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Towards modeling of naval systems interdependencies for cybersecurity

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Abstract—To ensure a ship’s fully operational status in a wide spectrum of missions, as passenger transportation, international trade, and military activities, numerous interdependent systems are essential. Despite the potential critical consequences of misunderstanding or ignoring those interdependencies, there are very few documented approaches to enable their identification, representation, analysis, and use. From the cybersecurity point of view, if an anomaly occurs on one of the interdependent systems, it could eventually impact the whole ship, jeopardizing its mission success. This paper presents a proposal to identify the main dependencies of layers within and between generic ship’s functional blocks. An analysis of one of these layers, the platform systems, is developed to examine a naval cyber-physical system (CPS), the water management for passenger use, and its associated dependencies, from an intrinsic perspective. This analysis generates a three layers graph, on which dependencies are represented as oriented edges. Each abstraction level of the graph represents the physical, digital, and system variables of the examined CPS. The obtained result confirms the interest of graphs for dependencies representation and analysis. It is an operational depiction of the different systems interdependencies, on which can rely a cybersecurity evaluation, like anomaly detection and propagation assessment.

Index Terms—Naval systems dependencies, cybersecurity, information technology, operational technology, graph representation.

I. INTRODUCTION

In 2016, a Royal Navy’s cutting-edge warship was broken down in the Persian Gulf due to a complete power failure. The ship was navigating on warm waters and this breakdown was caused by an overload of the intercoolers, which provide chilled air to the ship’s engines and gas turbines, when outside temperature rises. Such overload caused the gas turbines to overheat and shut down. Since the propulsion system powers everything on board, a complete power failure left the ship without propulsion or weapons systems (<https://www.theguardian.com/uk-news/2016/jun/07/destroyers-will-break-down-if-sent-to-middle-east-admits-royal-navy>, Visited on Jul. 22, 2021). As a consequence of the high interdependencies between the power generation system and

other vessel systems, the conception flaw led to a global system failure during an operational mission of the ship. This incident highlights the importance of the knowledge and management of maritime system interdependencies to avoid critical effects such a black-out during the whole ship’s life-cycle, from design to the end of her operational life.

Currently, the complexity and size of vessels are increasing the use of information technology (IT) and operational technology (OT) based systems. To ensure proper missions accomplishment, the operation status of vessels must be provided in real-time by controlling and monitoring multiple **interdependent systems**, defined as multilayered networks [1] of interacting systems and components, structured in functional blocks. These vessel systems are characterized by antagonistic features in terms of system design and operation, performance, reliability, and risk management requirements [2]. Often relying on Programmable Logical Controllers (PLC), those systems support navigation and communications safety, electricity, propulsion, and all basic amenities to sustain life on board, using Cyber Physical Systems (CPS). Yet, due to the lack of security by design and the implementation of proprietary technologies, vessel systems remain vulnerable during their long life-cycle. As a consequence, patch management and upgrading processes become very complex [3]. Additional conditions, such as growing interconnection between onboard systems to improve automation on ships, combined with the use of commercial off the shelf technologies and software, also mean that attacks targeting any system could propagate with an impact on numerous systems or the entire vessel. Furthermore, multiple physical and cyber threats could lead to anomaly propagation with dangerous consequences for the vessel [4].

It becomes thus obvious that the comprehensive cybersecurity impact assessment of maritime systems dependencies is a major need, from vessel design to maintenance in operational condition. Despite the importance of this critical risk, studies about it have not been detailed enough in the literature [5].

Such study of interdependent systems' vulnerabilities requires to examine both intrinsic and global perspectives, as well as to include inherent technical and physical maritime constraints [6]. In this article, we present a generic analysis to ease modeling for maritime interdependencies representation applying three abstraction levels, namely, physical, digital, and system variables. This analysis is intended to provide suitable information for a wide range of applications and different stages of a ship life-cycle. The proposed study is expected to specify basic interdependencies analysis that can be identified to enable cybersecurity evaluation from ship design to operational deployment.

The paper is organized as follows. Section II introduces previous works on naval systems interdependencies representations and analysis. In section III, we describe the challenges associated to the analysis of naval systems interdependencies and a proposal to address a generic evaluation. Section IV presents a case study to illustrate the proposed systems analysis. In Section V, we discuss the obtained results and outline several perspectives of our work.

II. RELATED WORK

Modeling is an important part of systems engineering to support functional, performance, and other types of analysis. It must be carried out with specific models during the whole ship life-cycle from development to operational deployment, and through multiple refurbishments. Several ships' systems interdependencies identification and characterization have been defined with different model representations for various ship's life-cycle modeling needs, like conception, components integration, and operational deployment.

Because of a ship's long lifespan, the conception stage is a fundamental analysis start point, based on the identification, characterization, and understanding of interdependencies between ship's systems. A model framework was defined to decompose a system into an architectural block composed of three representations – physical, logical, and operational [7]. These representations were then used to describe the dependencies between components of a given distributed system.

More elaborated models are necessary to go beyond the descriptions of single architectural block interdependencies, owing to the fact that there are multiple interconnections between systems and networks, which cannot be defined independently. An Information and Communication Technology architecture was proposed to visualize the generic structure and relationships between systems [8]. The model was defined with several generic layers to represent the multiple networks that compose a ship. In this model, the most representative and interoperable ship components involved in data and information exchange, from the *Instruments layer* to the *Off ship layer*, were represented. A ship architecture model was also proposed, relying on an extension of the Maritime Architectural Framework architecture [9]. This architecture was modeled as a multidimensional cube composed of different perspectives to provide a graphical representation of the system and the associated maritime domain [10]. It allowed identifying and

analyzing the interdependencies and interconnections among the vessel's systems.

Interdependencies modeling can also provide important information during the operational deployment of a ship. It is a vital requirement to analyze anomalies' impacts by estimating and quantifying potential propagation paths. Graph theory appears as an appropriate solution to address this need by modeling interdependencies as edges between nodes that represent ship's systems. A method was defined for identifying and analyzing attack paths in interconnected maritime cyber-physical systems [11]. This method applied graph modeling, representing each system as a node and each interdependency as an edge. It was applied to a navigational CPS. Although the resulting graph appears to be small (only composed of about ten systems), it is an interesting first approach to model and analyze the high interdependency of maritime systems.

Likewise, in a previous work, we defined a generic CPS-adapted model to examine how an altered subsystem could impact other subsystems it is connected to [12]. This study characterized and quantified the interaction between factors of each subsystem that tend to enhance or reduce simultaneously specific risks, having a cumulative effect. Several vulnerability scenarios were evaluated to anticipate critical failures.

III. MARITIME DEPENDENCIES DEFINITION AND ANALYSIS

A. Challenges of vessel interdependencies analysis

Maritime systems are complex concepts with specific characteristics and definitions depending on the field of application. The International Council On Systems Engineering provided a generic and inclusive definition for this notion: *A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not* [13]. Taking this definition as an undisputed concept, it appears that a system is both considered as a *unified whole* and an aggregation of *interacting or interdependent group of items, components or parts*. This duality is characterized in the literature as two different perspectives [14]:

- The external perspective, to define the system as a whole.
- The internal perspective, to describe the interacting components that compose a system.

Because of the numerous interdependent systems that compose them, vessels can be considered as **System of Systems (SoS)**. The MITRE Corporation defines this notion as *a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities* [15]. Those systems interact with each other through multiple interdependencies, to ensure the ship's proper functioning and mission success. Two systems are linked with an **interaction** when one of them influences the state of an element of the other, by exchanging energy, force, mass, or information [16]. This interaction is also defined as a **dependency**. Additionally, two systems are defined as **interdependent** when a bilateral dependency exists between them. For simplicity reasons, the terms dependency and interdependency are used interchangeably in this article.

In accordance with these system notions, we can identify two main types of dependencies that compose a vessel at different abstraction levels, depending on the chosen perspective. First, from the internal system perspective, there are dependencies between system components. Second, from the external perspective, when a system is characterized as a unified whole, the vessel is defined as a SoS composed of interdependent systems.

As introduced before, those dependencies are critical because they can produce cascading failures and provoke a tremendous impact on the whole ship [17]. Consequently, it is evident that their analysis is a crucial requirement, not only for the vessels cybersecurity, but for the whole maritime domain. Maritime dependencies should be analyzed and examined specifically, by addressing at least three challenges:

- Each dependencies layer must be modeled from the internal and external perspectives.
- Several models should cover the systems and subsystems heterogeneity, as well as their dependencies, in terms of characteristics, functions, and criticality.
- The whole ship's life-cycle, including design, development, and operation conditions, must be modeled with adapted dependencies models.

All these aspects should be assembled with a unified solution that covers the inherent characteristic disparities between ship classes.

B. Identification of maritime systems dependencies layers

In this work, we propose a first analysis according to a **maritime systems dependencies layers** definition and representation, as a guideline to initiate dependencies evaluation, following the internal and external system perspectives.

Concerned highly-dependent groups of systems include on-board systems [18], which constitute ship's functional blocks, along with the corresponding interdependencies at different abstraction levels. Two types of dependencies are defined: between systems of a given functional block and between systems of different functional blocks.

Five vital highly-dependent groups of ship's functional blocks systems are identified (Fig. 1):

Platform systems (1.1-1.6), that are critical for the ship's function, on which numerous key interdependencies are defined, from an external perspective (see also Fig.3). Otherwise, in agreement with the system's internal perspective, several **subsystems** are constantly interacting through different types of dependency: control command from a PLC to an actuator, measurement from a sensor to a PLC, or information exchange between two PLCs, etc. As an example we provide an illustration of these dependencies from an internal perspective of a generic platform system (1.2).

Bridge systems (2), on which dependencies relate numerous complementary systems encompassing diverse potential issues. For instance, dependencies between the **surface situation awareness components (2.1)** that gather information from **communication systems (5)**, like Automatic Identification System (AIS), Global Navigation Satellite System (GNSS),

radar, etc, on an Electronic Charts Display and Information System (ECDIS). Another key dependency is represented by the **Integrated Bridge Systems (IBS) (2.2)**, which combine navigation systems with navigation control and monitoring, propulsion, control, and monitoring information connected to **platform systems (1)**.

IT systems (3) used on-board, enable remote interactions for which dependencies are highly prone to be vulnerable. **Communication systems (5)** provide Internet, from satellite connection (SATCOM) or broadband cellular network relay (3G, 4G, 5G) in coastal navigation, to the **entertainment systems (3.1)** for crew members and passengers. Also, **third party systems (3.2)** with desktop applications allow distant monitoring, data collection, maintenance, safety and security of **platform systems (1) and bridge systems (2)**.

Specific IT or OT systems (4) are used, adapted to the mission and vessel type, like cargo control system for maritime trade, passenger servicing systems for cruise ship, or weapon management system for military vessels. Multiple dependencies result from mission-specific systems and each concerned **ship's functional block**.

C. Analysis of the maritime CPS dependencies from the internal perspective

In accordance with the previously identified system dependencies layers, we analyze a maritime CPS dependencies model. The examined model corresponds to one specifically adapted for industrial control CPS dependencies, from the internal perspective [12] and is part of the platform systems layer. It is based on the generation of a 3-levels graph that schematizes system components as nodes and their dependencies as edges. Three abstraction levels are defined, namely, physical, digital, and system variables.

Each node of a modeled CPS belongs to the digital or physical abstraction level, compliant with CPS's inherent properties. The third abstraction level of the model refers to system variables, modeled as nodes. Dependency links between them are defined with a state-correlation model [19], and schematized as edges. The generated 3-level graph is illustrated in Fig. 2. Components of each level are assigned as follows:

- **Digital subsystems:** Integrate networking and/or computing capacities (e.g. in Fig. 2 PLCs, and Supervisory Control and Data Acquisition system (SCADA)).
- **Physical subsystems:** Interact with a physical process, transmit measured data or receive control commands (e.g. in Fig. 2 pumps PU10 and PU11, and tank T7).
- **System variables:** Describe the CPS current state with measured and control variables, or component's internal variable (e.g. in Fig. 2 pump state s , flow f , and tank T7 level l_7).

Using the resulting graph structure, two main types of dependencies are defined from the system internal perspective:

- A first dependency type between subsystems of the digital and physical levels that designate digital/physical

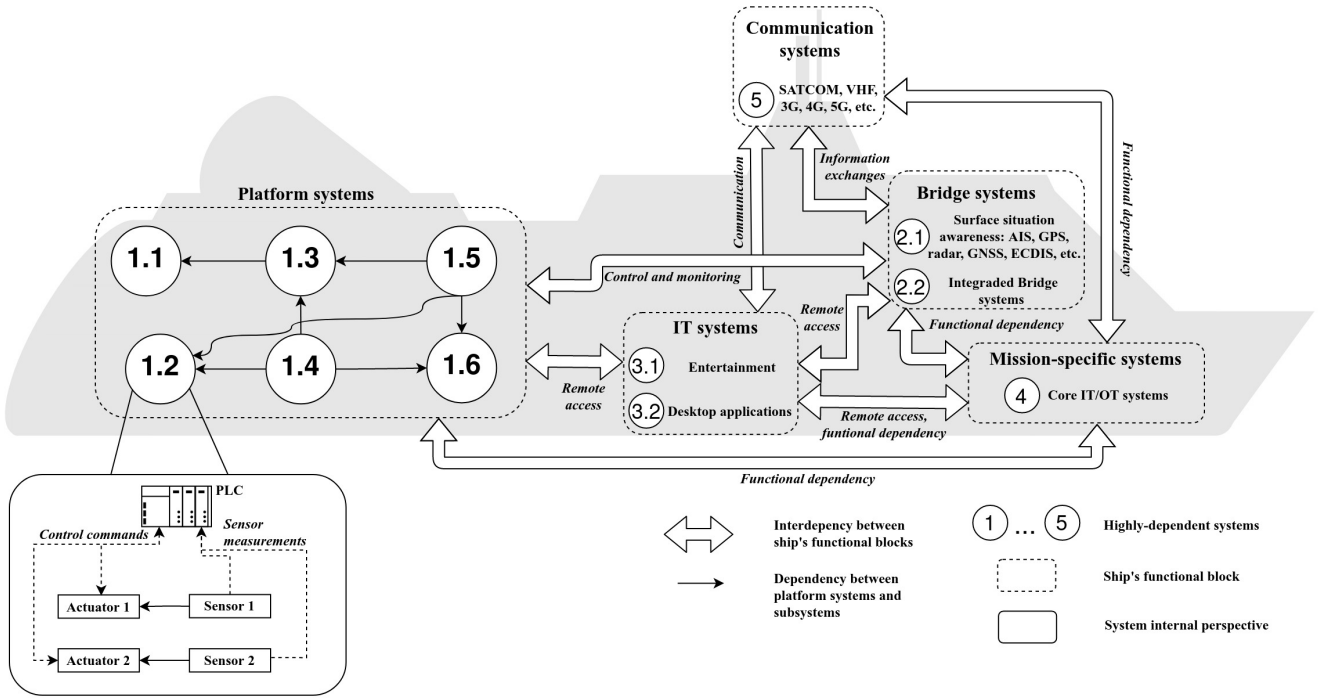


Fig. 1. Schematic definition of on-board systems interdependencies.

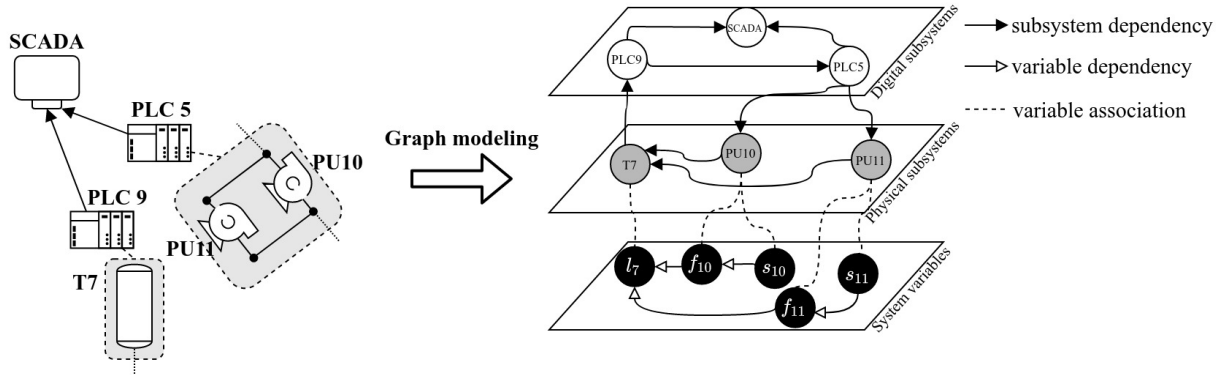


Fig. 2. Application of the graph model to a simplified water distribution CPS [12].

communication dependencies (e.g. sensor measurements transmission, PLC-to-actuator control command) or functional dependency (e.g. a pump in charge of filling a tank).

- A second dependency type between system variables of the third level that illustrates the impact of a given variable on others. This could be a structural impact – a variable deviation can cause the variation of others –, or an operational impact – subject to the activation of a specific value in other variables – dependency. Moreover, each system variable is associated to a given subsystem of the first two abstraction levels of the model.

The described graph was introduced in one of our previous works [20]. For this article we provide a more comprehensive

description of the main system layers and interdependencies characteristics.

IV. CASE STUDY

A. Water management systems

On board water supply is a major issue, considerably accentuated by the maritime domain inherent constraints. Space restrictions and mission specificities make difficult to set-up the distribution network, its monitoring, and maintenance. Depending on the application on board, water management is ensured by several auxiliary systems with different purposes. We distinguish two types of water management auxiliary systems. A first type is associated to drinking and basic uses water. It has a direct impact on crew members or passengers, related to its consumption and daily uses for basic amenities.

A second type of water management auxiliary system is employed to supply water to different specific systems, in charge of the ship's operational stability, as the cooling water system or ballast water, for example.

The control and monitoring of ship's water management systems is thus critical. Operators control and supervise the water management system using digital systems, on different on-board supervision points. Consequently, each water management system is associated to several dependencies that must be identified, specified, and analyzed. As mentioned above, these dependencies should be studied from both external and internal perspectives, and could differ from one ship to another. In the following subsections, we propose a generic identification of these dependencies. Thanks to the implementation of the previously proposed maritime systems dependencies analysis (Subsection III-B), a simplified schematic definition of only the water management systems dependencies is represented (Fig. 3).

B. Water management systems dependencies from the external perspective

Several interdependencies are associated to the water management systems. These dependencies are mostly functional, from one system to another, or characterize information exchanges for system control and monitoring. Being a major system, water management is defined with multiple dependencies to other **platform systems**. First of all, it receives electricity from the power supply system to guarantee the working of equipments like pumps. Then, the water management system is associated to the **propulsion system**, i.e. chilled water is used to limit thermal energy that could disrupt engines. Some vessels also optimize their stability during particular navigation conditions with a ballast **specific system**, i.e. gain stability by filling tanks on the lower-most part of the vessel with a dedicated water management system.

Ship's operators control and monitor the water management systems from the control post, located near the machinery room, but also from the bridge making use of the **Integrated Bridge System (IBS)**. A remote access can also be enabled with specific **IT systems**, through Internet connection provided by **communication systems**. Also, the ship's SCADA system could allow Remote Monitoring and Maintenance of the concerned water management systems.

According to the vessel's mission, on-board water consumption would be a point of concern. Especially for cruise ships, where water is just as crucial to ship's operation as fuel is (<https://www.royalcaribbean.com/blog/how-royal-caribbean-conserves-water-on-its-cruise-ships>, Visited on Jul. 23, 2021). In the future, smart consumption meters could be used to provide consumption feedback to passengers, in (near) real-time through specific **IT system**, to encourage consumption reduction. The effectiveness impact of such feedback has already been studied for a classic water distribution network [21]. This measure could be a part of maritime environmental policy soon, which is increasingly reinforced since the past

few years to reduce the environmental impact of maritime activities.

C. Water management systems dependencies from the internal perspective

A water management system is composed of several interdependent subsystems. Pumps, valves, tanks, drinking water production subsystem, and waste water treatment, among others, ensure classic hydraulic functions within the water management system. Those subsystems are controlled and monitored by several digital subsystems like PLCs. Multiple dependencies can be identified between these subsystems. For instance, a functional dependency between a pump that fills-up a tank to ensure the hydraulic operation. They are combined with other digital dependencies based on information exchange to ensure the physical process control and monitoring. For example, control commands from a PLC to a hydraulic actuator as a pump or a valve. Another dependency could also be identified through measured data transfer from a tank-level sensor to a given PLC in charge of the physical process control.

D. Maritime water distribution network

To illustrate the proposed approach of maritime system interdependencies analysis from an internal perspective, we chose a critical part of the water management system: the water distribution network for consumers use. The main objective of an on-board water distribution network is to satisfy the demand of the consumers, while guaranteeing an optimal quality level of the distributed water. However, improper water distribution is a potential path for infectious diseases transmission that could have major consequences [22]. Such possible disease outbreak could have a considerable impact, aggravated by imposed promiscuity as a result of space constraints and the ship's operation duration.

Depending on its class and mission, a vessel may transport up to 10,000 passengers and crew members. Besides the number of consumption points, the increase of uses and distribution complexity makes the on-board water management very demanding. In this context, on-board water management is similar to managing the water infrastructure for a small city [23]. For this reason, we adapted the well-known C-town water distribution network to our study case [24]. This network is composed of 388 nodes, 429 pipes, 7 tanks, 11 pumps, 4 valves (1 actionable), 9 PLC and 1 SCADA. Water storage and distribution depend on the water levels of 7 tanks, filled by 11 pumps. Each actuator, i.e. pumps and valves, and each sensor, are connected to one of the 9 PLCs which control or monitor each of them. A monitoring system collects the PLCs readings and coordinates the entire process. PLCs are controlling actuators in accordance with sensor readings, mostly collected from other PLCs.

E. Generated graph of the maritime water distribution CPS

As it has been previously indicated, each system and subsystem variable of the maritime water distribution CPS is

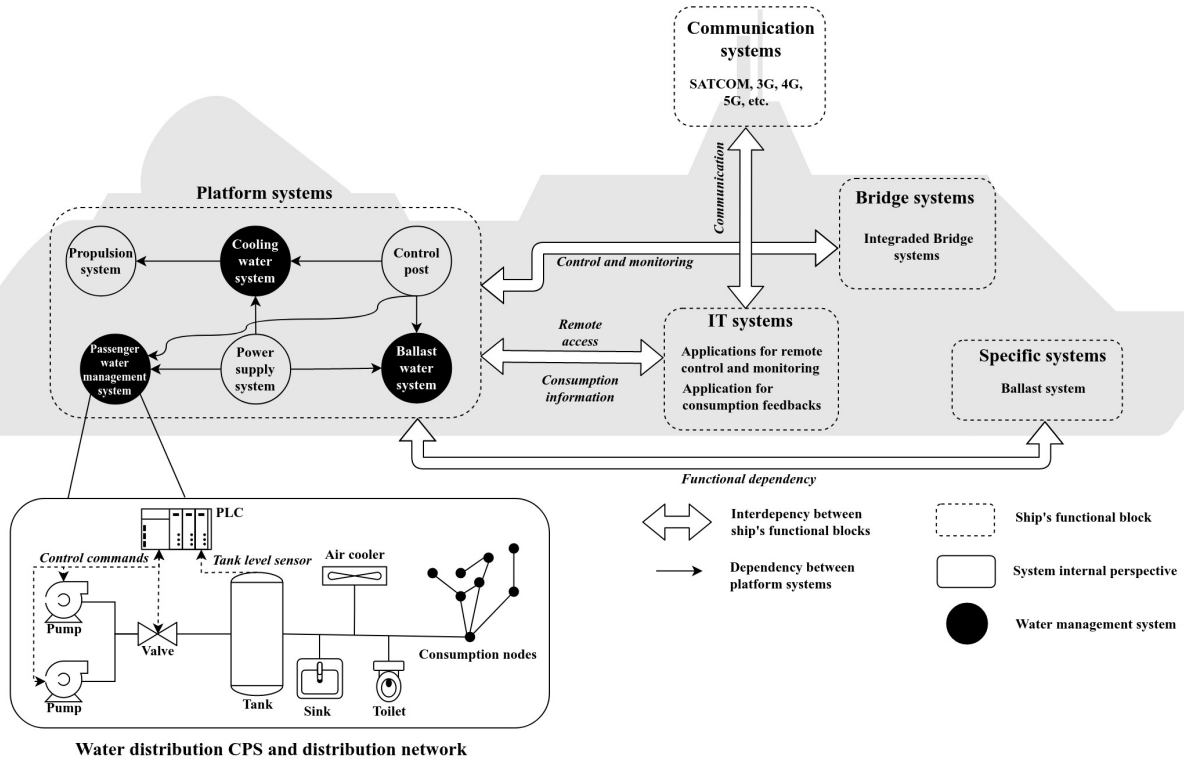


Fig. 3. Schematic definition of water management systems dependencies.

schematized in the generated graph as a node, while interdependencies between two nodes are represented by edges. The dependencies between system variables, determined as part of the system design process, are built from the subsystems interdependencies described in a study that characterized cyber-physical attacks on water distribution systems [25]. An illustration of the partial resulting generated graph model is shown in Fig. 2. The modeled part of the water supply network is in charge of the T7 tank. The tank-level is controlled by pumps PU10 and PU11 that are activated by PLC 5, according to the transmitted tank-level information from PLC 9 to PLC 5. All variable values of actuators and sensors are communicated through the PLCs-to-SCADA connections for process monitoring. This generated graph is an operational representation of the different systems interdependencies, which could be the starting point of cybersecurity evaluation, by means of assessing the relations between connected nodes.

V. DISCUSSION

The conceptualization of maritime systems interdependencies for cybersecurity is a major concern during the whole ship's life-cycle. Concrete examples have already demonstrated the significant consequences that could result from an incorrect understanding of those interdependencies. Furthermore, the level of dependencies between maritime systems is not likely to decrease in the near future. Quite the contrary, the ship's complexity increase associated with significant crew reduction, tend to reinforce this high-dependency aspect of

maritime systems. This seems to be confirmed by the progress of autonomous and remotely-operated ships.

We have proposed a generic analysis to formulate maritime systems dependencies definition and representation, highlighting the issues of this domain. Several global dependencies layers that compose a conventional ship have been identified from both external and internal perspectives. The proposed analysis has been illustrated with a specific use case of a critical system on board, the water management system for consumers use. A coherent representation of the analyzed system is obtained, in the form of a multi-level graph, from an internal perspective, by modeling the identified subsystems and corresponding interdependencies.

Other maritime systems' interdependencies evaluation from external and internal perspectives could also be proposed for different ship's life-cycle stages, as well as different ship's functional blocks, applying the described generic analysis. For instance, the potential impact of navigational systems dependencies if false navigation information is received [26]. Besides, it also appears to be necessary to deal with the dependencies identification and representation between the given ship and diverse external systems as other ships, unmanned vehicles, satellites, etc., in an adaptive manner and in agreement with the ship's mission. For example, naval ships are beginning to use the strategy of naval cooperative watch, a new tactical situational awareness capability based on information exchanges within a naval force composed of ships, aircrafts, and unmanned vehicles (<https://www.nava>

news.com/naval-news/2021/06/french-and-dutch-navy-conducted-joint-naval-cooperative-watch, Visited on Jul. 23, 2021). Ultimately, system dependencies representation and evaluation, as well as cybersecurity evaluation, should be incorporated to Maritime Cyber Situational Awareness [27], to improve ship cyber situation comprehension in real-time and in a predictive way.

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