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Ship-to-ship Dialogs Using A Finite State Machine

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Abstract

Collision Avoidance Systems require correct and unambiguous application of the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs). Ship-to-ship dialogs, aimed at sharing encounter data to comply with COLREGs and reaching maneuvering agreements, would help to reduce the risk of collision. Finite State Machine (FSM) is a mathematical model for describing the sequential behavior of a control program. Sequential function chart (SFC) based on FSM, is a graphical programming language for Programmable Logic Controllers, defined by the international standard IEC 61131-3. In this work, SFC language is used to model and program the set of states and transitions involved in the ship-to-ship dialogs initiated when one of them detects a risky situation. SFC facilitates the development, verification, and maintenance of the control program. The implemented ship-to-ship communications to share data will help in eliminating differences in decision-making and achieving safer encounters. An example of a risky encounter illustrates this assertion, not contemplated in the related studies consulted. The implemented dialogs will enable sharing information on the encounter characteristics and reaching agreements on the maneuvers to be performed, or maintaining a record about disagreements.

Keywords: Collision risk, COLREGs, Inter-ship communications, Discrete event systems

1. Introduction

According to the statistics on marine casualties [1,2], ship collisions remain high on the list of maritime accidents with the most serious consequences, with human actions being the first accident events. Reportedly, incorrect decisions by the Officers in charge of the Navigational Watch (OONW), misunderstandings in oral communication between them, and failure to take early actions are some main contributing factors in ship collisions.

A modern ship is equipped with devices and systems that provide information to the OONW about herself and nearby ships (targets), for e.g., static and dynamic values received via an Automatic Identification System (AIS). From these values, the Programmable Electronic System (PES) in each ship connected to her AIS can calculate the distance, bearing, Closest Point of Approach (CPA), and time to CPA (TCPA) for each target, as well as the manuevers to be performed based on the COLREGs. The PESs of the ships involved in the encounter can communicate to compare their information and display it in a way facilitating the decision-making by their OONWs.

Thus, ship-to-ship dialogs, sharing encounter data to comply with COLREGs and reaching maneuvering agreements between the two OONWs can help mitigate the collision risk.

This paper describes how these dialogs can be implemented.

- Section 2 presents an example of a close quarters situation illustrating some benefits of the inter-ship dialogs.
- Section 3 outlines the basic aspects of discrete event system (DES) models and languages. The associated state transition graph features facilitate the development of programs to implement the dialogs.
- Section 4 describes the structure of states and transitions in the developed program and the possible evolutions through the graph.

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• Section 5 explains how the program is tested and shows an example of the obtained results.

• Section 6 presents the main conclusions.

2. Ship-to-ship Dialogs as A Requirement to Reduce the Risk of Collision

In encounters between manual, semi-autonomous, and autonomous vessels, sharing data would be a fundamental navigational aid for correct decision-making.

As an illustrative example of this statement and to discuss its benefit, a ship-to-ship encounter case is shown (Figure 1) along with the possible ship responses with or without the reported communications between them.

Crossing situation (COLREG Rule 15): BLUE should keep out of the way and avoid crossing ahead of PINK.

RULE 16 Action by give-way vessel

Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear.

What distance corresponds to "so far as possible"?

Let us consider this Give-way distance as dPrealert. Thus, dPrealert can be defined as the distance to start maneuvering if the ship is a give-way vessel or a vessel that must not impede the passage or safe passage of another vessel.

RULE 17 Action by Stand-on Vessel

(a)

(i) Where one of two vessels is to keep out of the way the other shall keep her course and speed.

(ii) The latter vessel may however take action to avoid collision by her maneuver alone, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules.

(b) When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision.

(c) A power-driven vessel which takes action in a crossing situation in accordance with subparagraph (a)(ii) of this Rule to avoid collision with another power-driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side.

(d) This Rule does not relieve the give-way vessel of her obligation to keep out of the way.

What distance corresponds to "as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules"?

To determine when the stand-on vessel should act, we consider a distance (combination of time and speed), called dAlert. Thus, dAlert can be defined as the distance to start maneuvering if the ship is a stand-on vessel or a vessel whose passage must not be impeded, according to Rules 17 a) ii) and 17 b).

Let us quantify other terms:

• LRS. From Rule 7 (b): *Proper use shall be made of radar equipment if fitted and operational, including long-range scanning to obtain early warning of risk of collision*.

	BLUE	PINK
LAT (N,S):	N	N
degrees (0 .. 89) :	37	37
minutes (0 .. 59) :	0	3
seconds (0 .. 59) :	0	30
LON (E,W):	E	E
degrees (0 .. 179) :	0	0
minutes (0 .. 59) :	0	5
seconds (0 .. 59) :	0	30
Ini Course(0.0 .. 359.9):	0.0	310.0
Length (m):	100.0	300.0
Nav. status (0..15):	0	0
Angle ord.:	0.0	0.0
Speed ord.:	15.0	13.4
Visibility:	GOOD	GOOD
Radar detection:	YES	YES

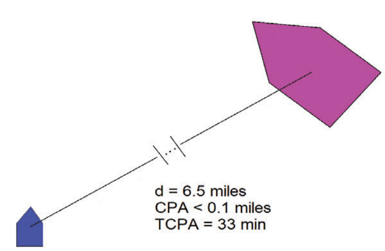


Figure 1. *Crossing situation, vessels in sight*

Crossing situation (COLREG Rule 15): BLUE should keep out of the way and avoid crossing ahead of PINK

• CPASafe. Minimum CPA, limit between safe distance and close quarters.

• TCPASafe. Minimum value for TCPA to avoid collision, if CPA < CPASafe.

And four logical terms:

• Safe distance: CPA ≥ CPASafe.

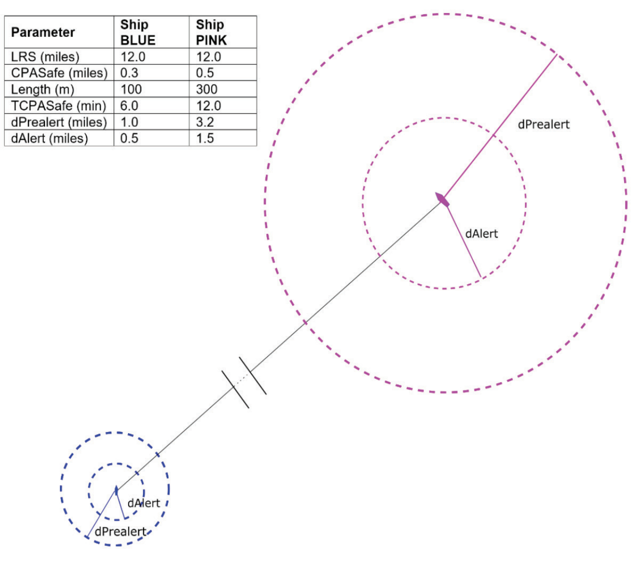
• Close quarters/Risk of Collision: CPA < CPASafe.

• Prealert condition: (CPA < CPASafe) AND [(distance ≤ dPrealert) OR (TCPA < TCPASafe)].

• Alert condition: Prealert condition AND (distance ≤ dAlert).

Evidently, these distances (dPrealert, dAlert, CPASafe) and time (TCPASafe) must be quantified (especially for autonomous ships) depending on the ship dynamics and her maneuvering parameters [3]. Each ship will have her own specific values for these distances and times; thus, the values will differ if the ships involved in the encounter have different characteristics.

Figure 2 collects and illustrates an example of values for the encounter shown in Figure 1. dPrealert and dAlert are approximately 20 and 9 times the lengths of the ships, respectively.



Parameter	Ship BLUE	Ship PINK
LRS (miles)	12.0	12.0
CPASafe (miles)	0.3	0.5
Length (m)	100	300
TCPASafe (min)	6.0	12.0
dPrealert (miles)	1.0	3.2
dAlert (miles)	0.5	1.5

Figure 2. *dPrealert and dAlert distances for both ships*

In this case, ship PINK is the Stand-on vessel, and ship BLUE is the give-way vessel. For the given values, BLUE will detect prealert condition (and must maneuver) when distance ≤1.0 miles or when TCPA <6 min, whichever occurs first.

However, before this situation, PINK enters in alert when distance ≤1.5 miles, so she is forced to maneuver (Figure 3a), according to Rule 17 (a)(ii).

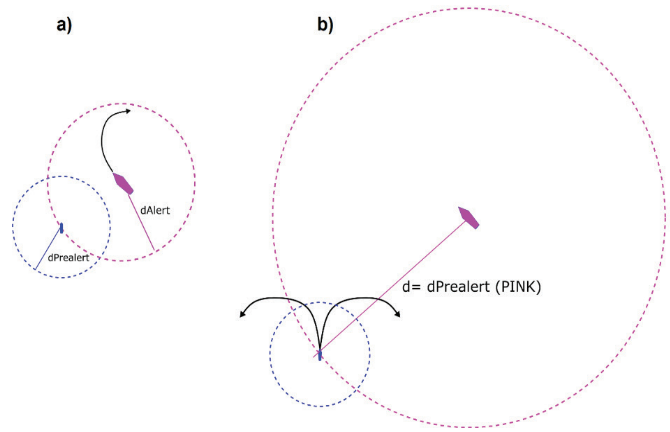


Figure 3. *Possible maneuvers: a) without dialogs; b) with dialogs*

What should BLUE ship do then? Her subsequent behavior is not contemplated by COLREGs, which will increase the risk of the encounter.

If both ships share their information about prealert and alert situations, BLUE will know that she shall keep out of the way when she enters in PINK dPrealert and will share her agreement (or disagreement) with the prescribed maneuver. This maneuver is shown in Figure 3b.

This encounter, without communications, can also generate different maneuvering decisions if the OONW of one of the ships considers that the vessels are in sight and applies Rule 15 (BLUE should maneuver) and the other considers that they are in a restricted visibility scenario, where both ships must maneuver (Rule 19).

The agreement for maneuvering can be achieved as follows: the PES on each ship receives dynamic data about own and target ships (position, heading, speed, ...) from the onboard equipment, calculates distance, bearing, CPA, and TCPA and determines the type of situation and the Rules to be applied for each encounter. In detecting a prealert condition, it will inform the OONW and exchange messages with the PES in the target ship.

An implementation of such communications is presented in Argüelles et al. [4], using Programmable Logic Controllers (PLCs) as the PES and AIS for data acquisition and communications.

3. Sequential Function Charts

A PLC is a robust and reliable programmable electronic device with proven use in the control of industrial processes. Its architecture and programming are defined in the IEC 61131 standard. The PLC structure mainly consists of the processing unit, memory, Input/Output modules, and communication interfaces. PLC executes its tasks in a cyclic mode (scan cycle), which consists of the following four steps:

(1) read the inputs from the periphery to the memory,

(2) execute the user program that reads and modifies the memory contents,

(3) write the values to the output periphery and

(4) perform internal tasks, such as checking for errors and storing the duration of the scan cycle.

Sequential function chart, SFC, is one of the five languages defined by the IEC 61131-3 standard. It is a graphical programming language that allows specifying the sequential control logic of a DES in an intuitive way. A brief introduction to this language is given below.

A DES is an event-driven system of discrete states, i.e., its state evolution depends on the occurrence of asynchronous discrete events in time [5]. Since the middle of the last century, several DES modeling approaches have been proposed, including Finite State Machines (FSM) and Petri Nets (PN) formalisms based on states and transitions.

Figure 4a shows a simple FSM an oriented graph that describes the DES. It consists of discrete states represented by circles and the transitions between them represented by arrowed lines. PNs enable modeling and analyzing more complex and concurrent systems. Figure 4b illustrates a graphical representation of a PN with places (states), transitions, and oriented arcs [6,7].

These state transition models, as graphical tools, represent the behavior of sequential systems graphically, facilitating the development of control logic and verification operations (through exhaustive testing) of requirement specifications. In addition, as mathematical tools, FSM and PN models are the basis for formal verification techniques to ensure the correctness of the safety-critical software [8,9].

GRAFCET (GRAphe Fonctionnel de Commande Etape Transition) is a specification language related to PN [10]. It was defined in 1977 and subsequently standardized as IEC 60848 [11] for the functional description of the behavior of the sequential part of a control system. This specification language is independent of any specific technology of implementation. SFC language defined in IEC 61131-3 [12], is based on IEC 60848 and is a specific programming language for PLCs.

In the IEC 61131 standard, the term Program Organizational Unit (POU) is used for all programming objects: PRoGrams (PRG), Function Blocks (FB), and Functions (FU), used to create a controller application.

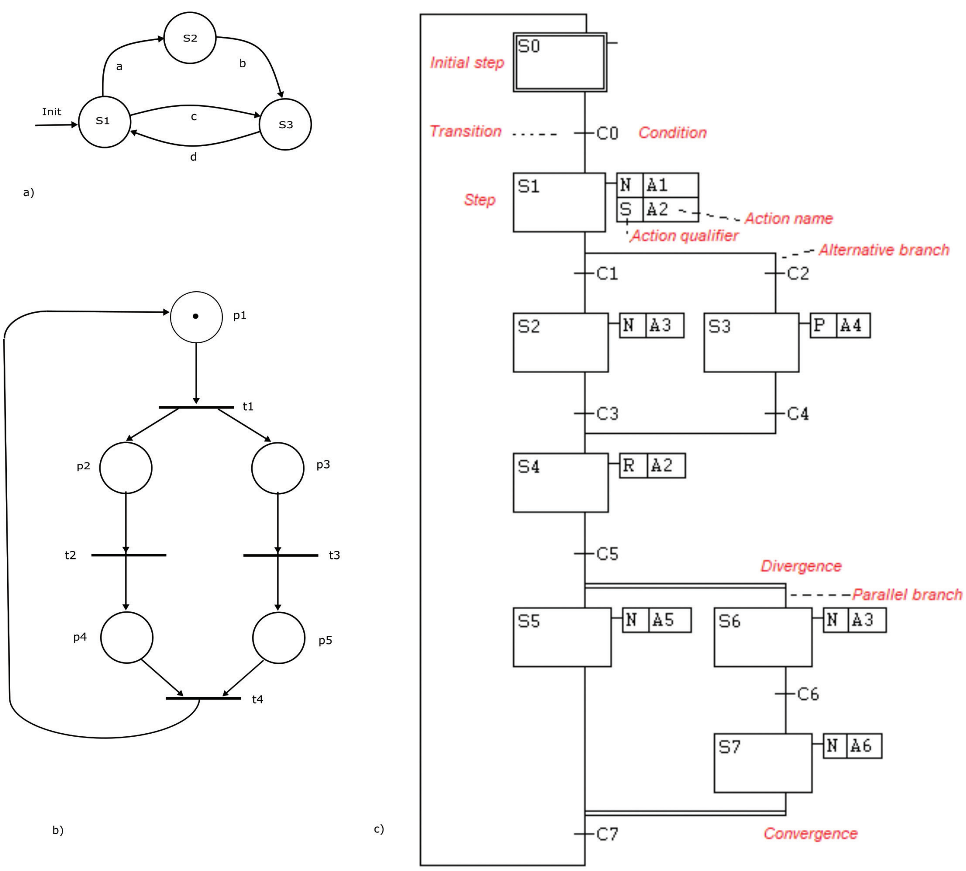


Figure 4. *Discrete event models: a) FSM; b) PN; c) SFC language*

FSM: Finite State Machine, PN: Petri Nets, SFC: Sequential function chart

A POU written in SFC consists of steps (states) and transitions. It has one initial step, and each transition is labeled with an associated condition. Zero, one, or more actions may be associated with each step. Figure 4c shows an example of an SFC.

Actions in the SFC include a qualifier, specifying the duration of the action, and a name, identifying the programmed instructions. Some qualifiers:

• N (Non-stored): The action is active as long as the step is active.

• P (Pulse): The action is executed just once if the step is active.

• R (Reset): The action is deactivated.

• S (Set): The action is activated and remains so until a Reset.

There are different types of transitions:

• simple transitions between two steps,

• alternative branching, i.e., the choice among several transitions,

• parallel branching with divergence from one step into a set of parallel steps and ulterior convergence into a single step.

In the first scan cycle of a SFC POU, the initial step becomes active, and the associated actions (if any) are executed. Then, at each cycle, all conditions on transitions starting at active steps are evaluated, and if true, the corresponding transition is enabled, changing the set of active steps.

4. SFC Implementation of Ship-to-ship Dialogs

SFC is used in this work to model and program the set of states and transitions involved in the ship-to-ship dialogs initiated when one of them detects a risky situation.

The controller application executed on the PLC of each ship includes a number (N) of FBs written in SFC, one for each target; 0 ≤ N ≤ Max, where Max: maximum number of targets.

When the PLC application running on a ship detects a target, it activates the initial step of an associated SFC (Figure 5).

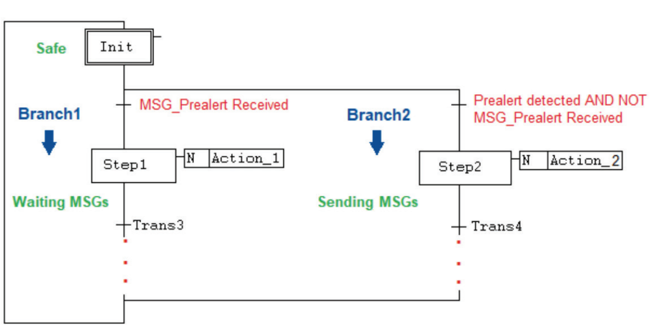


Figure 5. *Basic SFC for Ship-to-ship dialogs*

SFC: Sequential function chart

SFC starts from a safe state (safe situation), which is exited for one of two following reasons:

- A prealert message (*MSG_prealert*) is received from the target (branch1). While progressing through this branch, the target takes the initiative of the communication. The own ship's PLC waits for the messages and then responds (Figure 6).

- Prealert condition is detected (branch2). In this branch, the ship's own PLC takes the initiative. It sends messages and waits for replies from the target (Figure 7).

To avoid a possible simultaneous activation of both branches, in case both ships detect prealert at the same time, their initial conditions cannot be simultaneously true.

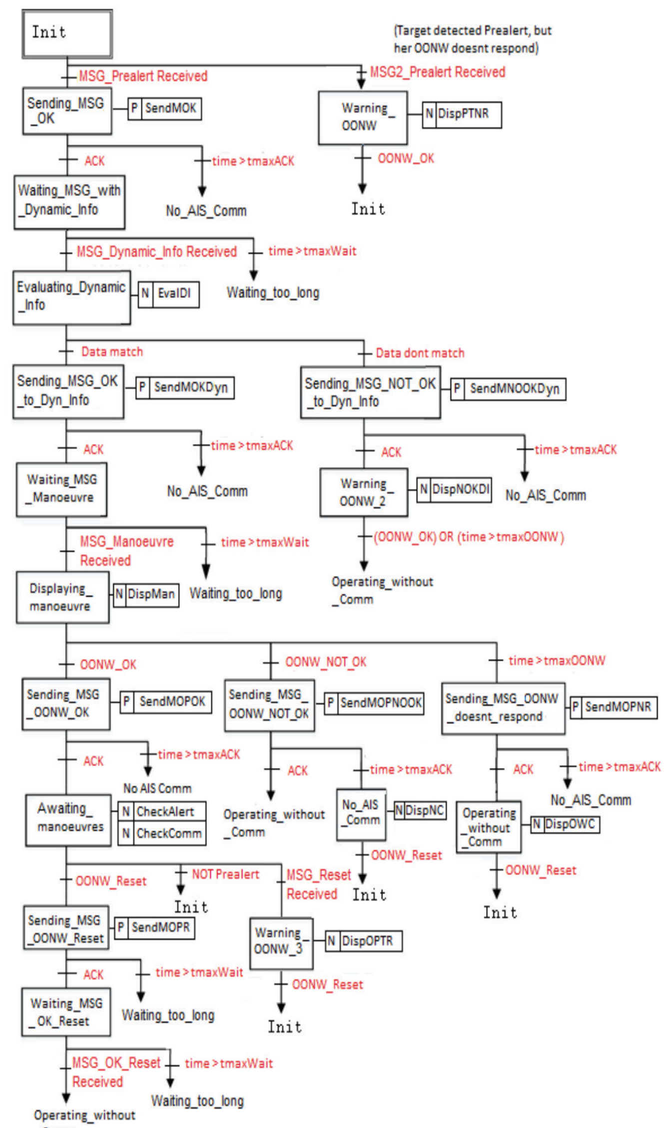


Figure 6. *SFC Branch1*

SFC: Sequential function chart

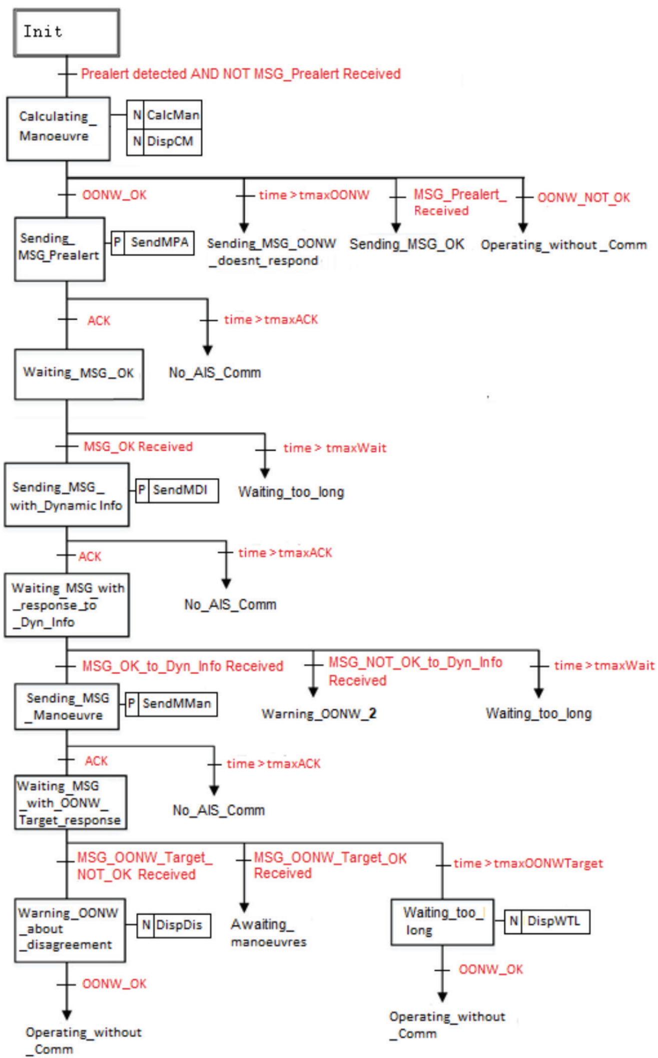


Figure 7. *SFC Branch2*

SFC: Sequential function chart

To this end, a priority is given to Branch1, including in the following initial condition of Branch2: *Prealert* detected AND NOT *MSG_Prealert* Received.

A feasible channel of communication between the PLCs of the ships can be achieved through their AIS stations, using standard messages 6 and 7 [13].

After sending a message, it is necessary to wait for the reception of the ACK issued by the AIS in the target, indicating that the message has been transmitted. If more time than expected (*tmaxACK*) elapses without receiving the ACK, it is understood that there has been a communication failure between the AIS stations, and the SFC moves to a *NO_AIS_Comm* step, wherein the operator is informed of the communication failure.

Other maximum waiting times associated with transitions should be established, as listed below:

- PLC communication message waiting time (*tmaxWait*).
- Waiting time for the OONW to respond to a received MSG (*tmaxOONW*).
- Waiting time for the target OONW to respond to the maneuvering proposal sent by own ship (*tmaxOONWTarget*).

The names of the actions in Figures 6 and 7 have been shortened to avoid overloading the images. Main assignments of the action POUs are as follows:

- *Send**: Generate the corresponding binary message and send it to the target.
- *Disp**: Display the corresponding text to inform the OONW.
- *EvalDI*: Compare the dynamic information sent by the target with the information available about it to check whether it is consistent. This dynamic information is included as parameters in the received message comprising visibility, navigational status, prealert and alert defined values, distance, bearing, CPA, TCPA, heading, speed, and the calculated situation according to COLREGs.
- *CalcMan*: With the dynamic data received from own and target ships, the calculated bearing, distance, CPA, TCPA, and situation, this POU determines what possible maneuver must be performed.
- *CheckAlert*, *CheckComm*: The step *Awaiting_maneuvers* is active if there is agreement between the OONWs of both ships about the maneuver to leave the prealert condition. While in this state, waiting for the agreed maneuver to be performed, *CheckAlert* determines if there is an alert condition. In that case, a warning is displayed, indicating that both ships must maneuver. *CheckComm* conducts periodic checking of the communication between the PLCs.

5. Results

The crossing situation described previously is used as an example for checking the operation of the developed POUs. These software tests require the simulation of the ship movements and the AIS messages for data acquisition and communications. The development of the models for the simulation of a ship movement follows the standard ISO 11674-A [14]. AIS messages have been simulated using OPC communications. All values to transmit are transformed into bit strings according to the standard approved by the International Telecommunication Union [15]. Each PLC acts as an OPC server to share the memory area reserved for messages. An application acting as an OPC client is responsible for reading the message string from the source PLC and writing it to the destination PLC.

The simulation starts with the data given in Figure 1. In our example, the PLCs in both ships, PINK and BLUE have an enabled SFC with the initial state active. At 3.2 miles (see Figure 2), PINK PLC detects prealert and activates its branch2 (see Figure 5). Then, it initiates the dialog with BLUE PLC. On receiving the message, the SFC running on BLUE progresses through its branch1.

Figure 8 shows the information visualized by each OONW with the data in the PLC of BLUE (PLC1) and PLC of PINK (PLC2), when PLC2 detects the prealert condition. In addition to the information received from the AIS on positions, headings, speed over ground, rate of turn, and the calculated data (distance, bearing, relative course and speed, CPA, and TCPA), BLUE OONW sees that both ships are Under way using engine (navigational status 0, from their AIS dynamic data) and the situation is crossing. T is on the Starbd Side O (crossing, PINK on BLUE's starboard side). PINK OONW sees that both ships are under way using engine, and the situation is crossing. T is on port side O (crossing, BLUE on PINK's port side) and the prealert SITUATION warning.

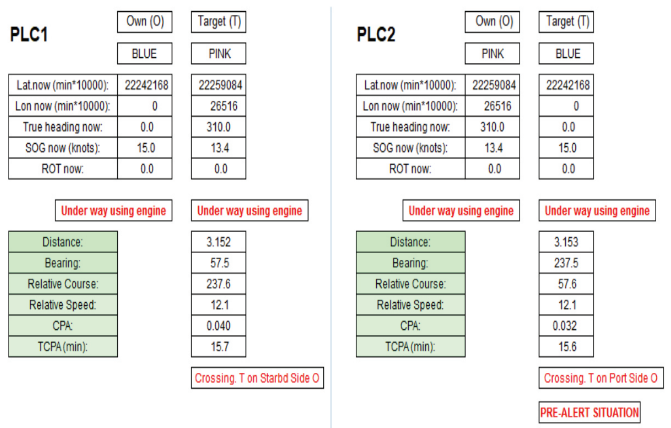


Figure 8. *Received and calculated data, PINK on prealert*

When PLC2 detects the prealert, and the evolutions through the SFCs start. Figure 9 shows the sequence of communications between PLCs and the messages displayed by the OONWs. First, PLC2 calculates the maneuver according to COLREGs and warns its OONW. If she/he agrees, it sends the message with the prealert to PLC1, waits for the reception of MSG OK, and later sends the message with the associated dynamic data to PLC1. PLC1 compares them with its own data and if they match, it sends MSG_OKDyn to PLC2. Then, PLC2 sends the MSG with the information about the maneuver and advises its OONW that it is waiting for an answer from BLUE OONW. PLC1 displays the received information, and if its OONW says OK, both PLCs inform about the agreement.

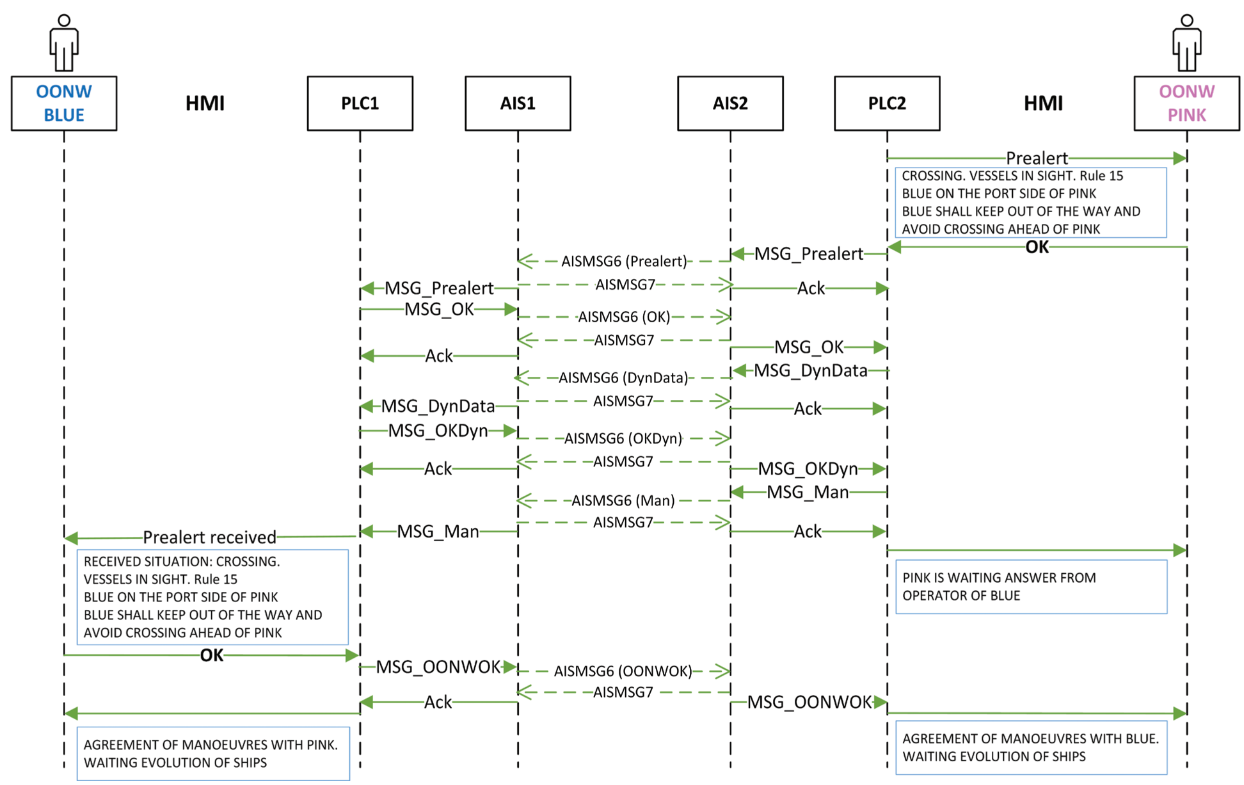


Figure 9. *Sequence of messages, in case of agreement between OONWs*

OONW: Officers in charge of the Navigational Watch

The same situation, but assuming a difference in the visibility criteria (PINK OONW considers that they are in a restricted visibility scenario and BLUE OONW that vessels are in sight) produces a sequence of messages shown in Figure 10.

The system informs both OONWs that PINK has entered in prealert, but that there is a difference in visibility considerations, and therefore, possible differences in maneuvering decisions. In this example, messages for OONWs in Figure 10 show the following:

• PINK OONW, after agreeing to apply COLREG Rule 19 sees that the target (BLUE) info is vessels IN SIGHT crossing starboard side (i.e., PINK is crossing on BLUE's starboard side). Therefore, PINK OONW infers that BLUE OONW will act according to this information and will apply COLREG Rule 15.

• BLUE OONW, considering that vessels are in sight, receives the message depicting that PINK is in prealert, and her info is vessels NOT IN SIGHT WITH RADAR, T FWD PSD O, O FWD T (BLUE forward on PINK's portside, PINK forward BLUE). Therefore, BLUE OONW infers that PINK OONW will act according to this information and will apply COLREG Rule 19.

Thus, both OONWs are aware that their maneuvering decisions may differ.

The graphical character of the language facilitates the design, verification, and validation of the software. It allows to visualize and check whether all possible states that the system can go through are considered, without probing how the actions are implemented. This makes it easier to understand how the system works for the potential users of the system.

The visualization of the program execution during software testing, showing which step is active at any given moment, makes it possible to check and verify all possible transitions.

6. Conclusions

A functional safety model has been developed for the prevention of ship-to-ship collisions, aimed at reducing the probability of occurrence of two dangerous factors among the main causes of these accidents:

• Errors in the detection of critical situations, and

• Errors in the decision-making on collision avoidance maneuvers.

For this purpose, the defined system is responsible for detecting and identifying the type of dangerous encounter, checking that both are handling the same information to suggest the manuever to be performed in compliance with COLREGs and to ensure that the operators of the vessels involved are aware of and accept (or not) the suggested maneuver.

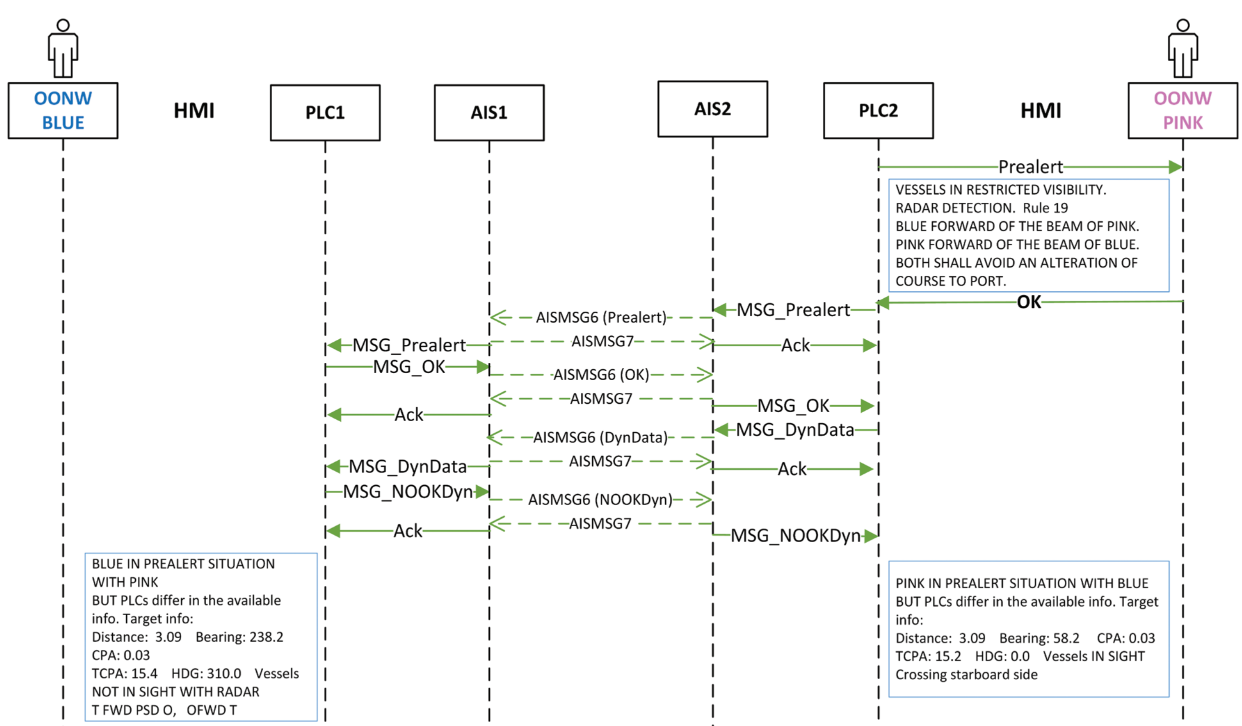


Figure 10. *Sequence of messages, in case of disagreement between data*

OONW: Officers in charge of the Navigational Watch

To reach these decision agreements, the system establishes a communication between the two ships. SFC, a finite state machine-based language, is used to model and program the set of states and transitions involved in the ship-to-ship dialogs initiated when one of them detects a risky situation. This language facilitates the development, verification, and maintenance of the program.

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