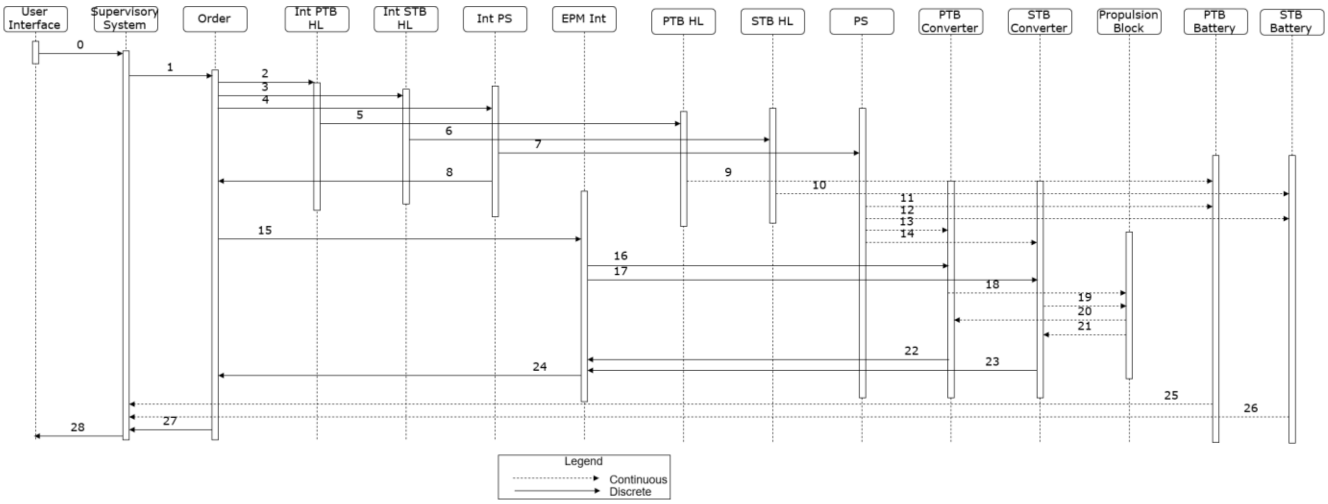

Figure 5. Sequence diagram for speed orders.

Table 1. Sequence diagram textual description

Communication	Description
0	*User* requests a new speed order to *Supervisory System*
1	*Supervisory System* transmits the new order to *Order class*
2	*Order class* requires new configuration to *Interface of Portside Hotel Load*
3	*Order class* requires new configuration to *Interface of Starboard Hotel Load*
4	*Order class* requires new configuration to *Interface of Propulsion Switchboard*
5	*Interface of Portside Hotel Load* commands *Portside HL* based on order received.
6	*Interface of Starboard Hotel Load* commands *Starboard HL* based on order received.

Communication	Description
7	*Interface of Propulsion Switchboard* commands *Propulsion Switchboard* new position
8	*Propulsion Switchboard* informs *Interface of Prop Swtch* of its new position
9	*Portside Hotel Load* consumes energy from *Portside Battery*
10	*Starboard Hotel Load* consumes energy from *Starboard Battery*
11	*Propulsion Switchboard* consumes energy from *Portside Battery*
12	*Propulsion Switchboard* consumes energy from *Starboard Battery*
13	*Propulsion Switchboard* adjusts voltage levels and limits to *Portside Converter*
14	*Propulsion Switchboard* adjusts voltage levels and limits to *Starboard Converter*
15	*Order class* sends speed order to *Interface of EPM*
16	*Interface of EPM* sends speed reference for *Portside Converter*
17	*Interface of EPM* sends speed reference for *Starboard Converter*
18	*Portside Converter* provides voltage and current to *Propulsion Block*
19	*Starboard Converter* provides voltage and current to *Propulsion Block*
20	*Propulsion Block* modifies its speed and rotation and inform to *Portside Converter*
21	*Propulsion Block* modifies its speed and rotation and inform to *Starboard Converter*
22	*Portside Converter* informs order fulfilled to *Interface of EPM*
23	*Starboard Converter* informs order fulfilled to *Interface of EPM*
24	*Interface of EPM* informs to *Order class* that order was fulfilled.
25	*Portside Battery* informs its charge level to *Supervisory system*
26	*Starboard Battery* informs its charge level to *Supervisory system*
27	*Order class* informs *Supervisory System* that speed order was fulfilled.
28	*Supervisory System* informs *User* that order was fulfilled.

Sequence diagram provides a mean to related classes identified and actual actions, thus allowing that the model to be further detailed. For instance, the Fig. 6 presents the collaboration diagram for all objects presented. Therefore, it is possible to characterize the methods of all classes required to represent the propulsion and electrical systems of a conventional submarine.

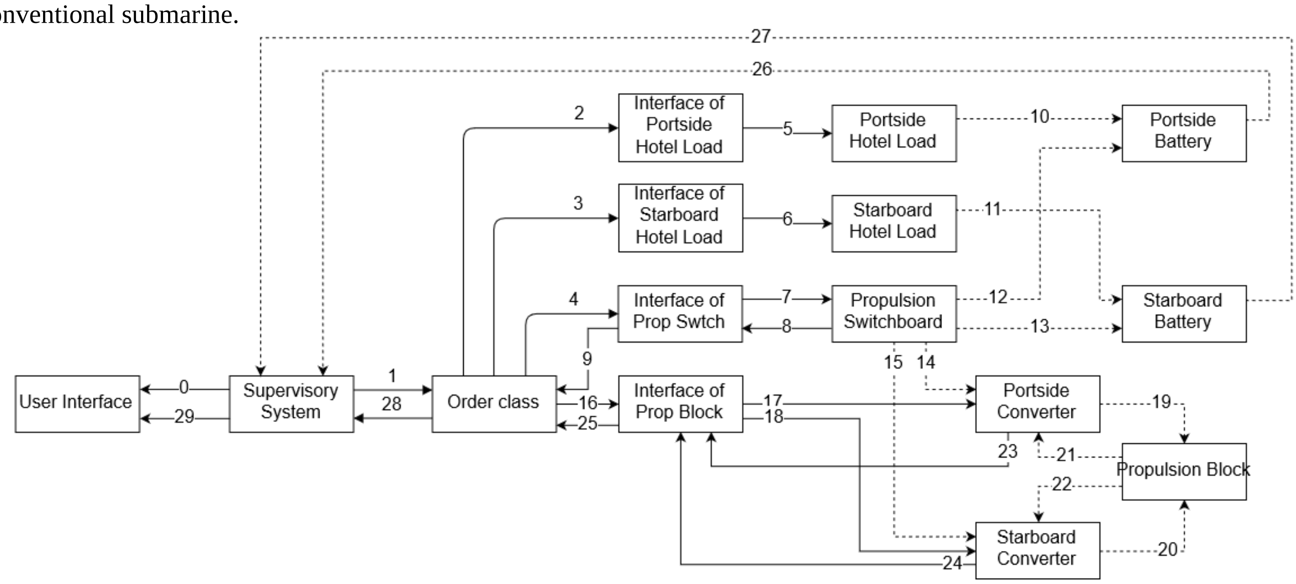

Figure 6. Collaboration diagram for speed orders. Lines follow legend present in Fig. 5.

Considering that each line in the collaborations should have a correspond method and that internal and external attributes are connect to each object model; hence all objects can be characterized in terms of methods and attributes. The Fig. 7 illustrates all classes with its attributes and methods, this description enables the next step of modelling of a conventional submarine where the class description must meet requirements established up to now. Next step aims to complete describe each class considering a predicate transition differential petri net to determine the individual behavior of each class.

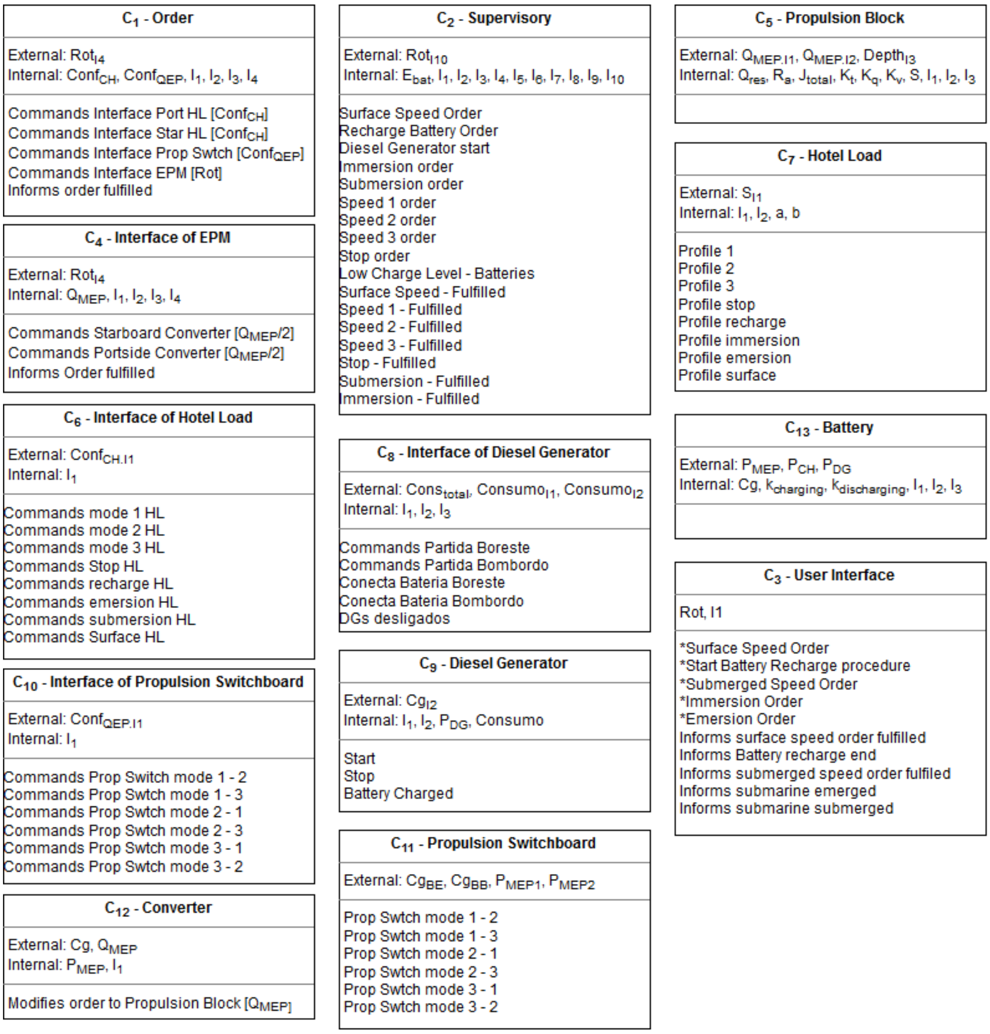

Figure 7. Methods and attributes for all classes identified.

Figure 8 depicts the *Supervisory System* class that represent for a part of supervisory system of the submarine that comprises the propulsion and electrical systems. In this figure, it is noteworthy that all methods are associated to a transition (PDT-OO element), that either call another object or be called by another object. All classes are designed in a similar way of that one, considering the sequence and collaboration diagram, as well as all information present in PFS model. Consequently, a set of PTD-OO Petri net where employed to describe each class, in a general view, all classes should have transitions enough to meet all methods described in Fig.7, additional transitions may be added, however their purposes are only to indicate internal changes, such as: change in differential equations or some internal variable update.

With all classes described as C_2 – *Supervisory System*, the complete model of a conventional submarine with full electric propulsion is obtained. As stated by Villani (2004), it is necessary to verify if the model attend to all requirements established for it at beginning of modelling process, for classic Petri nets, the designer must verify properties such as safety, for instance. For a PTD-OO Petri net, this requirement also should be verified by the designer of the model, this task can be done by means of simulation, implementing each class and object, accordingly to the complete model presented or by verifying properties derived from Petri net theory. In the present case the properties analysis was used to ensure the formal consistency of the models and the simulations to evaluate the behavior of the system under different situations that allow the study of the system from the points of view of each of the expert designers and clients involved.

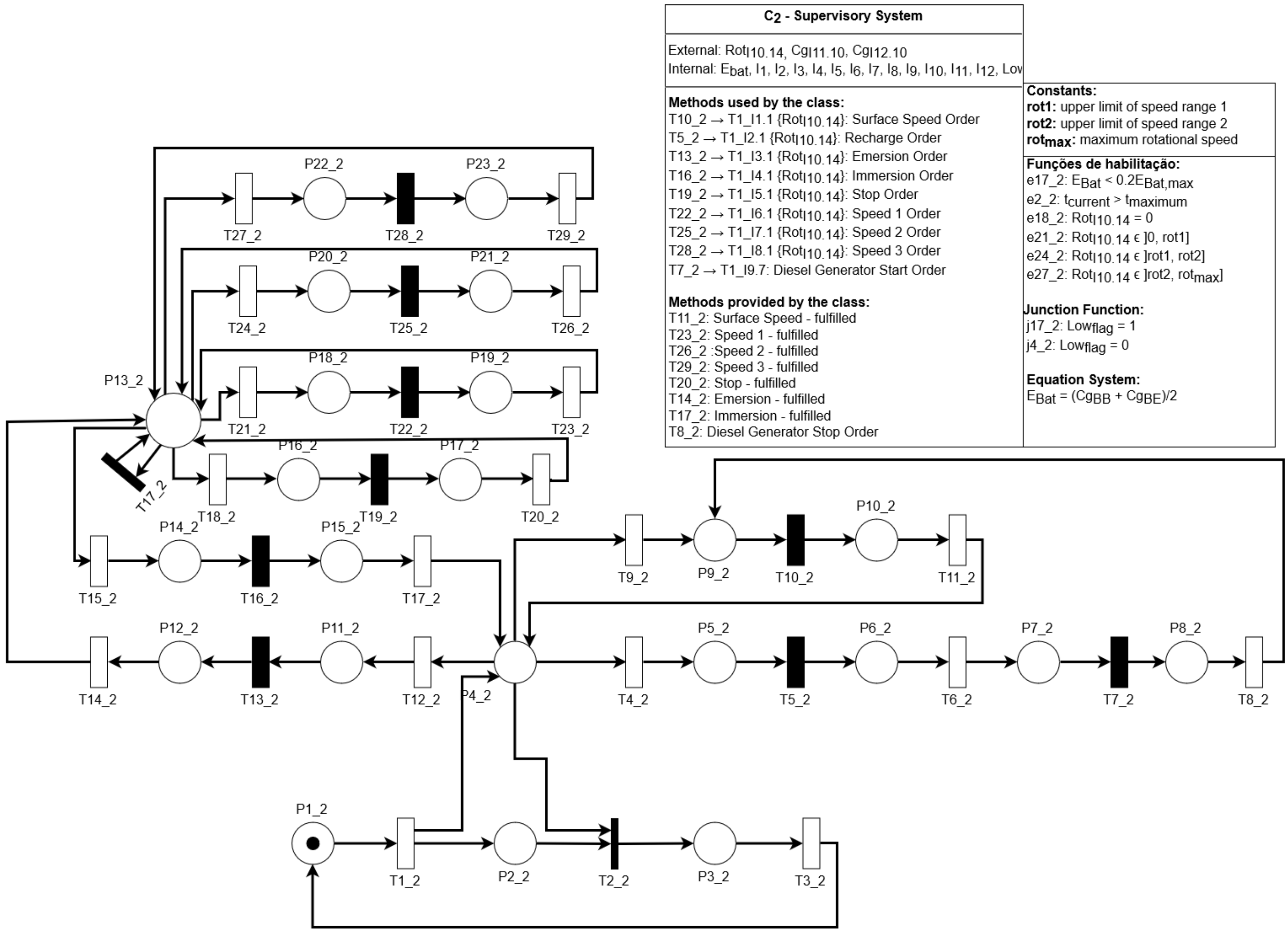

Figure 8. Class C_2 – PTD-OO Petri Net for C_2 - *Supervisory System.*

5. CONCLUSION

In this paper, it was presented as a model of the propulsion system for a conventional submarine was obtained based on the modeling procedure initially proposed by Villani (2004) not specifically for naval systems. The hybrid system approach provided a complete description of the submarine operation when navigating after leaving the departure port and before arriving to arriving port; this kind of model provides means to estimate several parameters that are important for submarine design, especially at early design phases where the premises and clients requirement are under discussions.

The model aids submarine designers comprehending client proposal, as well as identifying potential conflicting premises due to formal verification process. The propulsion and electrical systems of a submarine are approached from the point of view of hybrid systems, including elements that usually are neglect at early design phase, but now that can be considered to improve submarine designs.

The work developed motivates the development of specific tools to assist in the editing and analysis of the models. These tools (to be develops in the next step) should certainly facilitate interaction between submarine designers.

6. ACKNOWLEDGEMENTS

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