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Marine autonomous surface ship - control system configuration

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Abstract: This paper addresses the problem of marine autonomous surface ship (MASS) control. The contribution of the paper is the development of a control system configuration, done assuming fully autonomous MASS operation under distinct operational conditions. The overview of hardware and software selection is included.

Keywords: autonomous operation, marine autonomous surface ships, autonomous missions, control structure design, control system configuration.

1. INTRODUCTION

It is a burden of modern society to heavily depend on services and permanent access to goods. The trend is that this dependency is deepening constantly. This situation lays out demands on worldwide logistics for at least, approximately, 50 to 70 years. Nowadays, the logistic systems are considered to comprise a 24/7 supply chain which is essential for continuous delivery and industry 4.0. Under these circumstances, a human worker is becoming an inefficient element of a system. Moreover, introducing a human factor into this type of environment is beginning to pose a significant threat due to simple fatigue. To overcome these issues, large companies have started to develop and deploy automated — autonomous — delivery systems, e.g. an unmanned aerial vehicle (UAV) drone delivery system by Amazon.com, Inc. (Amazone). Historically, humans conquered 'seas' and the 'air'. And after the autonomous UAVs, the key players are now turning their attention into the seas once again with the help of a class of unmanned surface vehicles, namely, marine autonomous surface ships (MASSs) produced e.g. by Rolls-Royce and Intel (Rolls-Royce).

Unmanned autonomous ships are considered the future of maritime transport. Transport of products by sea is currently the cheapest and most ecological way of cargo transport. They open up new possibilities in the field of construction, design, and operation of the unit. Lack of crew on the ship will allow for reduction of systems served only by crew. This will save costs, reduce weight, and allow to carry more cargo. Removing elements related to the crew's operation on the ship, e.g. better use of the superstructure, should improve the reliability and efficiency of the unit's operation while reducing construction and operating costs. An additional reduction in the ship's maintenance costs would further emphasise the superiority of vessels in transport. Currently, the efforts of scientists, ship designers, equipment manufacturers, and classification societies are combined to adapt the existing legal regulations, to assess the technological capabilities of construction and operation of an autonomous unit at sea, and to assess the risk of introducing such an autonomous unit. There are many benefits and dangers associated with the construction and operation of an autonomous unit, and every effort should be made to minimise the latter. One of the benefits is to provide continuous and accurate communication with the mainland, and hence to increase communication and improve communication system management. Such communication will have to be bi-directional and accurate, as well as supported by many systems and creating redundancy in order to minimise the risk of failure. At the same time, the effectiveness of the ship's mission without a human presence on board will be based on integrated computer systems for navigation, control, management and decision making, as well as on the reliability of these systems.

The operation of all vehicles at sea is guided by international law, except for the facts related to the unmanned surface vehicles (USVs). The hard work of distinct international legislative bodies is now focused on soliciting key rules for enabling worldwide safe operation of USVs in terms of critical infrastructure.

An important issue is to determine the level of ship autonomy (Maritime Safety Committee, 2018). A number of maritime organisations and classification societies are working on the introduction of a definition of autonomy levels for surface vessels — autonomous seagoing vessels.

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When defining autonomy, in most cases only issues relating to the navigation system are considered. However, a seagoing vessel is a combination of a number of systems: propulsion, electricity, cargo and others. Therefore, the autonomy levels should apply to all systems on board, including navigation systems. Analysing the current levels of automation of onboard systems on ships, they vary considerably. Similar variations may exist for the autonomy levels of these systems. However, when determining the level of autonomy, the ship should be considered as a single system, with interconnected subsystems covering its overall operation. The other difficulty in defining the autonomy level is the possibility of dynamic transition between different autonomy levels, with a clear definition of responsibilities and decision-making for all possible scenarios. In addition, the autonomy levels must meet the condition of being able to use surface units in real projects. The maritime organisations and classification societies propose four to six levels of autonomy, depending on the assumptions made. In most of the autonomy levels developed by these organisations, there are some similarities. This applies to the lowest level of autonomy of a unit with human responsibility for action, while the highest level is the level at which the ship operates autonomously without human intervention in decision-making. The other proposed levels are differentiated. An example is the proposal of one of the classification societies of Bureau Veritas suggesting a division into 5 levels of autonomy. Correspondingly, the levels (l_i, $\forall i \in \overline{0,4}$) are divided as follows:

- l_0: *human handling* — operations are executed manually or automatically and all processes are executed under human control. The human being makes all decisions and controls all functions performed on the ship;
- l_1: *human management* — decision support, decision making, and actions are carried out by the human being, while the system only suggests decisions and actions;
- l_2: *human is responsible for action* — the human being must confirm decisions. The system evokes functions, and the human operator can reject decisions in a specified time;
- l_3: *human supervision* — the system does not expect confirmation, but the human operator is always informed about decisions and actions. The system evokes functions without waiting for human reaction;
- l_4: *fully autonomous* — the system does not expect confirmation, and the human being is informed only in case of emergency. The system calls functions without informing the human operator..

The Norwegian Forum for Autonomous Ships (NFAS) has prepared their own suggestions on the terminology used for autonomous vessels and includes suggestions on autonomy levels (l_i, $\forall i \in \overline{0,5}$):

- l_0: *decision support* — decision support and advice for the crew on the bridge, the crew makes decisions;
- l_1: *automatic bridge* — automatic operation, but under constant supervision of the crew;
- l_2: *remote control* — unmanned, continuously monitored and direct control from land;
- l_3: *automatic vessel* — unmanned under automatic control, supervised from shore;
- l_4: *limited autonomy* — unmanned ship, partly autonomous, supervised from shore;
- l_5: *fully autonomous* — unmanned and unattended vessel.

Rolls-Royce is so far the only company offering autonomous technologies among the organisations that have put forward proposals for the concept of autonomy. The division into levels (l_i, $\forall i \in \overline{0,4}$) has been confirmed in their projects and accordingly:

- l_0: *no autonomy* — all operational tasks are performed by a human operator, even in combination with warning or intervention systems. The operator handles the system safely at all times;
- l_1: *partial autonomy* — selected operational tasks are performed by a human operator, but some of the specified sub-tasks can be delegated to the control system. The operator has overall control of the system and operates the system safely at all times;
- l_2 *conditional autonomy* — Targeted operational tasks are performed by the automated system without human interaction and the operator performs the remaining tasks. The operator is responsible for the safe operation of the vessel;
- l_3: *significant autonomy* — targeted operational tasks performed by the automated system without human interaction and the operator performs the remaining tasks. The system is responsible for the safe operation of the ship;
- l_4: *full autonomy* — all operational tasks are performed by the automated system under all specified conditions.

The proposed autonomy levels must be tested and validated in real life projects to ensure their practical applicability.

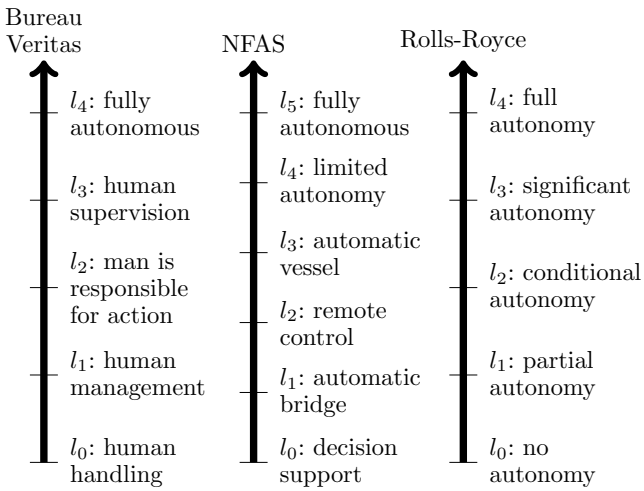

Fig. 1. Autonomy levels

The aim of this work is to create a system architecture concept of autonomous control and navigation for fully autonomous ship and the concept of integration of the modules associated with mission planning, understood as the safe passage of the ship from the start point to the end point, taking into account weather conditions and avoiding static and dynamic obstacles.

The main contribution of the paper is a comprehensive structural and (partial) algorithmic development of a control system necessary to invoke an autonomous USV operation under different operation conditions. Notably, it is clear that it is still far from being a sufficient solution as the autonomous operation on seas, mainly due to the heavy influence of disturbances and obvious environmental impact in case of undesirable change of operational state, e.g. to emergency (Brdys, 2014). The matters of operation and handling of the disturbance and emergency operating conditions and states require much more sophisticated approaches than those typically met in onshore process control (possible except when it comes to nuclear power generation).

The paper is organised in the following manner. The problem formulation is given in Section 2. Ship, sensor and actuator models have been described in Sections 3 and 4, respectively. The main contribution the proposed structures and algorithms is given in Section 5. Section 6 concludes the paper.

2. PROBLEM OF AUTONOMOUS SHIP CONTROL

Take $\mathbb{R}^{(\cdot)}$ to denote the $(\cdot)$-dimensional vector space over a real number field $\mathbb{R}$ and the quadruple $(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{d}, \boldsymbol{y})$, for which at each time instant the following holds:

$$\begin{aligned}(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{d}, \boldsymbol{y}) &\in (\mathbb{X}_{\mathrm{x}}, \mathbb{X}_{\mathrm{u}}, \mathbb{X}_{\mathrm{d}}, \mathbb{X}_{\mathrm{y}}) \\ &\subset (\mathbb{R}^{n_{\boldsymbol{x}}}, \mathbb{R}^{n_{\boldsymbol{u}}}, \mathbb{R}^{n_{\boldsymbol{d}}}, \mathbb{R}^{n_{\boldsymbol{y}}}),\end{aligned} \tag{1}$$

to denote the state, control and disturbance inputs and measurement outputs, contained in the state, control and disturbance input and measurement domains defined over the corresponding spaces, respectively. Then the dynamics $\mathcal{F}_{\mathrm{SS}}$ of a marine vessel (surface ship or simply plant) yields:

$$\mathcal{F}_{\mathrm{SS}} : \begin{cases} \mathbb{X}_{\mathrm{x}} \times \mathbb{X}_{\mathrm{u}} \times \mathbb{X}_{\mathrm{d}} & \mapsto \mathbb{V} \\ \mathbb{X}_{\mathrm{x}} \times \mathbb{X}_{\mathrm{u}} \times \mathbb{X}_{\mathrm{d}} & \mapsto \mathbb{X}_{\mathrm{y}} \end{cases}, \tag{2}$$

where $\mathbb{V} \cong \mathbb{R}^{n_{\boldsymbol{x}}}$ represents the velocity space.

The main features of $\mathcal{F}_{\mathrm{SS}}$ are such that it represents the nonlinear, mechanical, dynamic system endowed with high impact of uncertainty in terms of both parameters and inputs.

In general, the objective is to construct a sophisticated control system:

$$\mathcal{F}_{\mathrm{AC}} : \mathbb{X}_{\mathrm{op}} \times \mathbb{X}_{\mathrm{y_{mes}}} \mapsto \mathbb{X}_{\mathrm{u_a}}, \tag{3}$$

where: $\mathbb{X}_{\mathrm{u_a}} \equiv \mathbb{X}_{\mathrm{u}}$, $\mathbb{X}_{\mathrm{op}}$ is a set of admissible mission objectives, that enables considered marine vessel unit ($\mathcal{F}_{\mathrm{SS}}$) to carry out an autonomous execution of prescribed mission objectives. This is achieved by closing a loop using sensory information:

$$\mathcal{F}_{\mathrm{S}} : \mathbb{X}_{\mathrm{x}} \times \mathbb{X}_{\mathrm{d}} \mapsto \mathbb{X}_{\mathrm{y_{mes}}} \tag{4}$$

under mission operator guidance ($\boldsymbol{r}_{\mathrm{MP}} \in \mathbb{X}_{\mathrm{op}}$) and actuation by:

$$\mathcal{F}_{\mathrm{A}} : \mathbb{X}_{\mathrm{u_a}} \mapsto \mathbb{X}_{\mathrm{u}} \tag{5}$$

and results in obtaining a MASS class vehicle given by:

$$\mathcal{F}_{\mathrm{MASS}} \stackrel{\mathrm{def}}{=} \mathcal{F}_{\mathrm{SS}}|_{\mathbb{X}_{\mathrm{u}} = \mathcal{F}_{\mathrm{A}} \circ \mathcal{F}_{\mathrm{AC}}(\mathbb{X}_{\mathrm{op}} \times \mathbb{X}_{\mathrm{y_{mes}}})}. \tag{6}$$

The described setup is depicted in Fig. 2. The role of the operation center (OPC) is to assign mission and sub-mission objectives ($\boldsymbol{r}_{\mathrm{MP}}$) to possibly multiple MASS class vehicles under supervision based on mission status reports ($\boldsymbol{y}_{\mathrm{MP}}$), whilst $\mathcal{F}_{\mathrm{MASS}}$ is to carry out the mission.

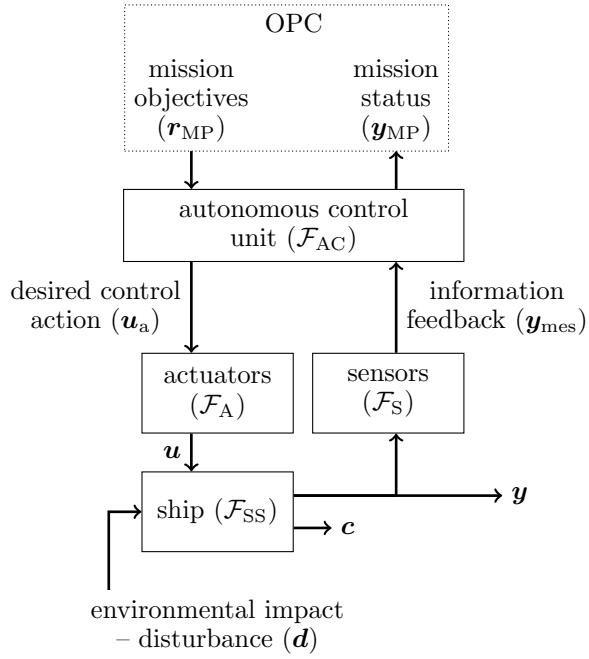

Fig. 2. General control structure

In this work, it is assumed that the marine vessel under consideration is equipped with a single propeller and rudder subsystem unit as a special case of multi-propeller and multi-ruder drive. The structural changes that one need to make to adjust the considerations for the latter case is to 'multiply' actuating $\mathcal{F}_{\mathrm{A}}$ subsystems and to consider vectors instead of scalars where appropriate.

A problem addressed in this work is to propose an adequate (internal) structure of $\mathcal{F}_{\mathrm{AC}}$.

3. SHIP MODEL STRUCTURE

As indicated in the previous section, $\mathcal{F}_{\mathrm{SS}}$ is characterised by nonlinear dynamic relations influenced by uncertainty in both parameters and inputs. In principle, this is a result of hydrodynamic phenomena acting on the immersed ship body and changes in the current ship state (carried load, velocity *etc.*). In terms of inputs, the marine vessel is immensely influenced by the environment. This impact is usually characterised by a countable and finite number of factors (typically considered additive stochastic disturbance inputs) such as e.g. wind, waves, and sea currents, or the water depth (Fossen et al., 1994). Under these unfavourable conditions, the ship is to maintain the desired (planned) trajectory (manoeuvre and cruise) by utilising onboard equipment such as e.g. rudder, main propeller, or tunnel thrusters.

Considering typical marine industry decomposition of marine vessel dynamic relations, $\mathcal{F}_{\mathrm{SS}}$ is considered to be composed of the following set of interacting subsystems: ship dynamics ($\mathcal{F}_{\mathrm{SS\,dyn}}$), ship kinematics ($\mathcal{F}_{\mathrm{SS\,kin}}$), disturbance model ($\mathcal{F}_{\mathrm{SS\,dis}}$), rudder ($\mathcal{F}_{\mathrm{SS\,rud}}$), and propeller ($\mathcal{F}_{\mathrm{SS\,prop}}$) as depicted in Fig. 3. The control input vector is typically considered as $\boldsymbol{u} \stackrel{\mathrm{def}}{=} [\delta, n, H]^T$, where its components denote the rudder angle and propeller revolution and pitch,

respectively. Consequently, the controlled output vector $\boldsymbol{c} \stackrel{\text{def}}{=} [\psi, \beta, u, v, r]^T$ is to consists of ship's heading, drift and velocity (u, v, r).

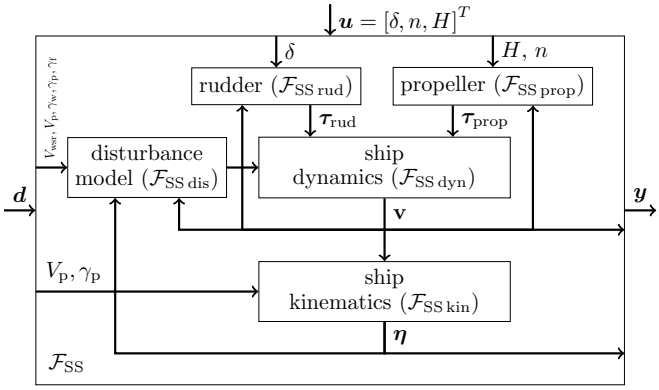

Fig. 3. Marine vessel subsystems

3.1 Ship kinematics and dynamics ($\mathcal{F}_{\text{SS kin}}$, $\mathcal{F}_{\text{SS dyn}}$)

Following e.g. the Newton or (equivalently) Lagrange formulation general equations of ship motion: $\mathcal{F}_{\text{SS}}(\dot{\boldsymbol{x}}, \boldsymbol{x}, \boldsymbol{u}, \boldsymbol{d}) = 0$ are developed using the Earth-fixed frame with the origin at an arbitrary point on the Earth's surface and the body-fixed frame with the origin at the center of gravity of the ship. The system is considered to consist of two subsystems describing ship kinematics ($\boldsymbol{\eta}$) and ship dynamics ($\boldsymbol{v}$). The vector $\boldsymbol{\eta} \stackrel{\text{def}}{=} [x, y, z, \phi, \theta, \psi]^T \in \mathbb{R}^6$ consists of ship's position (x, y, z) and roll, pitch, yaw (heading) $\phi, \theta, \psi \in [0, 2\pi]$ in the Earth-fixed frame driven by $\boldsymbol{v}$ w.r.t. $\mathcal{F}_{\text{SS kin}}$. The vector $\boldsymbol{v} \stackrel{\text{def}}{=} [u, v, w, p, q, r]^T \in \mathbb{R}^6$ reflects the ship's surge, sway, heave, roll, pitch and yaw velocities, respectively, in the body fixed frame and is driven by the net forces and torques resulting from actuators ($\boldsymbol{\tau}$) and disturbances ($\boldsymbol{\tau}_{\text{env}}$) w.r.t. $\mathcal{F}_{\text{SS dyn}}$. These two comprise the state vector $\boldsymbol{x} \stackrel{\text{def}}{=} \left[\boldsymbol{\eta}^T, \boldsymbol{v}^T\right]^T$. The input vector $\boldsymbol{\tau} = \boldsymbol{\tau}_{\text{rud}} + \boldsymbol{\tau}_{\text{prop}} \in \mathbb{R}^3$ represents the forces and torque coming from the rudder ($\mathcal{F}_{\text{SS rud}}$) and propulsion devices ($\mathcal{F}_{\text{SS prop}}$) in the body-fixed frame. The vector $\boldsymbol{\tau}_{\text{env}} = \boldsymbol{\tau}_{\text{wave}} + \boldsymbol{\tau}_{\text{cur}} + \boldsymbol{\tau}_{\text{wind}} \in \mathbb{R}^3$ describes in the Earth-fixed frame the environmental disturbances which come from wind, waves and currents, respectively.

3.2 Disturbance model ($\mathcal{F}_{\text{SS dis}}$)

The vector $\boldsymbol{\tau}_{\text{env}} \stackrel{\text{def}}{=} \mathcal{F}_{\text{SS dis}}(\boldsymbol{d}, \boldsymbol{x})$, where, typically, $\boldsymbol{d} \stackrel{\text{def}}{=} [V_{\text{wsr}}, V_{\text{p}}, \gamma_{\text{w}}, \gamma_{\text{p}}, \gamma_{\text{f}}]^T$ and V_{wsr} , γ_{w} are the average wind speed and direction, respectively. γ_{f} denotes the wave direction, and V_{p} , γ_{p} denote the sea current speed and related direction, respectively. These parameters describe, generally, high- and low-frequency forces and moments acting on the vessel. The low-frequency part, driven by loads generated by the 2nd-order mean and slowly varying wave, current and wind, has to be counteracted by the control inputs. The high-frequency part has to be filtered from the measurements by using e.g. Kalman Filter, particle Kalman Filter, backstepping observer or passive observer. Usually in the ship model, only the low-frequency part of $\boldsymbol{\tau}_{env}$ is considered assuming that one of the filtering techniques has been successfully implemented.

3.3 Rudder and propeller subsystems ($\mathcal{F}_{\text{SS rud}}$, $\mathcal{F}_{\text{SS prop}}$)

The role of the rudder and propeller subsystems is to bind the influence of rudder angle and propeller pitch and revolutions with the forces and torques exerted by these elements upon the ship body. This is done according to:

$$\begin{bmatrix} \boldsymbol{\tau}_{\text{rud}} \\ \boldsymbol{\tau}_{\text{prop}} \end{bmatrix} = \begin{bmatrix} \mathcal{F}_{\text{SS rud}} \\ \mathcal{F}_{\text{SS prop}} \end{bmatrix} (\boldsymbol{u}) \,. \tag{7}$$

3.4 Including operational states and conditions

As it has already been indicated, $\mathcal{F}_{\text{SS}}$ s constantly influenced by the surrounding environment. In fact, the impact of the environment in unfavourable conditions can make following the desired path an unfeasible task due to lack of actuation capabilities (e.g. limited propulsion power). Under such circumstances, the operating conditions enforce the MASS operation state to switch to the disturbance or even emergency operating state. The transition to the emergency state can also occur due to an inevitable collision event.

The consequence of autonomous operation requires the MASS unit to handle the operation in arbitrary operating conditions and states. Developing the required simulation or utility models for either simulation or monitoring/control synthesis tasks is, in general, very complex. This is mainly due to the complex phenomena that occur, e.g., during collision related to abrupt change of ship trajectory geometry. Therefore, it is considered conceivable to acquire (derive or learn) different models for distinct operational states and use the available models adequately. This approach results in a so-called hybrid system model where the dynamic model is extended by a set of discrete (e.g. binary) states ($\boldsymbol{x}_{\text{b}}$) used to select a model and a set of events to handle the transition between the (operational) states. This hybrid model can be interpreted as a joint dynamics model and an (finite) automata.

Finally, under the amendments described in previous lines, the augmented state is considered as $\boldsymbol{x}_{\text{a}} \stackrel{\text{def}}{=} \left[\boldsymbol{x}^T, \boldsymbol{x}_{\text{b}}^T\right]^T$. A suitable technical characterisation of hybrid systems is beyond the scope of this work. A comprehensive description of the idea can be found e.g. in Heemels et al. (2001).

4. SENSORS AND ACTUATORS

4.1 Sensors ($\mathcal{F}_{\text{S}}$)

In general, the measurement information acquired onboard can be divided into two categories: hard measurement ($\boldsymbol{y}_{\text{mes h}}$) and information feed ($\boldsymbol{y}_{\text{mes i}}$), so that ($\boldsymbol{y}_{\text{mes}} \stackrel{\text{def}}{=} \left[\boldsymbol{y}_{\text{mes h}}^T, \boldsymbol{y}_{\text{mes i}}^T\right]^T$). The first category consists of the information measured directly by the sensors mounted on ship, e.g. wind speed and temperature sensors, Global Positioning System (GPS), chip (ship) log, magnetic compass, inertial measurement unit (IMU), radar, lidar, or sonar devices *etc.* The second category is related with the communication links e.g. Automatic Identification System (AIS), *etc.* Notably, part of ship's equipment has its own diagnostic module. Therefore, this information where available is treated as measurement and included into $\boldsymbol{y}_{\text{mes}}$ as part of $\boldsymbol{y}_{\text{mes h}}$. The acquired measurement information is later used for state estimation.

4.2 Actuators ($\mathcal{F}_{\mathrm{A}}$)

In the described setup, the ship's actuation system ($\mathcal{F}_{\mathrm{A}}$) comprises servomechanisms for rudder control, fuel injection valve setting, and propeller fin positioning, so $\boldsymbol{u}_{\mathrm{FU}} \stackrel{\mathrm{def}}{=} [u_\delta, u_n, u_H]^T$, where u_δ, u_n, u_H represent the control signal required for $\mathcal{F}_{\mathrm{A}}$ to implement the desired control action. Moreover, it is assumed that the outgoing communication ($\boldsymbol{u}_{\mathrm{com}}$) is transmitted using the communication infrastructure included as part of $\mathcal{F}_{\mathrm{A}}$. Hence, it follows that $\boldsymbol{u}_{\mathrm{a}} \stackrel{\mathrm{def}}{=} \left[\boldsymbol{u}_{\mathrm{FU}}^T, \boldsymbol{u}_{\mathrm{com}}^T\right]^T$.

5. CONTROL STRUCTURE

In general, the proposed structure of $\mathcal{F}_{\mathrm{AC}}$ has a form of a hierarchical control system (Findeisen et al., 1980) which is obtained by functional and temporal decomposition of the plant dynamics (Godhavn et al., 1995; Śmierzchalski, 2013), namely $\mathcal{F}_{\mathrm{SS}}$ as depicted in Fig 4.

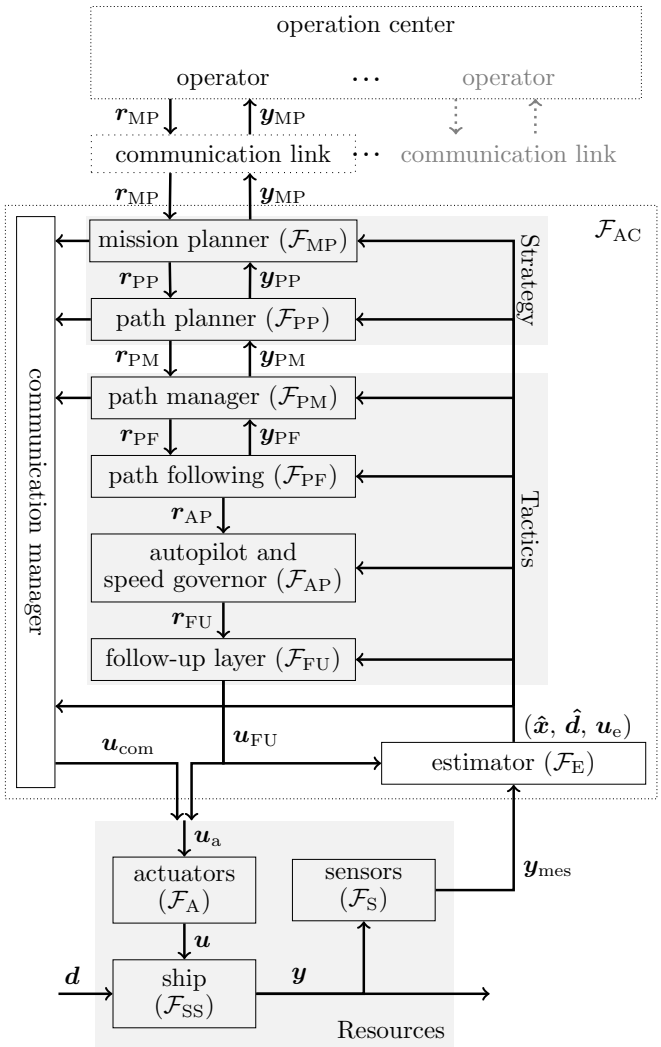

Fig. 4. Autonomous control structure

5.1 Estimator ($\mathcal{F}_{\mathrm{E}}$)

The role of the estimator is to acquire and supply the information critical for MASS operation. It is a complex system which combines the data from multiple sources to provide the information essential for all control layers. It consists of multiple subsystems (Fig. 5) acting on different time scales (analogously to the control system — Fig. 4).

In this work the estimator module is considered to include not only the state estimator ($\mathcal{F}_{\mathrm{E\,x}}$) but also the disturbance estimator ($\mathcal{F}_{\mathrm{E\,d}}$), including interaction, estimator and fault detection ($\mathcal{F}_{\mathrm{E\,fd}}$), and isolation and identification functionalities ($\mathcal{F}_{\mathrm{E\,fi}}$).

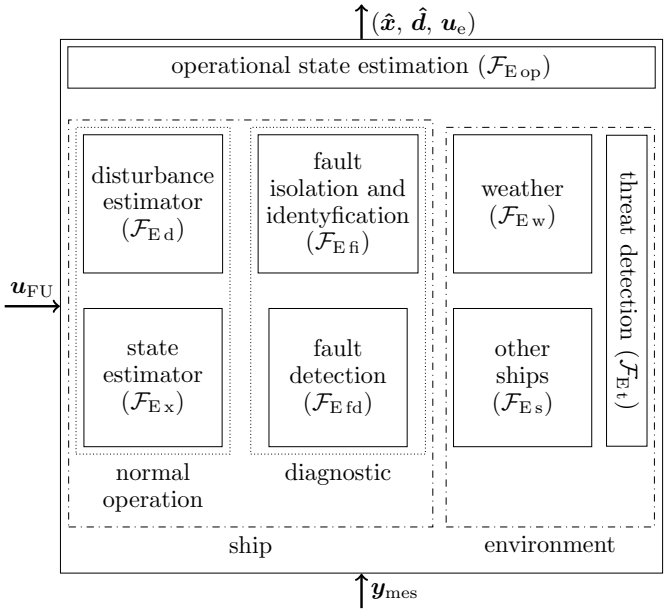

Fig. 5. General estimator structure ($\mathcal{F}_{\mathrm{E}}$)

Typically, the state and disturbance estimation ($\mathcal{F}_{\mathrm{E\,x}}$, $\mathcal{F}_{\mathrm{E\,d}}$) includes algorithms such as low-pass filter, extended Kalman filter (i.e. Grimble et al., 1980; Triantafyllou et al., 1983), or data fusion algorithms (i.e. Hall and Llinas, 1997). Concurrent solutions include i.e. Particle Kalman Filter, (which is robust to some degree to certain types of fault detection, isolation and identification, can be found in (Hwang et al., 2010; Korbicz et al., 2012), among other references.

Some of the disturbance inputs require special treatment due to their direct threat to MASS integrity of operation. This is done by invoking a threat detection estimator ($\mathcal{F}_{\mathrm{E\,t}}$) which includes weather impact ($\mathcal{F}_{\mathrm{E\,w}}$) (e.g. (Śmierzchalski, 2013)) and collision avoidance ($\mathcal{F}_{\mathrm{E\,s}}$) (e.g. (Li and Jilkov, 2003; Bole et al., 2013)).

Finally, on top of all is the operation state estimator ($\mathcal{F}_{\mathrm{E\,op}}$) which is crucial for the autonomous operation of the overall control system (Brdys, 2014).

5.2 Follow-up layer ($\mathcal{F}_{\mathrm{FU}}$)

The Follow-up layer

$$\boldsymbol{u}_{\mathrm{FU}} = \mathcal{F}_{\mathrm{FU}}(\boldsymbol{r}_{\mathrm{FU}}, \hat{\boldsymbol{x}}, \hat{\boldsymbol{d}}) \tag{8}$$

describes the relations between the reference for rudder deflection, propeller rotation speed screw pitch $\boldsymbol{r}_{\mathrm{FU}}$ and signals for control valves of rudder deflection cylinders, efficiency of injection pumps, and position of screw fin cylinders $\boldsymbol{u}$. The input to $\mathcal{F}_{\mathrm{FU}}$ consists of $\boldsymbol{r}_{\mathrm{FU}} \stackrel{\mathrm{def}}{=} [\delta_{\mathrm{z}}, n_{\mathrm{s}}, H_{\mathrm{s}}]^T$,

where: δ_z is the desired rudder angle, H_s denotes the desired pitch of propeller and n_s represents the desired propeller pitch ratio (or propeller revolutions for a fixed-blade propeller).

When during designing of this part of the ship's control system it is assumed that the rudder and the propeller work independently. The layer is implemented as a positioning control system (e.g. (Zubowicz et al., 2018)) so that:

$$\mathcal{F}_{\mathrm{A}} \circ \mathcal{F}_{\mathrm{FU}} \cong 1. \tag{9}$$

5.3 Autopilot and speed governor ($\mathcal{F}_{\mathrm{AP}}$)

The fundamental role of the autopilot (automatic ship course control system) is to control the position and attitude of the MASS. Therefore the autopilot is the control layer which is influenced by such disturbances as e.g. wind, wave, and sea currents. It is typically assumed that this control layer is composed of parallel controllers managing course and speed (e.q. (Tomera, 2010, 2017)) or course (heading) and position (e.q. (Witkowska and Śmierzchalski, 2018)). These controllers operate based on the references ($\boldsymbol{r}_{\mathrm{AP}}$) supplied from the layer placed higher in hierarchy, and on the estimated quantities obtained from $\mathcal{F}_{\mathrm{E}}$. The control signals generated by this layer ($\boldsymbol{r}_{\mathrm{FU}}$) compose the vector of command values for $\mathcal{F}_{\mathrm{FU}}$.

5.4 Path following ($\mathcal{F}_{\mathrm{PF}}$)

In principle, the role of trajectory tracking is to assure that the vehicle under control (MASS) reaches a prescribed position at a precisely set time. This is a very complex task considering the constantly active impact of disturbances (e.g. wind, wave, sea currents). In unfavourable conditions, we can surely foresee that a situation in which the prescribed point is not reachable at the desired time or has been reached in advance can easily occur. This makes disturbance estimation ($\mathcal{F}_{\mathrm{E\,d}}$)a crucial task for this control layer. Alternatively, a common practice is to forsake the trajectory tracking strategy for the path following approach, which makes the task of accounting for the two scenarios described in previous lines more tractable. These paths are typically constructed of line segments or circular orbits supplied in the form of $\boldsymbol{r}_{\mathrm{PF}}$ by the path manager $\mathcal{F}_{\mathrm{PM}}$ placed higher in hierarchy. Henceforth, the role of the path following ($\mathcal{F}_{\mathrm{PF}}$) control layer is to translate this path information ($\boldsymbol{r}_{\mathrm{PF}}$) into the desired course heading and speed ($\boldsymbol{r}_{\mathrm{AP}}$) being the reference for the subsequent autopilot (see Subsection 5.3).

5.5 Path manager ($\mathcal{F}_{\mathrm{PM}}$)

The path manager ($\mathcal{F}_{\mathrm{PM}}$) typically produces a set of straight lines or circular orbits to derive the (time-optimal) Dubins path that manoeuvres the MASS between the (static or dynamic) obstacles. These path segments span to connect the so-called waypoints (in general, points defined in space-time of joint body-earth frames) supplied by the path planner ($\mathcal{F}_{\mathrm{PP}}$) in the form of $\boldsymbol{r}_{\mathrm{PM}}$ (Fossen et al., 2003). This is the first layer that influences the actual desired path/trajectory shape and as such is the fastest to react, under the applied system decomposition, to any undesirable situation. Therefore it is only prudent to endow this layer with the ability to adjust the precise geometry of the individual segments using not only the $\boldsymbol{r}_{\mathrm{PM}}$ but also the information on the yet unaccounted obstacles to enable the so-called last-chance manoeuvring capabilities. Notably, this requires the information feed form $\mathcal{F}_{\mathrm{E\,s}}$ (e.g. (Śmierzchalski, 2013)) and the current information on the position error ($\boldsymbol{y}_{\mathrm{PF}}$). The path manager selects the algorithm for line or circular path following and with an appropriate set of commands supplies the reference to the subsequent control layer as $\boldsymbol{r}_{\mathrm{PF}}$ to enable path following (see Subsection 5.4). Moreover, the current command status information is fed as $\boldsymbol{y}_{\mathrm{PM}}$ to the higher control layer.

5.6 Path planner ($\mathcal{F}_{\mathrm{PP}}$)

The role of the path planner is to solve the task of motion planning that can be executed either by exploiting a point-to-point type algorithm or the behavioural scheme. The former is a sort of deliberate planning considered i.e. for a successful transport mission using MASS, while the latter is a type of reactive scheme in which the sensory data is utilised to find or learn the path or to cover an area e.g. invoking a rescue at sea mission. Considering these deliberations, the role of the path planner ($\mathcal{F}_{\mathrm{PP}}$) is to construct a series of waypoints for the subsequent path manager to invoke MASS operation under $\boldsymbol{r}_{\mathrm{PP}}$ command. The $\mathcal{F}_{\mathrm{PP}}$ is considered to have an internal (also hierarchical) structure to handle global waypoint planning. Global waypoints of return and arrival times to specific waypoints are determined taking into account the predicted hydrometeorological conditions. In the literature, this issue is called meteorological navigation (e.q. (Bijlsma, 2002)). During the course of implementation, this plan is subjected to periodic modifications and designated path corrections (dynamic or tactical planning) taking into account the short-term weather forecast. In order to adjust precisely the geometry of the individual segments, the information on the obstacles (both navigation and sensory data) needs to be accounted for. Notably, this also includes the feed form $\mathcal{F}_{\mathrm{E\,s}}$ (e.g. Śmierzchalski, 2013; Śmierzchalski and Michalewicz, 2000). These tasks are distributed between the layers accordingly. Moreover, the information on current path plans is fed as $\boldsymbol{y}_{\mathrm{PP}}$ to the higher level responsible for mission planning. The exact workflow of $\mathcal{F}_{\mathrm{PP}}$ is strictly dependent on the mission type and the command references prescribed by the layer placed higher in hierarchy, namely the mission planner, as well as on the information about obstacles obtained from maps, $\mathcal{F}_{\mathrm{E\,s}}$, $\mathcal{F}_{\mathrm{E\,t}}$ and $\mathcal{F}_{\mathrm{E\,w}}$ as described in (e.g. Śmierzchalski, 2013).

5.7 Mission planner ($\mathcal{F}_{\mathrm{MP}}$)

The top level of the structure (Fig. 4) includes planning the ship's mission. The role of the operator at this stage is to define the task (from $\mathbb{X}_{\mathrm{op}}$), e.g. the main goal of the voyage, which can be the seagoing ship's passage from the starting point to the end point. Such a system should define navigation strategies to be used in case the ship's mission is threatened. These strategies may include route change or abandoning, return to base, or mission continuation (at this point this 'decision making' layer depends

on the information from $\mathcal{F}_{\mathrm{E\,op}}$). The planning of the ship's mission should take into account static limitations resulting from the avoidance of static obstacles such as lands, shoals, canals, restricted navigation areas, etc. The second group of limitations consists of time constraints resulting from changing weather and/or hydrometeorological conditions. In this case, predicting the occurrence of weather risks in a given region on the basis of forecasts allows for modelling time constraints in the form of dynamic constraints. In maritime navigation, it is also necessary to take into account important parameters of the marine environment which directly affect the safety of the ship. These parameters may include wind force and direction, sea waves, currents, and the state of the sea (for instance, the direction of wind and waves is a very important parameter for container ship navigation). On the other hand, wind direction, waves, and/or sea currents can be used as additional energy to optimise the route (Szłapczyński, 2009; Śmierzchalski, 2013).

6. CONCLUSIONS

The main contribution of this work is that it delivers comprehensive structural development of the control system crucial for marine autonomous surface ship deployment. In the course of research, the control system is decomposed by functional or time-scale decomposition into layers to be handled by a hierarchical control system. The layers of the system are developed in a manner enabling autonomous operation of the considered vehicle. Structural development is the first and essential step to the development of control algorithms, which is part of the ongoing research work. It is foreseen that the structures and algorithms developed in the course of this research will be deployed on the variety of MASS class vehicles.

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