Legibility and Predictability of Protocol-Constrained Motion: Evaluating Human-Robot Ship Interactions Under COLREGS Collision Avoidance Requirements

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Abstract—**Human ship drivers use protocol-constrained motion to signal their intent to comply with collision avoidance rules when other means of communication are not readily available. By limiting allowable motions using the protocol constraints of the sea-going Rules of the Road (COLREGS), legibility criteria are well defined by existing human practice, regulation, and case law. Motion requirements of the COLREGS collision avoidance rules require vehicle action from a limited set of acceptable maneuvers when certain states of geometry and collision risk exist, thus promoting predictability. In this paper, predictable motion was realized using on-water experiments under the protocol constraints of COLREGS using several autonomous vessels and one human-operated vessel. By observing other vessels' states and motion during on-water experiments, the autonomous vehicles successfully performed both legible and predictable protocol-constrained maneuvers as observed by a neutral third party evaluation tool. On-water experimentation demonstrated the ability of a field of autonomous surface vehicles to successfully interact with a human-operated surface craft in accordance with COLREGS. Open questions are posed to the community for advancing human-robot interaction in protocol-constrained collision avoidance scenarios across all physical domains. The results presented in this paper demonstrate successful human-robot interaction to avoid collision during multi-contact on-water encounters under the protocol constraints of COLREGS using only the vehicles' motions for communication.**

I. INTRODUCTION

Advances in autonomous surface vessels will eventually lead to increasing traffic on waterways that are already used by human-operated vessels. Inherent to any two surface vessels sharing an area of water, a collision avoidance scheme is required. By adhering to the internationally agreed collision regulations (COLREGS[1]) [20], autonomous surface vessels interacting with human-operated vessels will continue practicing the protocols of collision avoidance maneuvers already familiar around the world.

Human ship drivers currently rely largely on the observed (visual, radar, etc.) initial state of other vessels as well as self-broadcast information (position, course, speed, etc.) from contacts in order to determine the complete contact picture. Once an operator understands the contact picture and deems a risk of collision to exist, a COLREGS rule set is assigned. This rule set largely depends on vessel type(s) (power-driven, sailing, etc.), mode(s) of operation (transiting, fishing, etc.), relative geometry, and relevant state variables (x, y, speed, course). The rule set assigned to the contact pair mandates whether one or both of the two vehicles must take action to avoid collision as well as any restrictions on the manner in which avoidance must be performed.

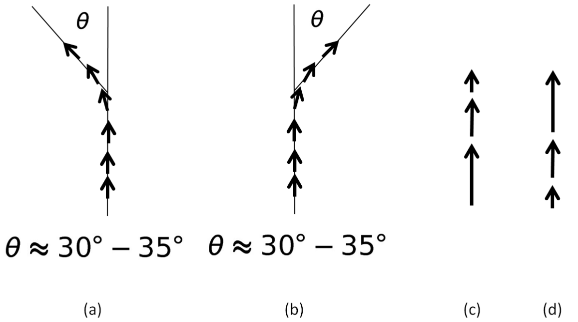

Figure 1. Example legible motions using protocol-limited maneuvers: (a) apparent turn to port, (b) apparent turn to starboard, (c) apparent slow down, and (d) apparent speed up.

Human drivers often use the contact's track data in conjunction with observed course and speed deviations to infer that correct collision avoidance action is being taken in accordance with the COLREGS protocol. Figure 1 shows the four basic allowable maneuvers including turning to port, turning to starboard, decreasing speed, and increasing speed. Case law and common practice provide for minimum course changes that are deemed sufficient to constitute adherence with legibility. These course and speed changes enable human ship drivers to communicate agreement regarding the required rule set using only the vehicle's motion, infer intent of the other vessel's collision avoidance action(s), and demonstrate positive action to adhere to the Rules and reduce the risk of collision.

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[1] COLREGS refers to international rules as formalized at the Convention on the International Rules for Preventing Collisions at Sea, developed by the International Maritime Organization, and ratified as an international treaty by Congress. These rules were further formalized by the U.S. International Navigational Rules Act of 1977 [20], and are sometimes referred to as the Collision Regulations outside the United States.

In collision avoidance situations where a common spoken language is not available, this inference of intent from motion between human operated vessels acts as the primary means to safely and efficiently transit on the sea. Each vehicle assumes only that other contacts will maintain constant course and speed at initial detection unless and until a legible maneuver is performed within the constraints of the allowed maneuvers of each rule. By enabling sea-going robotic vessels to invoke COLREGS collision avoidance constraints in addition to detecting a contact's motion over time, a robot maneuvers similarly to its human counterparts in both a legible and predictable fashion. This common protocol enables humans and robots to interact in a manner largely similar to any two human-operated vessels whose masters do not speak the same language without explicitly programming robots to infer intent.

This paper presents the approach required for robots and humans to effectively and safely interact using only knowledge of position, heading, speed, type of vessel, and mode of operation over time in open-water collision avoidance scenarios under the protocol constraints of COLREGS. On-water experiments demonstrate a human's motion being successfully observed and acted upon by multiple robotic vessels and vice versa while adhering to the protocol constraints of COLREGS.

II. LITERATURE REVIEW

COLREGS-based collision avoidance occurs throughout the literature, though multi-contact collision situations often appear in sequence rather than simultaneously. Encounters are often further restricted to canonical or near-canonical geometries. On-water testing continues to be the exception rather than the norm for testing autonomous collision avoidance, especially when human-operators are considered. On-water experimentation for COLREGS was first demonstrated by Benjamin *et al.* [5, 7]. Various alternative COLREGS collision avoidance algorithms for autonomous vessels were proposed by Lee [14] (Fuzzy Relational Products) and Perera [15, 16] (Fuzzy-Bayesian). Further testing using COLREGS was demonstrated for an ocean-going catamaran by Filimon [12]. Woerner [25] showed that protocol constraints result in more safe, efficient, and predictable maneuvers than non-protocol constrained collision avoidance.

Several authors claim compliance with COLREGS protocols without specifying the degree or scope of compliance. In Kuwata's work [13], the head-on rule was shown to appropriately eliminate all turns to port. It did not, however, appear to prefer courses that were "readily apparent" (COLREGS Rule 8) when finding a turn to starboard. Case law defines apparent course maneuvers to consist of a minimum of 35° turn while common practice often requires no less than 30° of heading change [1, 10, 21, 22]. Courts have found that head-on maneuvers with insufficient turns (i.e., not readily apparent) are in fact non-compliant and, when a collision occurs, partly to blame as it is harder to infer the intent of such a slight change of heading. Figure 2 demonstrates apparent and non-apparent maneuvers. Other authors such as Shah [18] consider that it "may be in the USV's best interest to actually breach COLREGS" such as turning to port to avoid a collision when explicitly prohibited by the Rules. Breaches such as this reduce the legitimacy of the predictability assumption and must be avoided. Many authors often simply claimed COLREGS compliance without any quantification or definition of scope.

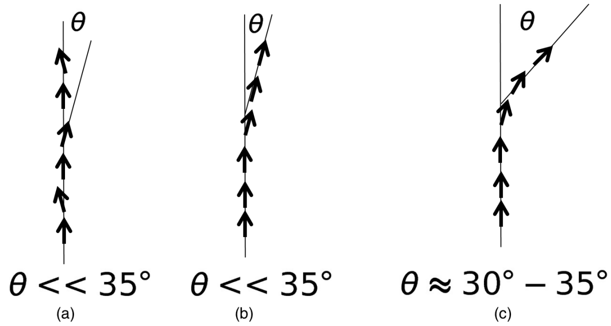

Figure 2. Three maneuvers: sensor and environmental noise while maintaining course and speed, a non-apparent maneuver of approximately $10°$, and a COLREGS-compliant maneuver of approximately $35°$. The first maneuver (a) presents a vessel attempting to maintain course and speed. While the observer sees sensor and environmental noise common to ships operating on the high seas, the view from an observers long range radar may appear as small changes in course or speed as shown by the tangent line of approximately $10°$. The second maneuver (b) represents a small course change of approximately $10° - 15°$ with a tangent line similar to the noise perturbation of (a). To a distant observer, this could appear indistinguishable from sensor or environmental noise and is therefore disallowed by the COLREGS. The third maneuver (c) represents the legible, "readily apparent" maneuver required by COLREGS with a course change of $\approx 30° - 35°$.

Dragan *et al.* [11] formalized the legibility and predictability of motion for humanoid robots. Dragan showed mathematically that a trade space often exists in human-robot interactions such that legibility comes at a price of predictability. This was shown using the "goal to action" and "action to goal" flows common in the literature. Dragan emphasizes the need for autonomous designers to focus motion planning on legibility rather than predictability.

Similar work in the aerial community exists, however most work focuses on maintaining sufficient range separation at closest point of approach (CPA) rather than adhering to the Rules of the Air. Choi [9] found a collision likelihood for a single fixed collision range threshold with multiple unmanned aerial vehicles without adherence to the Rules of the Air. Aoude [2, 3] developed algorithms for both human and autonomous ground vehicles to assess threats to safety based on uncertainty in nearby vehicles' future trajectories.

The concern with readily apparent (i.e., legible) maneuvers rests with the ambiguity of a series of successive subtle (i.e., small) course maneuvers that are not easily recognized by other human operators. Therefore course maneuvers are required to be large enough to be easily recognized and allow for response by other vessels in their vicinity. Motion perturbations inherent to the operating environment of the high seas often cause noise in visual and radar information consistent with the subtle changes that are expressly prohibited. The notion of identifying larger course and speed changes compared to several successive yet small changes stems from a human operator's ability to identify a vessel's legible motion under many concurrent limitations including:

- operating at large ranges to the contact
- being constrained to the sea surface (altitude or depth separation is not possible)
- having only a limited height of sensors
- and having only visual, radar, and self-reported information regarding the contact.

Human involvement inherently complicates collision avoidance protocols. A study by the U.S. Federal Highway Administration [17] found that human car drivers presented with a scenario of stopping suddenly behind another vehicle at a yellow light differed greatly on identifying possible mitigating behaviors or engineering solutions. This likely stems from the inconsistent conditions (time, distance, geographic region, presence of passengers, etc.) at which human drivers choose to stop suddenly at a yellow light rather than accelerate and possibly run a red light. This tradespace of achieving objective (continuing without stopping) and following protocol (stopping if able) is addressed for COLREGS compliance situations by Woerner *et al.* in [23, 24].

III. PROTOCOL-CONSTRAINED MOTION

COLREGS rules for interactions between power-driven vessels without other restrictions may be largely characterized as one of three modes: overtaking (Rule 13), head-on (Rule 14), and crossing (Rule 15). While other rules exist, these fundamental modes allow for thorough testing of power-driven vessel encounters. The overtaking and crossing modes each identify one vessel as being required to "give-way" (Rule 16) and the other to "stand-on" (Rule 17). While specifics vary for each rule, COLREGS usually requires vessels to either take early and substantial action (course or speed change) to avoid collision while signalling compliance or to maintain their course and speed as though the contact did not exist.

Table I presents the nomenclature used throughout this paper. An overtaking rule designates a give-way vessel and stand-on vessel that must comply with both Rule 13 (overtaking) as well as Rule 16 (give-way) or Rule 17 (stand-on). This multi-rule requirement also exists for crossing vessels. Head-on vessels must both maneuver and are therefore only labeled R14. Figure 3 demonstrates the three modes considered in this paper. Explicit requirements of each rule are presented in COLREGS [20] while implicit requirements from case law may be found in [1, 10, 19, 28]. The Rules give guidance and requirements under many situations, though they are intentionally written vaguely to capture the human component of ship driving. However, the vessel master's intuition does not always succeed and collisions inevitably occur.

The nature of travel on the sea surface traditionally limits the degrees of freedom for vessels signalling intent from motion to be strictly contained in course changes, speed changes, and the combination or lack thereof. For the purposes of legibility, the protocol constraints of COLREGS assert key limitations on movement during maneuvers. COLREGS protocol and its associated case law require that threshold levels of change for course and speed must be significantly apparent when compared to expected noise due to environmental and sensor fluctuations. These limitations are analogous to imposing mathematical constraints on the legibility equations of Dragan's motion formulations.

Table I
NOMENCLATURE OF COLREGS RULES

Rule(s)	Vessel 1	Vessel 2
Overtaking	R13/16	R13/17
Head-on	R14	R14
Crossing	R15/16	R15/17

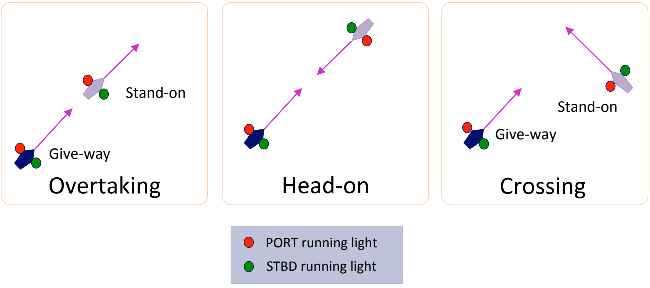

Figure 3. COLREGS Overtaking, Head-on, and Crossing Encounters

By knowing the required rule set from observable relative positions, modes of operation, and types of vessels, a vessel's motion (or lack thereof) immediately and clearly communicates the vessel's intent of collision avoidance rule compliance (or lack thereof). Relative to Dragan's motion formulations, the predictability of a vessel's motion is easily mapped from a given rule set once a vessel determines its requirements and the reciprocal requirements of the contact in question.

For any vessel that can accurately and reliably detect a contact's real-time position, direction of motion, and type of operation, a legible maneuver is detectable and the expected maneuver is known. Figure 2 shows three maneuvers for consideration of how the protocol enforces legibility. The first maneuver (a) presents a vessel attempting to maintain course and speed. While the observer sees sensor and environmental noise common to ships operating on the high seas, the view from an observers long range radar may appear as small changes in course or speed as shown by the tangent line of approximately 10°. The second maneuver (b) represents a small course change of approximately $10° - 15°$ with a tangent line similar to the noise perturbation of (a). To a distant observer, this could appear indistinguishable from sensor or environmental noise and is therefore disallowed by the COLREGS. The third maneuver (c) represents the legible, "readily apparent" maneuver required by COLREGS with a course change of $\approx 30° - 35°$.

Figure 1 demonstrates the legibility constraints on COLREGS-based motion using an apparent course change to starboard, an apparent course change to port, an apparent speed change to slow, and an apparent speed change to speed up. These constraints on motion reduce the feasible means of

Algorithm 1 Evaluating Protocol-Constrained Motion

```
procedure PSEUDOCODE FOR ANALYZEMOTION()
    Input: initial contact detection
    for each contact report do
        process: $x, y, \theta, v$ (absolute)
        calculate motion: $x, y, \theta, v$ (relative to ownship)
        calculate range, time, and pose at CPA
        calculate risk of collision
            ▷ configurable; default $r_{cpa} < R_{pref}$ using terms of [24]
        if rule set not yet determined then
            if sufficient data && risk of collision then
                determine COLREGS rule set
                    ▷ see Alg. 5 of [24]
                determine allowable ownship maneuvers
                    ▷ codified in [20]; expanded in [1, 10, 19, 24, 28]
                determine predicted contact maneuvers
                    ▷ codified in [20]; expanded in [1, 10, 19, 24, 28]
            else continue to next contact report
            end if
        end if
        calculate contact maneuver(s) from perceived motion
        evaluate contact maneuver(s) with respect to predictions
        set ownship actions based on contact maneuver and Rules
    end for
end procedure
```

communication to the following:

- course changes sufficiently large to be apparent based on the sensing modality (human vision, radar, AIS, etc.)
- speed changes sufficiently large to be apparent based on the sensing modality
- both a speed and course change sufficiently large to be apparent
- no appreciable course or speed change
- an ambiguous course or speed change that immediately implies a contact is non-compliant with respect to the protocol if not under environmental stress or using a noisy sensor.

IV. APPROACH

With the known list of applicable rules and constraints on motion given by protocol, both predictability and legibility are well defined. From analysis of a contact's raw track data relative to ownship, motion may be converted to a rule set and evaluated using the Algorithm 1. This algorithm allows for a contact at initial detection to be tracked from state reports (visual, radar, etc.). Each updated track point may be mapped to previous track data to construct a trajectory including absolute and relative position, course, and speed including changes thereof. From these values, inference may be made as to the contact's compliance with the protocol-based rule set.

V. ON-WATER EXPERIMENTAL SETUP

Up to five autonomous vessels of varying speeds interacted in successive, non-deterministic, non-canonical encounter geometries with a human-operated[2] high-speed motorized kayak as shown in Figure 4. Experiments were conducted on the Charles River at the Massachusetts Institute of Technology in Cambridge, MA, USA.

Robotic vessels were attempting to drive the straight line path assigned between two waypoints. The human's vessel (shown in red) operated in a similar straight track that was not necessarily identical to a robot's track. The pattern of Figure 4 allowed for simultaneous overtaking, head-on, and crossing encounters. The human's track was picked to allow for varying collision avoidance encounter geometries as well as COLREGS protocol requirements.

The robotic vehicles turned 180° upon successfully reaching the end of track and continued to their previous starting point. The varied speeds of robots, environmental conditions, and natural deviations from track for contact maneuvers created non-deterministic times and positions relative to contacts when approaching the track intersection point (center of star pattern). The on-water Monte Carlo experimentation of this collision avoidance scenario allowed for testing multiple rule requirements while also giving the human experimenter flexibility to approach vehicles at various points in their transit to create a collision avoidance interaction.

The human at times maneuvered contrary to the requirements of the rules to further stress the autonomous vessels. The robots were then expected to observe that the human continued on original course and speed while assuming a worst case activity prediction that the human would continue without maneuvering in accordance with the Rules.

Several deviations from expected human motion included:

- maneuvering without regard to the presence of the autonomous vessels
- maneuvering in violation of the collision avoidance rules
- approaching the autonomous vessels at unsafe speeds
- completing an appropriate collision avoidance maneuver and subsequently approaching to an unsafe range (curious human observer of the autonomous vessel)

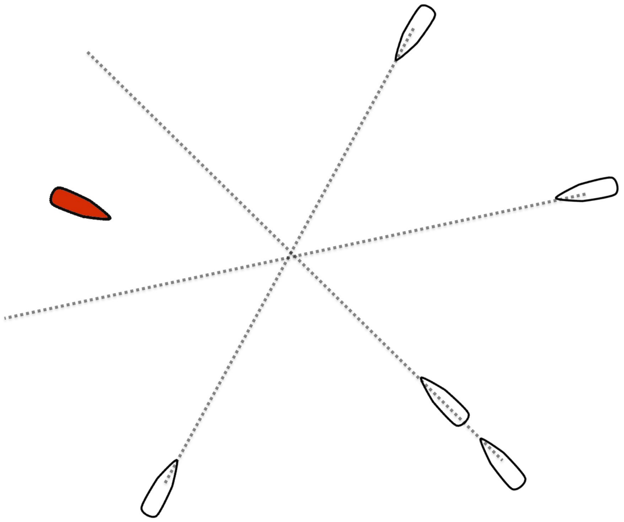

Figure 4. On-Water Testing Geometry with Human (red) and Robots (white)

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[2] The vessel was operated by the first author of this paper.

Table II
SCENARIOS FOR ON-WATER EXPERIMENTATION

Scenario	Description of 5-Vessel Encounter Scenario
I	Open ocean star pattern (baseline; robots only)
II	Open ocean star pattern with human-robot encounters

Two scenarios using the same star pattern of Figure 4 were developed to test the ability to avoid collisions using legibility and predictability of protocol constraints, as shown in Table II. A baseline scenario allowed for an all-robot field to interact using rules and configurations consistent with each other. The second scenario introduced a human to perturb the system as described above. Robots were running MOOS-IvP [6, 8] as the overall autonomy system with COLREGS based on [4].

Safety score was computed using the algorithms presented by Woerner *et al.* in [24–27]. The safety score quantifies the observed range and pose at closest point of approach as a function of the desired range and pose at closest point of approach based on designer configuration parameters. Protocol score was computed using algorithms presented by Woerner in [24]. Protocol scores use track data of each contact to independently determine the required rule set for each contact, determine appropriateness of maneuvers, and issue a grade to quantify performance with respect to required maneuvers.

Nominal values of both protocol and safety score calculations were presented in detail in [24]. Safety scores range from 0 to 100 with 100 being safe and 0 being a physical collision. A score of 100 was assessed for a vehicle whose observed pose-corrected range at closest point of approach was equal to or greater than the ownship-desired range at CPA. Penalties were assessed for violating certain pose-corrected range milestones such as the minimum desired range at CPA and a range considered to be a "near miss" using a linear interpolation function. Protocol was computed using a configuration consistent with the values outlined in [24] for power-driven vessels. Protocol score ranged from 0 to 100, with 100 being perfect compliance (consistent with COLREGS, case law, and configuration parameters) and 0 being totally non-compliant. By assessing safety and protocol compliance together, a more complete understanding of the underlying autonomy decisions may be realized.

VI. ON-WATER RESULTS

The baseline experiment of Scenario I included 1496 on-water vehicle-pair encounters. The on-water human-robot experimentation of Scenario II included 532 human-robot vehicle-pair encounters totalling 39.8 vehicle-hours of interaction. Table III shows the number of encounters for each scenario. In 85 of these 532 encounters, the vehicles determined that they did not fall within the requirements of the protocol constraints and thus were assigned to a CPA-only mode where vehicles simply avoided each other without restrictions on course or speed changes. The primary means of entering this mode was a determination that no risk of collision existed for the encounter.

Table III
NUMBER OF ON-WATER ENCOUNTERS OBSERVED PER SCENARIO

Scenario	Rule Set					
	R13/16	R13/17	R14	R15/16	R15/17	CPA-only
I	224	224	232	997	997	318
II	102	102	96	297	297	170

Figure 5 demonstrates an example on-water encounter showing multiple simultaneous collision avoidance maneuvers based only on detection of contact position, course, and speed over time of an all robot field using human-based rules. Results showed that introducing the human component into the field resulted in a slight decrease in mean safety score for interactions that required a maneuver in accordance with COLREGS as shown in Table IV and Figure 6. Protocol scores demonstrated results similar to those of safety scores as shown in Table V and Figure 7.

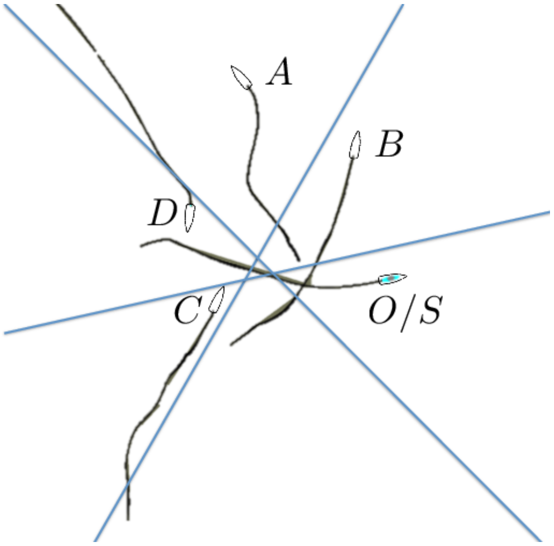

Figure 5. The geometry for the 5-vehicle, 3-track on-water experiment of Figure 4 shows concurrent maneuvers required for multiple simultaneous COLREGS rules. Ownship's (O/S) accompanying decisions were based only on observing other contacts' motions and applying appropriate collision avoidance protocol constraints. O/S and contact vessels A through D maneuvered for each other according to COLREGS.

The one anomaly in the described protocol score reduction for robotic vehicles in a human encounter is the case of the vessel that is the crossing giving way vessel. In this case, humans likely gave way earlier than their robot counterparts due to driving entirely by visual cues rather than having access to exact range information for all contacts. The robots in this case likely achieved a greater mission efficiency than their human counterparts. This highlights a case where more experimentation is warranted to determine if insights may be taken from robot behavior to improve mission efficiency while remaining consistent with human driving characteristics. The likely cause stems from the human driver having a vehicle that is more maneuverable and quickly makes a large course change. The early and clear action by the human likely allowed a stand-on robot to maintain course and speed without necessarily reasoning about possible action if range closed sufficiently to create an *in extremis* situation.

Table IV
MEAN SAFETY SCORE

Scenario	Rule Set					
	R13/16	R13/17	R14	R15/16	R15/17	CPA-only
I	91.92	92.82	93.45	91.72	93.23	99.40
II	84.81	85.97	89.45	86.10	87.43	99.03

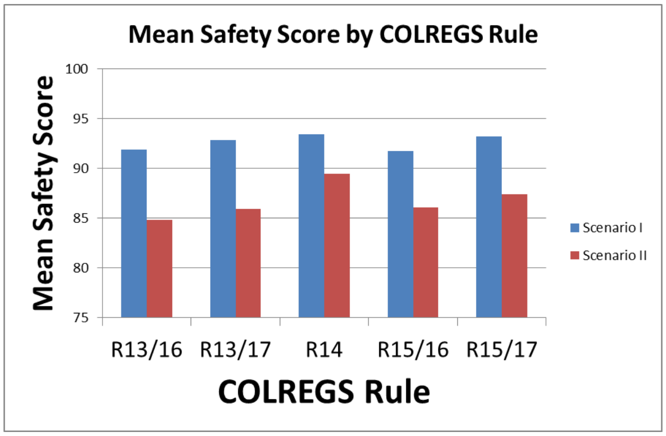

Figure 6. The mean safety score of on-water experiments demonstrated a consistent reduction when a human was introduced into the collision avoidance encounters.

Table V
MEAN PROTOCOL SCORE

Scenario	Rule Set				
	R13/16	R13/17	R14	R15/16	R15/17
I	77.11	56.44	84.54	53.04	66.17
II	72.98	52.58	76.58	56.19	58.56

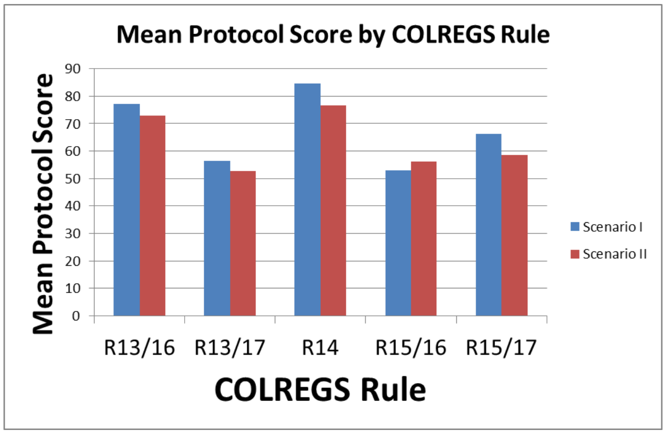

Figure 7. The mean protocol score of on-water experiments demonstrated a consistent reduction when a human was introduced into the collision avoidance encounters with the exception of R15/16.

VII. FUTURE WORK AND OPEN QUESTIONS

Demonstration in this work of the on-water collaboration to avoid collisions raises several open questions for both the robotics and maritime communities. These questions largely address how humans and robots should interact in the future, especially regarding any necessary changes to collision avoidance protocol requirements. Questions include the following:

1) Do the rules as written sufficiently characterize how humans behave, or should changes be made to the underlying rule set to better capture actual human behavior in collision avoidance scenarios?
2) Will (or should) humans alter their behavior if robots strictly adhere to the collision avoidance rule set?
3) Should robots alter their behavior by deviating from the collision avoidance requirements to mimic humans[3]?
4) For multi-contact encounters, will observable motion at the initiation of a maneuver allow activity prediction for immediately subsequent collision avoidance encounters?
5) Can robots learn nuanced intent from legible protocol-constrained motion? Can they then adapt to geographic or vessel-type specific behavioral trends of humans?
6) Can ingestion of large quantities of human track data allow a deep learning for robots in protocol constrained motion rather than attempting to code specific rules?
7) Would this lead to performance more consistent with existing human performance than strict rule compliance?
8) How might other protocols learn from COLREGS and experimental results to reduce collisions, increase efficiency, and improve safety in their physical domains?
9) Should protocols strive for consistency in rules, legibility, and predictability across physical domains?

VIII. CONCLUSION

The application of protocol constraints on motion result in a limited set of allowable motions. By specifying apparent motions, legibility becomes more clear and approaches a discrete set of states. Vessels not complying with the protocol's set of allowed maneuvers may be identified as having unpredictable tracks. Similarly, predictability has been codified in the Rules: by knowing a contact's relative motion information at time of initial detection, a contact's predicted motions are reduced to a limited set of allowable options. Deviation from this set immediately signals non-compliance with the Rules. Because the COLREGS protocol was written for the open ocean human operator where sensor noise and environmental factors are prevalent, the use of ship motion has become the primary means of communicating intent especially in geographic areas lacking a common spoken language. This paper demonstrated that robots may successfully interact with humans by complying with the same protocol that has been adopted for communication-limited human interactions on the high seas without explicitly coding intent inference.

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[3] This question may be similarly presented to the autonomous car community by asking if robots should transit through amber lights at intersections where stopping may result in an increased risk of being hit from behind by a human driver who is capable of stopping but chooses not to do so.

ACKNOWLEDGMENTS

This work was supported by the U.S. Office of Naval Research (Code 33: Robert Brizzolara; Code 311: Behzad Kamgar-Parsi, and Don Wagner) and Battelle (Mike Mellott). The MIT Sailing Pavilion generously provided staff and equipment to support on-water experimentation on the Charles River. Portions of this paper first appeared in [24].

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