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Unmanned Aerial Surveillance System for Hazard Collision Avoidance in Autonomous Shipping

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Abstract— **Autonomous ships require a sense-and-collision-avoidance functionality based on surveillance of the ocean surface in order to detect unmapped and potentially non-cooperative obstacles and hazards, and to engage into evasive manoeuvres to avoid impending collisions. In this paper, we study the concept of using an autonomous ship being assisted by an unmanned aerial surveillance system (UASS) that provides information to the ship in order to implement collision avoidance in compliance with the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS). The motivation is that a UASS provides complementary sensing capabilities that can be combined with a conventional maritime radar and Automatic Identification System (AIS) to detect smaller obstacles that may be hidden in clutter, behind other objects, or submerged close to the surface. We propose a system architecture and implement a simulation environment to illustrate the concept and study the feasibility of the key control algorithms based on receding-horizon optimization.**

I. Introduction

The concept of unmanned ships offers potential advantages in regard to vessel design and construction as well as a reduction in operating costs relative to traditional manned ships. Applications may range from autonomous surface vehicles (ASVs) for oceanographic research [1] to ships for short sea cargo shipping [2] and longer distance freight [3], as well as specialised vessels for high-risk military operations.

Autonomous operation of a ship requires that guidance, navigation and control is performed with high levels of reliability, performance, and safety. A key enabling factor for this is the real-time surveillance of the ship's environment in order to avoid grounding and collision with other ships, vessels, people, marine mammals, submerged containers (ocean trash), and other obstacles that may be encountered. While stationary hazards such as shallow water, structures, reefs or islands can be avoided with accurate electronic mapping, avoiding free-floating and intermittent hazards and obstacles requires advanced sensor systems. Large ships are expected to carry AIS (automatic identification system) transmitters that broadcast radio signals containing position and other information about the ship that can be picked up by other ships and authorities. This, however, is not the case for smaller surface vessels. Hence, in order to be able to detect the wide range of potential obstacles, on-board sensors such as radar, LIDAR and camera can be used to scan the environment of the unmanned ship [4], [5], [6]. While some of these sensing modalities can operate over relatively large distances, they require line of sight to the obstacles, and that the obstacles are clearly distinguished from background. Therefore, these sensors may not always be effective. Satellite remote sensing is usually not a viable and cost-effective alternative since there may not be full coverage at any position and time, data may not always be available in real-time, they require extensive communication resources, and may not have the resolution and accuracy to detect small obstacles.

The main purpose of this research is to assess the potential of using an unmanned aerial vehicle (UAV) as a mobile and elevated platform for sensors such as radar, LIDAR, and visual and infrared spectrum cameras. We call this concept Unmanned Aerial Surveillance System (UASS). The UAV can operate as a scout performing low-altitude aerial surveillance ahead of the ship in a neighborhood of its planned path. In addition to the

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obvious advantages of redundancy and additional information provided by more sensors, the clear benefit of being elevated at a suitable altitude is that the line of sight is extended, and objects at the ocean surface can be observed at a much more direct angle where it is possible to detect and classify objects that could otherwise be hidden in clutter from sea waves and wakes, solar reflections or other disturbances. Submerged objects close to the surface, such as logs, swimmers, and whales can possibly also be detected. A further benefit of being closer and at a more direct angle is that the obstacles' motion can be observed with higher resolution and detail such that objects can be more easily recognized, identified and tracked using machine vision, pattern recognition and signal processing techniques since more detailed features can be observed, [7]. This can be used for accurate tracking and prediction of obstacle trajectories that reduce the risk of collision with the ship. Such an augmented sensing system could also be used to improve the assessment of the ship's right to keep its course or its responsibility to stay away according to the traffic rules at sea, and enable opportunities for earlier re-planning such that hazards and obstacles can be more easily classified and avoided. This could lead to safer and more efficient ship operations.

Although the concept of Unmanned Aerial Surveillance Systems (UASS) is applicable to both manned and unmanned ships, our motivation in this work is on unmanned ships and boats operating autonomously or with a remote pilot in a coastal environment. One example of application is in support of shipping and marine operations in arctic in waters with icebergs, growlers and other ice features [8]. This is becoming of increasing importance as the ship traffic in the arctic is increasing due to new shipping routes and exploitation of resources such as minerals and petroleum.

II. The Challenges

While an UASS has potential advantages, there are also several challenges and potential limitations:

- Optical UAV sensors such as laser/LIDAR and passive cameras require high visibility that may prevent their usefulness in rain, snow and fog. In the future, this may be less of a problem as robust algorithms for robotic vision are developed and advanced radar systems such as SAR are scaled down in cost, size, weight and becomes common in small UAVs.
- Small UAVs operability may be restricted due to strong wind and icing conditions.
- Since the UAVs need to have both long endurance and a ground speed that is significantly larger than the ship's cruise speed, the use of multi-rotors is not expected to be viable. Also, while the UAVs may be envisaged to be operated from onshore bases, the benefits of autonomous refueling or charging on the ship is also appealing. This might, however, require capability for autonomous launch and precision recovery of winged aircraft on a very restricted landing area, as well as robot-enabled UAV set up for the next launch.
- Air traffic management, airspace regulations, and radio communication requirements in autonomous Beyond-line-of-sight (BLOS) UAV operations in coastal and maritime environments are other challenges [9], [10].

In regard to the ship, there are currently no dedicated rules and regulations for unmanned ships, so we consider the main requirements related to collision avoidance that apply to all ships as given by the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) by the International Maritime Organization (IMO), [11]. They implicitly impose requirements on what kind of information must be provided by the sensor system, and what are the correct actions in the various situations that could occur.

A wide range of collision avoidance control algorithms, many of them implementing some degree of compliance with COLREGS, are reviewed in [12], [13]. None of them, however, scale very well to manage a large number of highly dynamic obstacles in dense traffic and at the same time can accurately take into consideration the dynamics of the ship, steering and propulsion system, as well as environmental disturbances such as wind and ocean current. The collision avoidance functionality in this paper is therefore formulated as a finite-horizon and finite-scenario hazard minimization problem over a finite number of control policies. The optimization problem is solved in a receding horizon implementation with a re-optimization based on real-time updated information at regular intervals, e.g. every 5 seconds. Predictive control with optimization over control policies is chosen since it provides a computationally efficient and robust way to implement complex control decisions by using a predictive simulation model, [14]. The hazard associated with the ship trajectory resulting from a given control policy is evaluated using a ship simulator that operates much faster than real time. It makes predictions that takes into account the dynamics of the ship, steering and propulsion system, the control policy, as well as wind and ocean current. A cost function is derived considering the constraints and objectives of collision avoidance and COLREGs compliance, with some similarities to [15]. The constraints are implemented as penalties in order to ensure that the best possible control policy can be chosen also when collision with at least one obstacle seems unavoidable. Certain key parameters and assumptions are discussed and analyzed, and simulations provide a proof-of-concept.

III. System overview

The overall objective of the autonomous system is to provide trajectory planning for the ship in order to travel to its target destination along a path that is close to its nominal planned path without collision, grounding, or violation of COLREGS.

In order to support the navigation and guidance we assume the following information and capacities are available:

- Electronic map of static hazards.
- Grounding-safe nominal path to the target destination.
- Real-time measurement of the ship's position, velocity, heading and yaw rate.
- Mathematical model of ship for prediction of future trajectory in order to evaluate the effect of steering and propulsion commands on the dynamic capability to change course and speed, as well as winds and ocean currents.
- Estimates of wind and ocean current forces acting on the ship.
- Ship sensors such as radar, lidar, camera or infrared thermal imager that can be used to detect obstacles within line of sight.
- UASS under command and control by telemetry radio link from the ship, with daylight or thermal camera (or similar sensor suite) and real-time processing for detection, recognition and identification of obstacles and their position, velocity, heading and size.

Figure 1 illustrates the main sub-systems and the information flow between them.

The nominal input to the Ship Autopilot from the Mission Planing and Execution is assumed to be the command for speed-over-ground and the desired path parametrized by a sequence of way-points. The Collision Avoidance System (CAS) searches for grounding- and collision-free trajectories close to the ship nominal trajectory, given the measured positions and predicted trajectories of obstacles. The CAS outputs the course angle offset command that is given to the autopilot. Notice that the CAS needs to consider trajectories (with explicit representation of time) while in the autopilot there is a decoupling of position and time into path guidance (steering) and propulsion control. The reason is that time is important in the collision avoidance since the obstacles are moving and the ship has slow dynamics. The speed is normally kept close to a nominal cruise speed, but may be reduced, set to zero, or reversed, upon command from the Collision Avoidance System (CAS). The CAS can also provide alarms in terms of messages to onshore operators, radio telemetry, or sound and light signals. Further descriptions of the CAS functionality are given in section VII.

The ship's on-board navigation system provides measurements (typically from a global navigation satellite system (GNSS)) of position and velocity. The on-board navigation system is also assumed to provide a list of obstacles estimated positions and velocities, from the ship on-board sensors such as radar and AIS. This information is processed by the ship situation awareness and sensor fusion (SASF) system, which also commands the UAV. Based on an assessment of the current situation, the SASF decides the target search area for the UASS and sends commands in terms of an updated list of way-points for the UAV to visit. The UASS op-

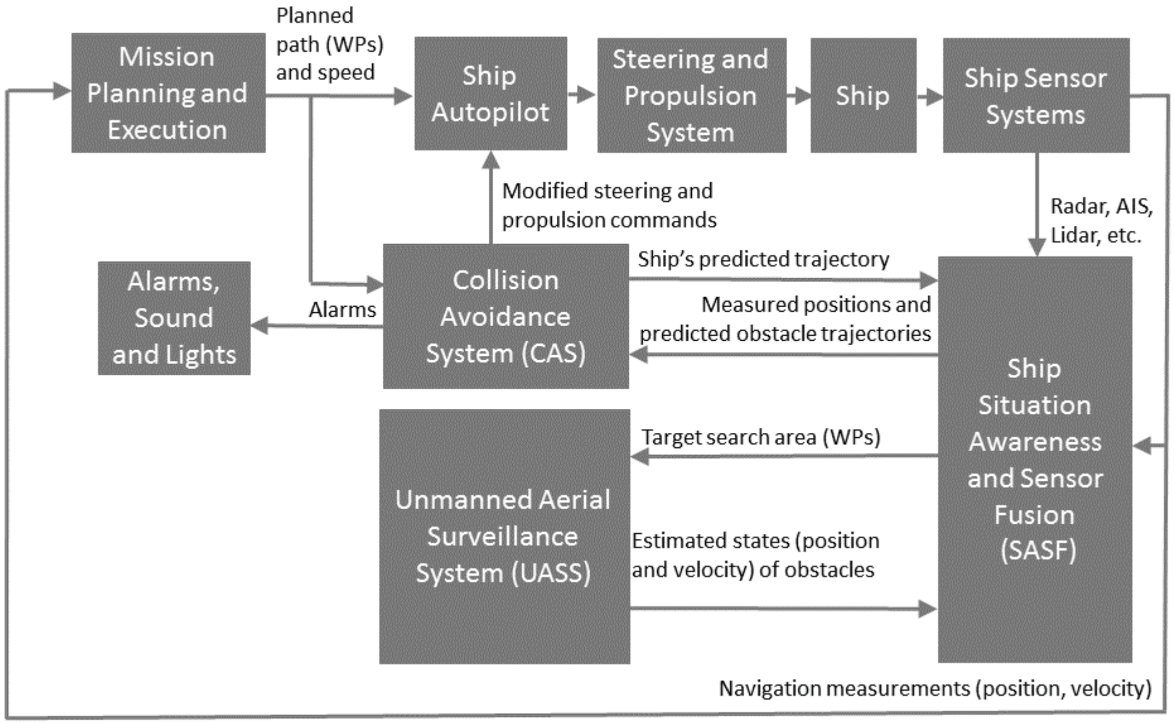

Fig. 1. Block diagram illustrating the information flow between the main modules in the system.

erates according to the current waypoint lists, and collects images for machine vision processing. The machine vision detects, recognizes and estimates the position and velocity of potential obstacles by processing a sequence of images in real-time and associates with a database of typical and recently encountered obstacles [16], [17]. The SASF system cross-references and fuses the data from the different sources before the list of obstacles and their state and predictions is updated and made available to the CAS.

IV. Requirements for Collision Avoidance

This section summarises of the main technical and operational requirements from the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS) by the International Maritime Organization (IMO), [11], which are directly applicable to our case study. In particular, the following rules have a bearing on the ship collision avoidance system:

- **Rule 6 - Safe speed**. The following should be considered: Visibility, traffic density, stopping distance and turning ability, wind/waves/current, navigational hazards, draught vs. depth, radar state.
- **Rule 8 - Actions to avoid collision.** Actions shall be made in ample time. If there is sufficient sea-room, alteration of course alone may be most effective. Safe distance is required. Reduce speed, stop or reverse if necessary. Action by the ship is required if there is risk of collision, also when the ship has right-of-way.
- **Rule 13 - Overtaking.** A vessel overtaking another shall keep out of the way of the vessel being overtaken.
- **Rule 14 - Head-on situation.** When two power-driven vessels are meeting on nearly reciprocal courses so as to involve risk for collision, then alter course to starboard.
- **Rule 15 - Crossing situation.** When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way.
- **Rule 16 - Actions by give-way vessel.** Take early and substantial action to keep well clear.

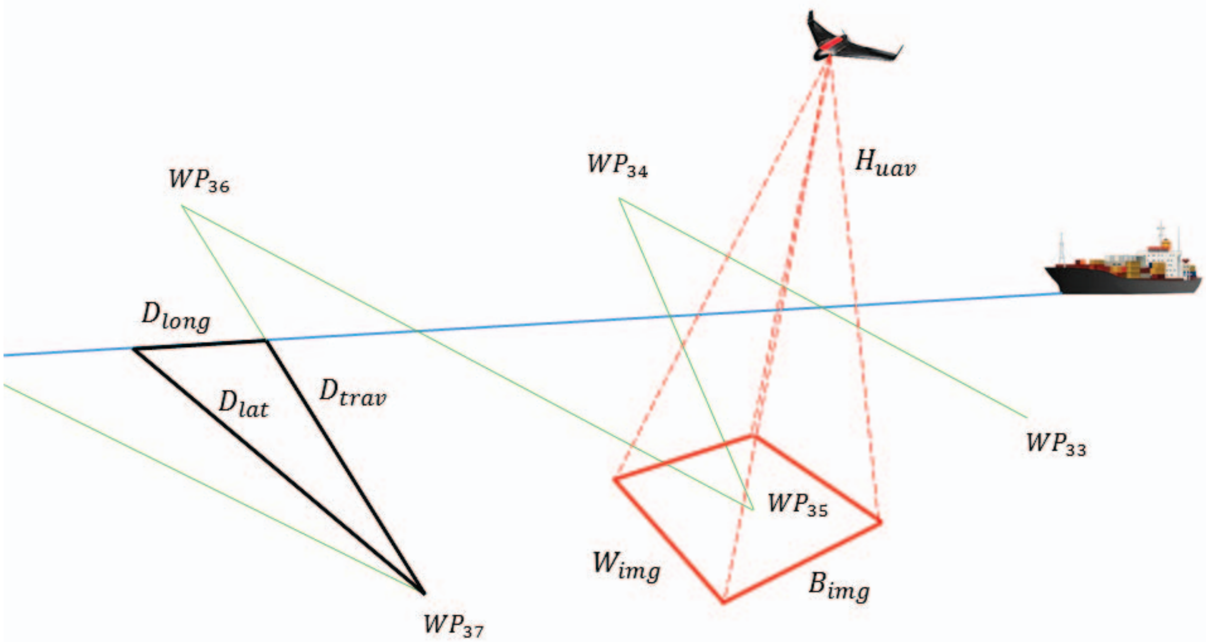

Fig. 2. Conceptual overview.

- **Rule 17 - Actions by stand-on vessel.** Keep course and speed (be predictable) if possible. If it is necessary to take action, then the ship should try to avoid to alter course to port for a vessel on her own port side.
- **Rule 18 - Responsibilities between vessels.** (With some exceptions), a power-driven vessel shall keep out of the way of: a vessel not under command, a vessel restricted in her ability to manoeuvre, a vessel engaged in fishing, and a sailing vessel.

In addition, there are requirements for light and sound signals as well as some rules that apply in special areas denoted as narrow channels and traffic separation schemes. For simplicity, they are not considered here.

V. Unmanned Aerial Surveillance System Design Parameters

For the UASS design, we assume that the UAV tracks a sequence of way-points that normally alternate between the port and starboard side of the planned ship trajectory as illustrated in Figure 2. This is described in more detail in Section VI-B, and the key parameters defining the UASS capability are discussed next.

If the image width is $\mathcal{R}$ pixels and we require that 1 pixel corresponds to Δ meters on the ground in order to be able to detect the objects and features of interest, we must ensure that the image on the sea surface is not wider than

$$W_{img} = \mathcal{R}\Delta \tag{1}$$

The UAV's camera system is assumed to have a fixed field of view (FOV) angle ϕ_{fov} such that the flight altitude above sea H_{uav} does not exceed

$$H_{uav} = \frac{W_{img}}{2\tan(\phi_{fov}/2)} \tag{2}$$

In order to ensure that the entire area is scanned, with a degree of overlap $\beta \in [0,1)$, we must require that the longitudinal travel per leg (D_{long}, see Figure 2) satisfies

$$D_{long} = (1-\beta)\frac{W_{img}}{2} \tag{3}$$

Consider the speed of the ship (v_{ship}) and the UAV (v_{uav}). Clearly, in order for the UAV to stay at a constant average distance ahead of the ship, we need the search pattern's travel D_{trav} to satisfy

$$D_{trav} = \left(\frac{v_{uav}}{v_{ship}}\right) D_{long} \tag{4}$$

In order to extend the capabilities of the system, it is found that the use of a camera with a relatively small FOV (telescopic lens) in a pan-tilt unit to sweep sideways will greatly increase the FOV and resolution of the aquired data, [17], [18]. Suppose the camera is mounted in a pan-tilt unit that sweeps the ocean surface such that $\mathcal{R} = k_{sweep}\mathcal{R}_{cam}$, where $k_{sweep} \geq 1$. One can easily derive that the system's FOV is extended to

$$\begin{aligned} \phi_{fov} &= 2\tan^{-1}\left(k_{sweep}\tan(\phi_{cam,fov}/2)\right) && (5) \\ &\approx k_{sweep}\phi_{cam,fov} && (6) \end{aligned}$$

A relevant question is how to choose the design parameters in order to ensure that a moving obstacle is not able to pass through the surveyed area without being detected, since obviously the UAV must travel at finite speed and cannot survey all points at the same time. Assuming the obstacle is close to the ship's planned trajectory and is moving towards the ship at a maximum speed $\overline{v}_{obst}$, the following inequality can be derived by considering the travel time the UAV needs from leaving the middle of the lateral leg until it is back at the middle of the next lateral leg:

$$\overline{v}_{obst} \leq \left(\frac{\beta}{1-\beta}\right) v_{ship} \tag{7}$$

To increase $\overline{v}_{obst}$ one must accept that the width of the search area D_{lat} is reduced, which is not desirable, and the parameter β should be chosen as an optimal trade-off between these two objectives.

For example, consider a FLIR Tau2 thermal camera with $\mathcal{R}_{cam} = 640$ pixels and 19mm lens giving $\phi_{cam,fov} = 32°$. A typical design is given in Table I where we consider a detection threshold of 0.25 m/pixel.[1] It is shown that the system can scan a 1440 m wide area with 40% overlap when the UAV speed is $30\ m/s$, the ship speed is $6\ m/s$, which leads to maximum $\overline{v}_{obst} \leq 4\ m/s$ for guaranteed detection when the obstacle is close to the ship's planned path. Note that this is guaranteed only for straight paths and less performance may be expected during an evasive maneuver, such that additional safety margins should be built into the design and tuning.

[1]According to the Johnson criterion, [19], [20], detection typically requires 1 pixel, recognition reqires 4 pixels, while identification requires 6 or more pixels.

TABLE I

DESIGN EXAMPLE.

Parameter	Symbol	Value
Camera FOV	$\phi_{cam,fov}$	32°
Image dimension	$\mathcal{R}_{cam}$	640 pixels
Obstacle detection threshold	Δ	0.25 m/pixel
Sweep factor	k_{sweep}	3
System FOV	ϕ_{fov}	81.4°
System Resolution	$\mathcal{R}$	1920 pixels
System Image Width	W_{img}	480 m
UAV Altitude	H_{uav}	279 m
Overlap	β	40 %
Ship speed	v_{ship}	6 m/s
UAV speed	v_{uav}	30 m/s
Longitudinal travel per leg	D_{lon}	144 m
Lateral travel	D_{lat}	705 m

We will further assume that the UAV provides information about detected obstacles in real-time over its telemetry radio link to the ship. This information can be generated by machine vision, signal processing, target tracking, as well as geo-referencing and time-tagging using the UAV's navigation system, [16], [17], [7].

VI. SHIP SITUATION AWARENESS AND SENSOR FUSION (SASF)

A. *Sensor fusion, obstacle tracking and prediction*

The obstacles detected, recognized and identified by the ship's sensors and UASS may not be consistent for several reasons. Certain obstacles may not be in the FOV of the UASS. Likewise, some obstacles may not be in the line of sight of the onboard sensors. Observations may be weak, noisy or intermittent, making it non-trivial to distinguish an obstacle from noise, clutter, background or other obstacles.

Based on these observations, some estimates of the obstacles position and velocity are needed. Simple methods include least squares curve fitting of the observed data from which these parameters can be extracted. In this concept study, we consider this sufficient, although in a practical implementation it is recommended to use more advanced methods such as Kalman filtering and advanced data association methods for the sensor fusion and obstacle tracking, taking into account different uncertainty levels, currently unobserved obstacles and intermittent measurements, e.g. [21]. The estimates are used to define short-term predictions in terms of straight line trajectories

$$\overline{\eta}_i^{lat}(t) = \hat{\eta}_i^{lat} + k_{lat}\hat{v}_i^N(t-\tau_i) \tag{8}$$

$$\overline{\eta}_i^{long}(t) = \hat{\eta}_i^{long} + k_{long}\hat{v}_i^E(t-\tau_i) \tag{9}$$

where k_{lat} and k_{long} are constants that convert units from meters to degrees in the given area, t is a future point in time, and τ_i is the time of last observation.

The output of the SASF module is assumed to be in the form of a list of obstacles indexed by i with the following information:

- τ_i - time tag (GPS clock)
- $\hat{\eta}_i^{lat}, \hat{\eta}_i^{long}$ - latitude and longitude of the obstacle's estimated center position at time t_i
- $\hat{v}_i^N, \hat{y}_i^E$ - north and east components of the obstacle's estimated velocity vector at time t_i (meters/sec)
- σ_i^{pos}, σ_i^{vel} - standard deviations of position and velocity estimates (meters) (meters/sec)
- $\hat{\psi}_i$ - estimated heading of the obstacle at time t_i (degrees east of north)
- ℓ_i, b_i - length and breadth of obstacle i in longitudinal and lateral directions, respectively (meters)
- ID_i - identification code
- CAT_i - category: Power-driven ship larger than 20 m, power-driven ship smaller than 20 m, fishing, not under command, sailing, unknown.

B. UASS search area and way-point generation

An algorithm for defining the UAV way-points is considered in this section. We will assume that the UAV will follow a zig-zag-like scanning pattern along the planned ship trajectory as illustrated in Figure 2.

A simple algorithm, sufficient for this concept study, is developed as follows:

1) Compute a predicted ship position at a given look-ahead distance d_{scan} along the predicted ship trajectory.
2) If the previous way-point was port, compute a new way-point at a distance D_{lat} directly starboard of the position computed in step 1. Otherwise, compute a new way-point at a distance D_{lat} directly port of the position computed in step 1.
3) Wait until the way-point is reached, and go to 1).

The parameter d_{scan} should be chosen large enough such that the ship has enough space and time to make an evasive maneuver. When turning, the ship's trajectory course rate is considered when planning UAV way-points in order to increase the chance of discovering obstacles in areas close to the ship and that are not previously scanned. A simple strategy to implement this, is to let the UASS scan at a look-ahead distance

$$d_{scan} = W_{img}/2 + T_{ahead}\left(\frac{v_{ship}}{v_{ship}^{max}}\right)\left(1 - \frac{|r|}{r_{max}}\right)$$

where r is the ship's yaw rate, r_{max} is its maximum value and T_{ahead} is the look-ahead horizon for the UASS.

A more advanced search strategy should take into account and respond to the following potentially conflicting objectives:

- Confirm weak/uncertain/possible detections from the ship sensor system.
- Employ search and track functionality to ensure updated estimates and observability of tracked obstacles, [22].
- More advanced planning to resolve uncertainty if the ship abruptly changes course to move into an area where there is no recent accurate and reliable observations.

VII. Collision avoidance system (CAS)

The CAS is a standalone external system to the autopilot and mission planning functions on the ship. The mission planner and execution module is assumed to deliver a list of way-points (WPs) and a nominal speed to the autopilot, that executes this plan by giving commands to the steering and propulsion system. The autopilot is assumed to accept alternative commands from the CAS in the form of a *course offset* and *propulsion override command*, and execute PID speed control and LOS guidance for course steering, [23].

We employ a CAS as described in [14]. The CAS decides its control policy by evaluating a finite number of scenarios using a ship simulator that operates much faster than real time. Each scenario is defined by the current state of the ship, the predicted trajectories of the observed obstacles, a control policy (course offset and propulsion command) that is assumed to be fixed on the prediction horizon. The nominal scenario (LOS guidance along the nominal path with no course offset and at nominal speed) is accepted if the hazard is sufficiently low. If not, the least hazardous control policy is selected among the alternatives that represent a finite number of evasive maneuvering scenarios. The predictive simulation should include effects of wind and ocean current that may have a significant effect on the ship, in particular if the decided control action is to stop. The hazard minimization criterion is based on a weighted evaluation of collision hazard, grounding hazard and COLREGs compliance. The strategy recognizes that there may be conflicting objectives and constraints, such that a compromise may be made to determine minimum hazard. The alternative control policies and hazard criterion are described in more detail in [14].

VIII. Simulations

In order to assess the feasibility of the proposed concept, the own ship is simulated - also in the collision avoidance algorithm - using the standard three-degrees-of-freedom horizontal plane motion model in [23]. This includes the dynamics of the steering (rudder) and propulsion (diesel engine) systems. The UAV is assumed to follow the planned straight legs of the path since a small UAV's turning radius is relatively small compared to the spatial scales involved.

Due to space constrains on the paper, we only showcase one illustrative example. Figures 3 and 4 show the results of a simulation case when there are multiple slow obstacles that are not detected by the primary ship sensors (radar and AIS).

In the simulated scenario, the UASS first detects obstacle 6, and the CAS commands a turn to starboard to avoid in accordance to the COLREGS. Shortly after also obstacle 2 is detected but only a minor adjustment of the course is needed to avoid it. At this point, until time 18 min the hazard is considered low. Then the UASS detects also obstacle 8, and a sharper turn starboard is commanded by the CAS to avoid. The hazard increases until the obstacle is passed at a relatively safe distance of 500 meters. At time 22 min, the obstacle 5 is detected by the UASS, and just a minor adjustment of course is commanded in order to overtake obstacle 5 before the CAS commands a turn to port in order to return to the planned path. No reduction of speed was found necessary by the CAS.

The simulation example shows the effectiveness of the strategy in a complex multi-obstacle scenario. The UAV's path is well chosen to survey the area ahead of the ship. All obstacles that are in a crossing or head-on situation are passed on the port side as required by COLREGS.

IX. Conclusions

This paper explores the concept of a UASS and demonstrates its effectiveness through simulation studies. Key design parameters of the UASS are discussed. Based on the simulation results, we conclude that the approach seems feasible and relatively effective in relation to support the collision avoidance of relatively slowly moving ships. Only slowly moving obstacles at relatively short distance can be expected to be detected with relatively high certainty, which may be sufficient since relatively fast moving obstacles may be expected to be detected by a maritime radar also at relatively large distance. We emphasize that the UASS is not intended to be the primary sensor system for obstacle detection and tracking on the ship, but rather a secondary system that can provide redundancy and complementary capacity for detecting objects.

The sub-systems and functions described could be improved by incorporating more realistic assumptions. Hence, the results in the paper should be considered preliminary. In particular, the UASS trajectory planning could be optimized to yield better detections and predictions, and the sensor fusion should consider more comprehensive uncertainty representations. The collision avoidance strategy can be extended with additional scenarios accounting for uncertainty in predictions.

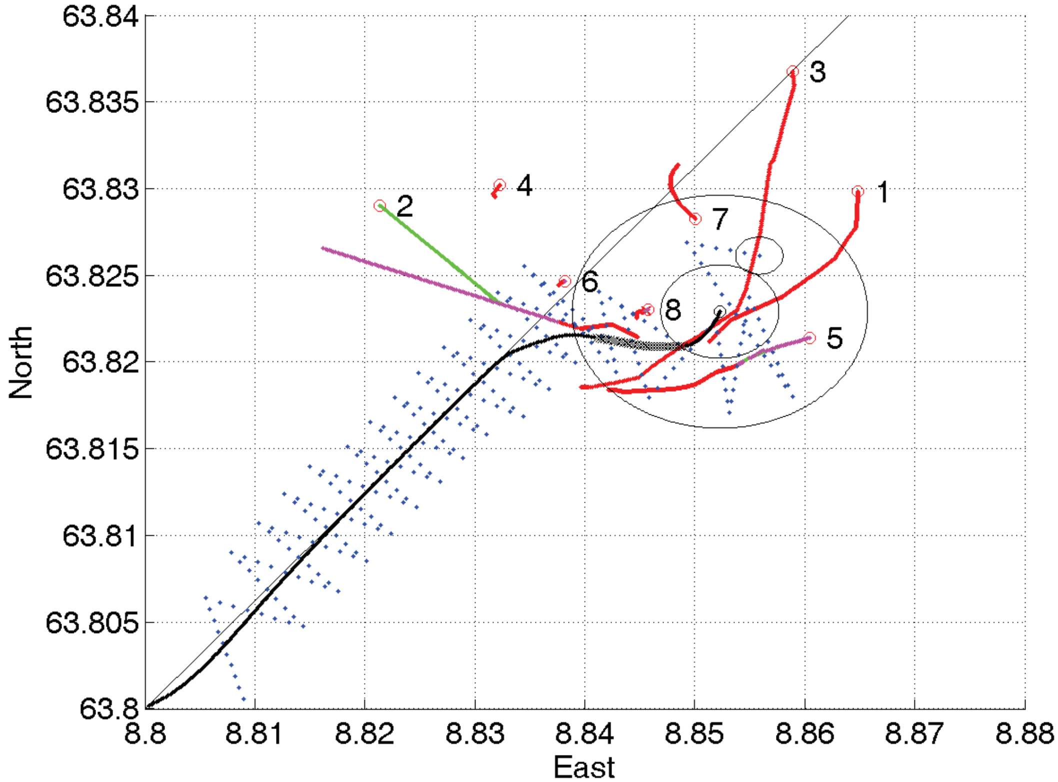

Fig. 3. UASS simulation scenario and results. In the North-East position plot, the black straight line is the path between the two waypoints. The black curve is the path of the own ship up to a final time. The larger circle denotes the area where COLREGS compliance is enforced by the CAS. The red and green curves denote the paths of the obstacles up to a final time marked by a small red or green circle. The curve is red when the obstacle is not detected, and turns green once the obstacle has been detected for the first time. It can be seen that the predicted obstacle positions (magenta curves) are established when the UASS detects the obstacle for the first time, and that the estimated positions will deviate from the true positions when there are no further updates. Since there are multiple obstacles, their path are identified by a number. The smaller black circle in front of the UAV illustrates the camera system field of view at the time. The blue dotted curve shows the path of the UAV.

Acknowledgments

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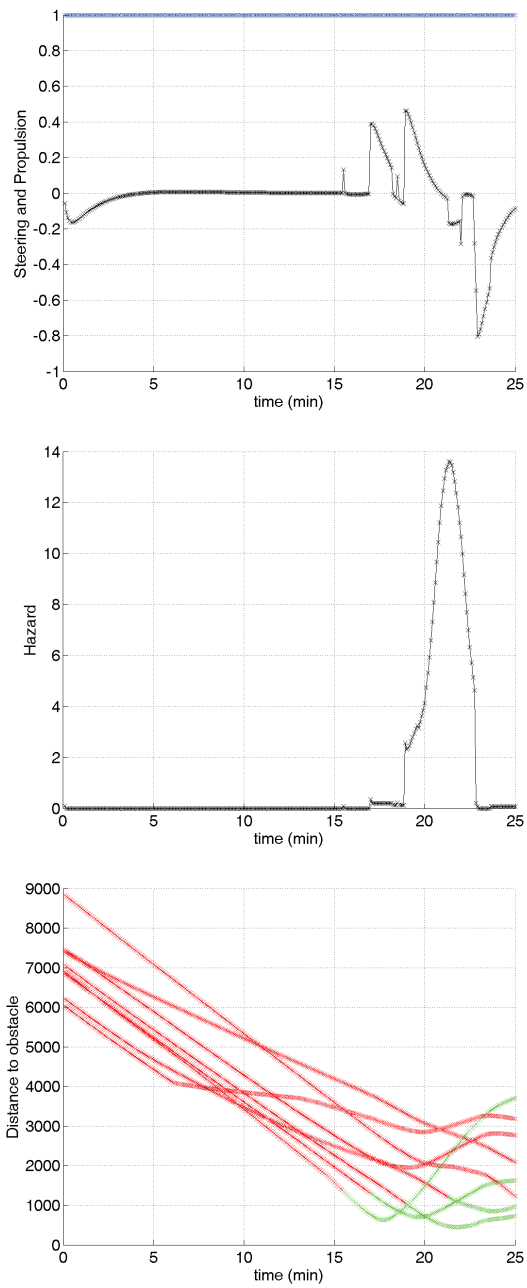

Fig. 4. UASS simulation scenario and results. The Steering and Propulsion plot shows the propulsion command (dark blue) and rudder angle (black) as a function of time. The Hazard plot shows the predicted hazard (a weighted evaluation of collision hazard, grounding hazard and COLREGs compliance [14]), with the optimal control policy, as a function of time. The distance plot shows the distance between each obstacle and the own ship as a function of time. Also here, green indicates that the obstacle has been detected, while red represent undetected obstacles.

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