Operational Synchronization for MASS in VTS Areas

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***Abstract*—Autonomous and automated vessels are expected to operate safely and predictably in VTS-controlled waters while achieving an equivalent level of safety to manned ships. Today, compatibility between ship-side and shore-side operational assumptions is maintained through human interpretation and communication. As onboard human mediation is reduced or removed, this compatibility becomes an explicit system requirement that current autonomy, VTS and digital maritime service frameworks do not address. This paper identifies *operational synchronization* as the missing system-level property that determines whether the ship and VTS can algorithmically verify that their combined binding constraints admit a non-empty viable state region and detect when it becomes empty. We derive the required structure for this property, formalize it as a viable-set condition and show how synchronization violations become inspectable system states rather than implicit disagreements. Without this explicit property, safety claims about compliance, predictability and coordination remain informal and reliant on conservative assumptions or human intervention, limiting their transparency and scalability as autonomy increases.**

***Index Terms*—Maritime Autonomous Surface Ships, MASS, Vessel Traffic Services, VTS, operational synchronization, autonomous navigation, maritime safety**

I. Problem Context

In port approaches, fairways, locks and traffic separation schemes, navigational safety depends on coordinated adherence to institutional constraints and procedures that support collision avoidance [1], [2]. Vessel Traffic Service (VTS) organizations manage traffic by combining sensor observations, procedural rules and negotiated intent through voice-based (VHF) interaction with shipboard crews [3]–[5]. These interactions report vessel state, interpretation of instructions, negotiation of intent, handling of exceptions and commitments under uncertainty [6]. For Maritime Autonomous Surface Ships (MASS), these interactions must be replaced by machine-interpretable interfaces. Current digital exchanges between ships and shore (e.g. AIS messages, ETA reporting or port-call data) are largely syntactic and descriptive. They do not capture the semantics of intent, action constraints or conditional commitments that VTS relies on to ensure predictability and safety. This limitation becomes particularly visible in remote and automated navigation contexts, where maintaining reliable situational awareness already requires substantial onboard interpretation beyond the exchange of raw data [7], [8]. Therefore, the coordinated traffic management is based on assumptions, which are no longer guaranteed once human mediation is removed. This affects all IMO MASS degrees, but becomes operationally critical for degrees 3 and 4 [9].

II. Limitations of Existing Approaches

Modern onboard autonomy systems typically construct situational pictures optimized for real-time geometric accuracy and short-horizon prediction, derived primarily from local sensor data [10]. In contrast, shore-side VTS use management-oriented operational pictures designed to ensure the safety and efficiency of navigation, emphasizing shared consistency, regulatory authority and traffic organization, often with higher latency and coarser spatial resolution [11]. Each picture is internally coherent but incomplete with respect to the other's objectives. Exclusive reliance on the VTS operational picture fails to meet real-time safety requirements, while sole reliance on onboard situational awareness fails to support institutional authority and coordinated traffic management. Simple fusion of onboard and shore-side data can obscure provenance and responsibility, which in turn would undermine auditability and post-incident accountability. At the same time, existing VTS and MASS system descriptions do not specify expected vessel behavior when onboard assessments and VTS assumptions diverge, relying on human conflict resolution instead [12]. This paper addresses this gap by defining operational synchronization as a constraint-based system invariant whose violation can be evaluated, simulated or reconstructed by certification authorities [13].

III. Operational Synchronization

For an action executed in VTS-controlled waters to be considered safe and compliant, it must be possible to justify the action with respect to three interdependent sources of operational constraint: the physical traffic and hazard situation [14], the applicable local rules and instructions [3] and the assumptions held by coordinating authorities [15].

In conventional operations, this justification is constructed and maintained through continuous human interpretation and communication between ship and shore. As onboard human mediation is removed, this justification can no longer be assumed to emerge implicitly. It must instead be supported by the technical system itself. Exchanging large volumes of raw sensor data, such as LiDAR or radar point clouds, is infeasible due to bandwidth and latency constraints and would still not ensure safe maneuver execution. Instead, safety depends on whether the assumptions, constraints and responsibilities underlying the exchanged information are mutually aligned at the moment action is taken. This alignment is captured by the *operational synchronization* between the vessel and the VTS. Operational synchronization exists when:

- both parties know which situational elements and constraints are authoritative for the considered actions,
- both can assess whether their binding constraints are compatible within a relevant spatio-temporal region, and
- both can detect when divergence becomes safety-relevant and requires explicit resolution.

Operational synchronization is therefore a system-level property required to make claims about compliance, mixed traffic predictability and equivalence to manned operations.

IV. Requirements for Operational Synchronization

To make operational synchronization definable and inspectable, the situational picture must be treated as a distributed system with distinct responsibility, authority and provenance rather than a unified representation [16]. From this, we derive three minimal structural requirements:

1) Distributed Ownership of Situational Information: Onboard systems are responsible for low-latency state estimates, dynamic object tracking and action execution. Shoreside systems are responsible for regulatory constraints, traffic organization measures and coordinated intent. This ownership reflects responsibility and update constraints without imposing uniform accuracy requirements.

2) Context-Dependent Authority: The relative relevance of onboard and shore-side information to action decisions varies with operational context, such as proximity to infrastructure, traffic density and phase of voyage. This variation determines how conflicts between situational elements are arbitrated.

3) Defined Convergence Scope: There must exist a bounded spatio-temporal region within which both the underlying situational elements and their safety-relevant interpretations, e.g. conflict detection or regulatory state classification, are required to converge consistently under the responsible decision authority. Outside this region, divergence is tolerable provided it does not affect safety-critical assessments or compliance obligations. Note that these requirements do not prescribe specific sensors, message formats or communication protocols. Instead, they aim to define the minimal structure needed for operational synchronization to be possible.

V. Operational Synchronization as an Inspectable System Property

A. Behavioral Constraints

Operational synchronization is required whenever action decisions are executed onboard while action-relevant constraints originate both onboard and shore side. In such settings, safety and compliance depend on mutually compatible behavioral assumptions between vessel and VTS. These assumptions concern what the vessel may or must do at the moment they begin to matter. To make this requirement inspectable at runtime or offline, synchronization is defined over constraints rather than a shared representation or world model.

Both the vessel and the VTS reason in terms of constraints. The vessel maintains a set of action-relevant constraints C_{vessel}, while the VTS maintains a corresponding set C_{VTS}. Each constraint is a statement about acceptable vessel behavior over a limited spatio-temporal scope. Examples include remaining within a cleared corridor, adhering to a local speed limit, avoiding entry into a restricted area before a given time, maintaining a minimum distance to a tracked target or respecting vessel-specific capability bounds such as stopping distance. In this sense, constraints encode requirements and expectations about compliant behavior.

Each constraint carries only the minimal metadata needed to make disagreements explicit and resolvable. This includes its spatio-temporal scope, a validity horizon after which it expires or must be refreshed, its provenance (such as onboard sensing, VTS instruction or published procedure), a constraint class (such as physical obstacle, safety of navigation, coordination or regulatory) and an indication of whether it is binding or advisory. Importantly, binding statuses are used solely to support operational decision policy. They do not assert legal authority or liability.

B. Synchronization Region

Perfect agreement between C_{vessel} and C_{VTS} is neither realistic nor required. Divergence at long range or over long horizons is normal and often harmless. What matters is agreement where decisions become difficult or impossible to reverse. We therefore introduce the notion of a synchronization region $\mathcal{R}$. $\mathcal{R}$ is a bounded spatio-temporal region around the vessel within which divergence between onboard and VTS constraints can directly affect safety or regulatory compliance. The extent of $\mathcal{R}$ depends on vessel dynamics such as stopping distance and turning limits, on traffic density, action complexity and on communication latency with an upper bound given by the applicable VTS service area. Outside $\mathcal{R}$, disagreement may exist without forcing immediate action. Inside $\mathcal{R}$, disagreement cannot be ignored.

C. Context-Dependent Binding of Constraints

Not all constraints are equally binding in all contexts. Physical obstacles and collision avoidance constraints may override coordination constraints. Advisory constraints may be deprioritized without violating operational expectations. We assume the existence of a declared decision policy, provided

as part of the operational configuration for a given VTS area, that specifies precedence among constraint classes and binding statuses as a function of operational context. This policy is explicit, versioned and loggable without altering legal responsibility. Instead, it defines operational conflict handling. Applying this to a set of constraints gives a subset that is binding for the action under consideration. Operational synchronization can now be defined in intuitive terms. Synchronization holds when, within the synchronization region $\mathcal{R}$, the vessel and the VTS assume mutually compatible binding constraints. Equivalently, the viable state set $\mathcal{V}(\mathcal{R})$ induced by the combined binding constraints must be non-empty.

D. Testable Synchronization Condition

This yields a testable synchronization condition. Let $\mathcal{R}$ be the synchronization region and let $X(\mathcal{R})$ be the set of reachable vessel states x within $\mathcal{R}$. Because not all constraints are operationally binding in every context, we introduce a declared decision policy P that selects the subset of constraints that are binding for the action under consideration. We define

$$C_{\text{bind}} = P(C_{\text{vessel}} \cup C_{\text{VTS}}), \tag{1}$$

where C_{bind} is the set of constraints that must be satisfied within $\mathcal{R}$. Now, operational synchronization is defined by non-emptiness of the viable state set within $\mathcal{R}$. We define:

$$\mathcal{V}(\mathcal{R}) = \{x \in X(\mathcal{R}) \mid x \text{ satisfies } C_{\text{bind}} \text{ within } \mathcal{R}\}. \tag{2}$$

Synchronization holds if

$$\mathcal{V}(\mathcal{R}) \neq \emptyset. \tag{3}$$

If the viable state region is empty, the onboard and shoreside assumptions are operationally incompatible within the safety-relevant scope. Thus, synchronization requires the existence of at least one feasible state $x^\star \in X(\mathcal{R})$ that satisfies all currently binding constraints within $\mathcal{R}$, i.e., $x^\star \in \mathcal{V}(\mathcal{R})$. This makes the incompatibility explicit and detectable. Figure 2 summarizes this condition as the coupling between the onboard and VTS operational pictures through constraint sets, decision policy and synchronization indicator.

Failure to meet (3) constitutes a synchronization violation. Because this condition is computable at runtime or reconstructable offline, incompatibility becomes an explicit system state rather than an interpretive judgment and must trigger conflict resolution or predefined fallback. For monitoring purposes, we define the synchronization indicator evaluating (3):

$$S(\mathcal{R}) = \begin{cases} 1, & \text{if } \mathcal{V}(\mathcal{R}) \neq \emptyset, \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

Hence, a synchronization violation corresponds to $S(\mathcal{R}) = 0$. Checks for non-emptiness of $\mathcal{V}(\mathcal{R})$ may be conservative or approximate. However, if there is insufficient confidence that $\mathcal{V}(\mathcal{R}) \neq \emptyset$, the condition is treated as violated and the system assumes $S(\mathcal{R}) = 0$. When $S(\mathcal{R}) = 0$, detection alone is insufficient and the system must produce an inspectable explanation that supports resolution. Given the admissible region A_c per constraint c, we generate a conflict certificate $\Gamma \subseteq C_{\text{bind}}$. Γ is a small subset of binding constraints whose joint admissible regions eliminate feasibility, i.e., the reachable state set $X(\mathcal{R})$ has no intersection with the admissible region that satisfies all constraints in Γ simultaneously:

$$X(\mathcal{R}) \cap \Big(\bigcap_{c \in \Gamma} A_c \Big) = \emptyset, \tag{5}$$

Γ is logged with provenance, class, binding/advisory status and validity horizons for auditability and resolution. During resolution the system relaxes advisory constraints first and escalates only if binding constraints remain infeasible, i.e., $\Gamma \subseteq C_{\text{bind}}$. Then the provenance of Γ selects the resolution channel. VTS-originated coordination or regulatory constraints trigger a request for revision, withdrawal or updated clearance. Onboard safety-of-navigation constraints trigger predefined fallback such as slow or hold with VTS notification. If both contribute, or feasibility cannot be established with sufficient confidence, the system applies safety-preserving fallback while requesting updated VTS constraints where applicable.

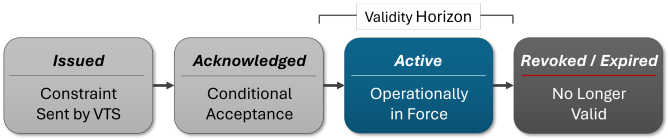

Fig. 1. Lifecycle of a VTS-originated constraint. Only constraints in the *active* state are included in C_{VTS} and contribute to C_{bind}.

E. Lifecycle of VTS-Originated Constraints

VTS-originated constraints are treated as conditional commitments with an explicit state progression. Each constraint transitions through the states *issued*, *acknowledged*, *active*, and *revoked / expired*, as shown in Figure 1.

An *issued* constraint represents a clearance or instruction communicated by the VTS but not yet relied upon onboard. Upon *acknowledgement*, the vessel declares conditional acceptance within the stated spatio–temporal scope and validity horizon. A constraint becomes *active* once it is operationally in force. This activation does not waive onboard safety-of-navigation constraints, but makes the coordination commitment explicit and time-bounded. A constraint transitions to *revoked / expired* state when withdrawn by the VTS, when its validity horizon elapses or when communication loss prevents the onboard system from confirming that the constraint remains active. In this state, the constraint is removed from operational consideration and predefined fallback behavior may be triggered. This explicit lifecycle ensures that membership in C_{VTS} (and consequently in C_{bind}) is temporally well-defined and inspectable at runtime and offline.

Example. Consider a vessel approaching a port fairway under VTS control. The VTS issues a clearance to proceed within corridor K over a specified interval. Once acknowledged and active, this clearance introduces a coordination constraint into C_{VTS}. Concurrently, onboard sensing detects a temporary obstruction entering the corridor within $\mathcal{R}$, introducing a physical safety constraint into C_{vessel}. Under the declared policy P, both constraints are classified as binding.

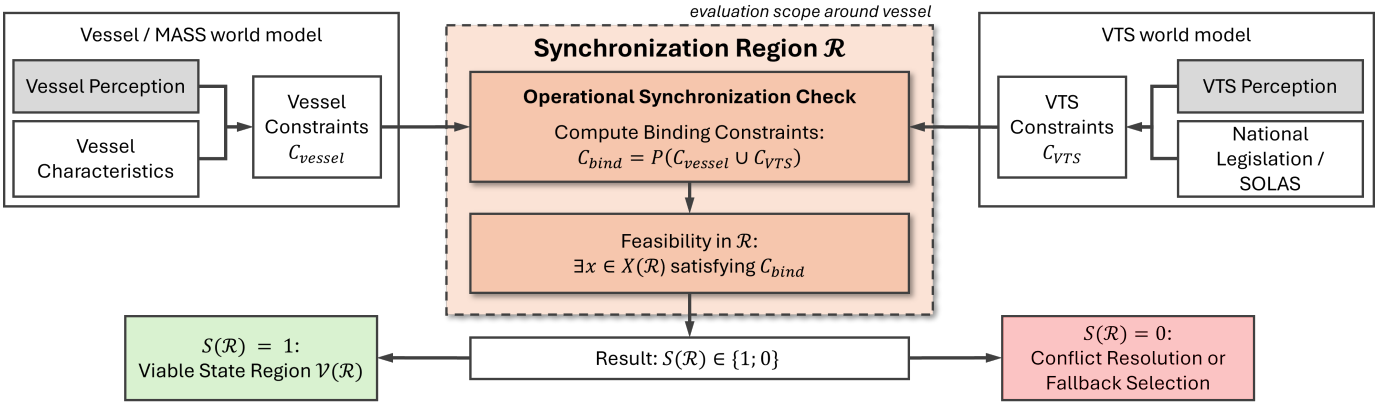

Fig. 2. Constraint-based operational synchronization between the MASS onboard situational picture and the VTS operational picture. Each side derives active behavioral constraints from its respective information. Within the synchronization region $\mathcal{R}$ (spatio-temporal evaluation scope around the vessel), the declared decision policy P determines the binding constraint set C_{bind}. Synchronization holds if the viable state region $\mathcal{V}(\mathcal{R})$ induced by C_{bind} is non-empty, satisfying C_{bind} within $\mathcal{R}$. The resulting indicator $S(\mathcal{R})$ permits continued operation when $\mathcal{V}(\mathcal{R}) \neq \emptyset$ and triggers conflict resolution or fallback selection.

If $\mathcal{V}(\mathcal{R}) = \emptyset$ (equivalently $S(\mathcal{R}) = 0$), the synchronization condition is violated. The system must therefore either negotiate an updated corridor constraint or find an alternative solution (e.g. holding position), while logging the active constraints and the policy outcome. Thus, operational synchronization reduces to the check $\mathcal{V}(\mathcal{R}) \neq \emptyset$ within a bounded region.

VI. Implications and Scope

Framing VTS–MASS interaction as a synchronization problem between onboard and shore-side information shifts the focus from telemetry exchange to the maintenance of compatible situational commitments. This perspective enables rule-governed handling of disagreement, explicit detection of incompatibilities and systematic post-incident auditability.

The model developed in this paper addresses a currently missing system-level definition in autonomous maritime operations. By formalizing operational synchronization as a required system property, it provides a structural basis for consistent reasoning about ship–shore coordination in VTS-controlled waters. Future validation should instantiate C_{vessel}, C_{VTS} and P in simulated or replayed port-approach scenarios. Questions of organizational authority transfer, legal responsibility allocation and human–machine interface design at VTS centers are outside the present scope.

VII. Conclusion

As maritime autonomous surface ships (MASS) enter regulated waters, coordination assumptions that are currently handled through human interpretation in VTS operations become explicit engineering requirements. This work identifies operational synchronization between onboard autonomy and shore-side management as a necessary system property for safe and predictable operation in VTS-controlled environments.

By framing operational synchronization in terms of binding behavioral constraints rather than shared world models, disagreement in authority, interpretation and coordination becomes explicit and machine-readable rather than reliant on subjective judgment. This provides a concrete basis for runtime monitoring, post-hoc analysis and structured safety arguments.

Establishing operational synchronization as an explicit system property is a prerequisite for credible certification approaches and for the coherent integration of MASS into existing maritime traffic management frameworks.

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