Thesis Title

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Abstract

Faculty of Science and Engineering
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Master of Science (Technology)

Thesis Title

by Emil AURA

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too...

Acknowledgements

The acknowledgments and the people to thank go here, don't forget to include your project advisor...

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List of Abbreviations

COLREGs   Convention on the International Regulations for Preventing Collisions at Sea, 1972
FMF   Fuzzy Membership Function

1 Introduction

International Regulations for Preventing Collisions at Sea [1] [2]

2 Theory

2.1 Unmanned Surface Vehicles

[3]

Unmanned Surface Vehicles (USV) or Autonomous Surface Crafts (ASC) are vehicles operating the seas without a crew on-board. USVs encompass both fully autonomous vehicles, from now on referred to as ASCs, and semi-autonomous vehicles. Development of USVs has been ongoing for the last two decades [4]. However, majority of the USVs developed are of the semi-autonomous type [5], [6], meaning that they depend on human intervention to some extent usually by a supervisor located on shore. Although semi-autonomous USVs greatly increase the safety of the operating personnel [5], they do not completely remove the need for human interaction. Supervision of several semi-autonomous vehicles can be admittedly be handled by a single person, which significantly decreases the amount of person-hours needed to accomplish a specific mission [4]. The person-hours needed for surveillance could, however, be removed completely by a ASC. It is, therefore, of great interest to overcome the challenges associated with ASCs.

2.1.1 Usage

Yuh, Marani, and Blidberg [7] mention that roughly two-thirds of the earth's surface is covered by water, with an average depth of the oceans being 3688 m [8]. Thereby, adding up to vast amount of explorable areas of which 95 % is yet to be seen by human eyes [9]. Although ASCs are situated on the surface of the ocean they can greatly increase the efficiency of Unmanned Underwater Vehicles (UUV) by acting as a gateway between UUVs and services, such as GPS, not easily available in underwater environments [5].

"Unmanned surface vehicles: An overview of developments and challenges, author=Liu, Zhixiang and Zhang, Youmin and Yu, Xiang and Yuan, Chi, journal=Annual Reviews in Control, volume=41, pages=71–93, year=2016, publisher=Elsevier" [5] have, furthermore, compiled a list of potential applications of USVs, along with previous research on the topics. The list is divided into four major categories: Scientific research, Environmental missions, Ocean resource exploration and Other applications. Many of the applications mentioned would require the vehicles to interact with other vessels. It is therefore crucial for the USVs to follow the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) explained in section 2.2.

2.1.2 Challenges

USVs operate in a highly variable environment, both regarding climate and traffic density. Algorithms and systems developed should, therefore, be usable bot in severe weather conditions and in densely trafficated ports and fairways.

The Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs), presented in section 2.2 aims to ensure collision avoidance among vessels, although they are written to be interpreted by humans. Furthermore, situations where multiple rules are in effect are quite common . These aspects pose challenges when translating the COLREG rules into computer understandable code [10].

The fact that USVs often operate on open seas where reliable communication channels can be limited and weather conditions harsh, pose additional challenges regarding guidance and sensor failures [5].

2.2 COLREG

Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) consist of 38 rules, grouped into five different sections, designed by the International Maritime Organization (IMO). The rules were adopted 1972 and entered into force 1977. COLREGs was designed to ensure traffic separation between vessels in an increasingly populated environment back in 1972 and it is, therefore, sometimes referred to as the Rules of the Road for maritime vessels. COLREGs has since been in use and mandatory to adhere to on international waters, although it has received amended several times [11].

National regulations might differ from the COLREGs to some extent. However, COLREG mention that 'Nothing in these Rules shall interfere with the operation of special rules made by an appropriate authority for roadsteads, harbours, rivers, lakes or inland waterways connected with the high seas and navigable by seagoing vessels. Such special rules shall conform as closely as possible to these Rules.' [12]

2.2.1 Parts

This subsection will present the different parts of the COLREGs regulations, with emphasis on the parts related to manoeuvring an USV in international waters. Information in this subsection is taken from the official COLREG regulations [12] if not otherwise specified.

Part A General

Rule 1 covers which vessels that are affected by the COLREGs regulations. This includes all vessels navigation on high seas and all waters connected therewith. Additionally, it specifies that special rules regarding roadsteads, harbours, rivers, lakes or inland waterways connected with the high seas and navigable by seagoing, shall conform as closely as possible to these Rules.

Rule 2 states that the COLREG rules does not in any way free the vessel, owner, master

or crew from responsibility to follow the rules and act according to ordinary practice of seamen.

Rule 3 Defines the meaning of words used in the regulations, such as: vessel, power-driven vessel, sailing vessel, length, and breadth.

Part B Steering and Sailing

Rule 4 simply states that all rules in Part B Section I (rules 4-10) apply in any condition of visibility

Rule 5 states that all vessels shall at all times maintain proper look-out by sight and hearing and all other available means to ensure the best possible situation awareness.

Rule 6 states that vessels shall maintain a speed so that they can take proper and effective action to avoid collision and stop within distance appropriate to the prevailing circumstances and conditions.

Rule 7 states that all vessels shall use all means possible to determine if a risk of collision exists. This includes the use of radar equipment, however, caution should be exercised not to trust insufficient data. Moreover, Rule 7 states that any doubt whether a risk of collision exists, shall be treated as if a risk exists. Finally it specifies that a constant compass bearing between two vessels, means that the two vessels are on collision course with each other. However, a constant bearing is only a sufficient condition for a risk of collision not a necessary one. Close range, large vessels or a tow might pose a collision risk, without a constant bearing.

Rule 8 concerns actions to avoid collision. Actions shall, for instance, be taken according to the rules and as far as possible be conducted in ample time and large enough so that they are easily observable by other vessels. Small alterations should in other words be avoided. Course alterations might, moreover, be accompanied by a lowering of speed, if necessary to ensure in the vessels passing each other at safe distance.

Rule 9 concerns navigation in narrow channels and is therefore not of interest for the scope of this thesis.

Rule 10 Concerns Traffic Separation Schemes ruled by IMO. These are traffic route systems developed for particularly congested shipping areas [13] and, therefore, not of interest for the scope of this thesis.

Rule 11 simply states that all rules in Part B Section II (rules 11-18) apply to vessels in sight of each other.

Rule 12 concerns sailing vessels and is therefore not of interest for the scope of this thesis.

Rule 13 specifies action to be taken by a vessel (give way vessel) when overtaking another vessel (stand on vessel). The give way vessel shall keep out of the way of the stand on vessel. A vessel is considered to overtake another vessel when approaching the other stand on vessel from a direction more than 22.5 °abaft the stand on vessels beam, i.e with a relative bearing between 112,5 °and 247,5 °from the stand on vessel.

Rule 14 defines a head-on situation as well as actions to be taken in case of a head-on situation. A head-on situation is when a vessel sees another vessel ahead or nearly ahead, i.e. it

can see the masthead light in line or both sidelights. The give way vessel shall in this case alter its course to starboard.

Rule 15 states that vessel coming from starboard, i.e right, has the right of way in a crossing situation. The give way vessel shall if possible avoid crossing ahead of the other vessel and, therefore, alter its course to starboard.

Rule 16 states that give way vessel shall take action as early as possible.

Rule 17 states that give way vessels shall keep their course and speed, provided that the give way vessel acts according to the regulations or if the actions by the give way vessels are insufficient to prevent a collision.

Rule 18 specifies responsibilities between vessels of different type. For instance a power driven vessel shall give way for a vessel engaged in fishing.

Rule 19 specifies reduced visibility operations. Vessels should proceed at speeds appropriate to the circumstances and use radar to determine collision risks. Speed should be reduced to minimum if a vessel can hear another vessels fog horn apparently forward of her beam.

Part C Lights and Shapes

Part C specifies the lights and shapes a vessel shall exhibit, and when they should be used. These are therefore not of interest for the scope of this thesis, with the exception of *rule 21 and 22*, which specify the arcs that specific lights should cover as well as the distance the should be visible from.

Masthead lights cover a 225 °arc from 247,5 °to 112,5 °and should be visible from at least 2-6 miles, depending on the length of the vessel.

Sidelights are green on starboard side and red on port. They cover a 112,5 arc from 0 relative bearing to 112,5 and 247,5 respectively. They should be visible from at least 1-3 miles, depending on the length of the vessel.

Part D Sound and Light signals

Part D specifies sound and light signals and is not of interest for the scope of this thesis.

Part E Exemptions

Is not of interest for the scope of this thesis.

2.3 Previous research Collision Avoidance Algorithms

USVs have been in development since at least 1993 when MIT started its Sea Grant College Program, Autonomous Surface Craft (ASCs) [4]. Different approaches have been tried over the years, most of which have not taken COLREG into account. This section will look into some of these approaches as well as their pros and cons.

Soltan, Ashrafiuon, and Muske [14] developed a system for under-actuated unmanned surface vehicles where obstacles are approximated as elliptic shapes. These ellipses represent stable limit cycle solutions and planned trajectories are tracked by the vessel through a sliding mode control law. However, their research does not mention COLREG. Xu, Stilwell, and Kurdila [15] have done a formal analysis of path planning algorithms based on level set method, with the focus on making the process more efficient for large areas. This is done by reducing the number of level set function updates needed as well as the size of the updates. The approach might, however, still be slow for large areas and it does not respect COLREG. Kim, Kim, Shin, *et al.* [16] uses an approach based ion Theta* called *angular rate-constrained Theta* (ARC - Theta*)*. COLREG is not yet considered but mentioned as future work. The algorithm does great in comparison with algorithms using SE(2) grid map-based path planning or 3D A*, even though the algorithm considers the performance of the vessel. El-Gaaly, Tomaszewski, Valada, *et al.* [17] have made experiments with a low-cost model using a smartphone as the only sensor. The model is made for low-cost autonomous watercraft in riverine environments and assumes that all objects are static. Its computational cost is, therefore, low but use cases limited. Lee, Kwon, and Joh [18] combines fuzzy logic with modified virtual force fields to create an COLREG compliant algorithm. The fuzzy logic rule-set used consists of about two hundred rules, which might be computational challenging. The authors does, however, mention that the rules-set might be streamlined.

2.3.1   behavior-based control and multi-objective action selection

[10], [19]

2.3.2   near-field reactive control technique

[20]

2.3.3   relative coordinate based collision avoidance strategy with integration of an evolutionary path planner

[21]

2.3.4   simple manual biasing scheme and a direction priority sequential selection (DPSS) strategy under COLREGs.

[22]

2.3.5   a rule-based repairing A* (R - RA*) algorithm in com- pliance with COLREGs

[23]

2.3.6 velocity obstacles (VO)

[24]

2.3.7 Trajectory planning with adaptive control primitives for autonomous surface vehicles operating in congested civilian traffic

[25]

2.3.8 other

[26]–[29]

2.4 Fuzzy set theory and logic

The concept of fuzzy sets was first mentioned by Zadeh [30] in 1964 as a way of dealing with sets of objects, where an objects membership to a set can be represented by a value in the real interval [0, 1]. Compared to classic set theory where to membership is restricted to the two values of one and zero. Fuzzy logic enables one to define sets such as "old men" or "vessels on nearly reciprocal course" [30], which facilitates the process of converting human abstract reasoning into computer understandable logic.

2.4.1 Fuzzy sets

The fuzzy set "all old men" can be defined in the following way. Let the *universe set* $\mathbf{X}$ be the set of ages [0, 100]. The set of old men can then be written as $A = \{a \in \mathbf{X}|a \text{ is old}\}$ [31]

However, the set requirement 'is old' is still undefined and therefore vague. Defining the threshold of being old at an age of 60 does divide the universal set $\mathbf{X}$ into subsets of 'old' and 'not old', but the division does not distinguish between humans aged 1 and 59. Fuzzy set theory introduces the concept of membership functions, to solve this problem. A Fuzzy Membership Function (FMF) describes the grade of membership of a in A. This function is often written as $\mu_A(a)$. Figure 2.1 shows a very simple linear FMF for the example $A = \{\text{'is old'}\}$, where for instance $\mu_A(10) = 0.1$. Similar FMFs can be defined for young and middle-aged which results in the graph seen in figure 2.2 [32].

A fuzzy set can then be written as an array of tuples consisting of the objects and its associated membership value: $A = \left\{(x, \mu_A(x)|x \in X)\right\}$ [33], which gives $A = \{(0, 1), (10, 0.9), (20, 0.8), \dots, (90, 0.1), (100, 0)\}$ for the example $A=\{\text{'is young'}\}$ in figure 2.1 [32].

2.4.2 Fuzzy logic

Fuzzy sets and set theory can in the same manner as classical boolean sets be used to define logical expressions. Fuzzy logic allows for half-truths, i.e. truth values in the interval [0,1].
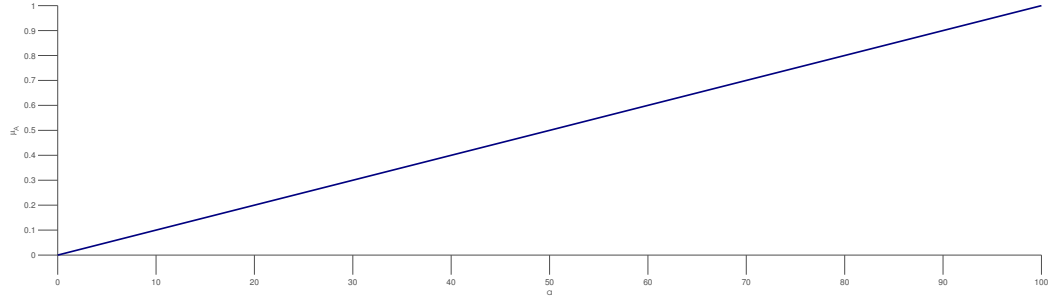
FIGURE 2.1: Fuzzy membership function for $\underset{\sim}{A} = \{'\text{Is old}'\}$
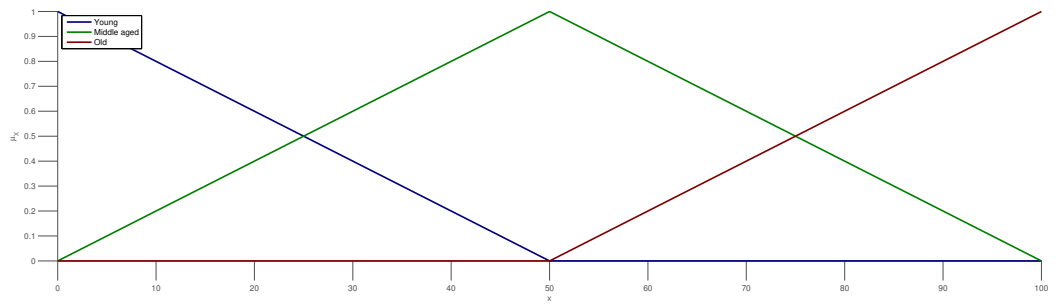
FIGURE 2.2: Fuzzy membership function for $\underset{\sim}{A} = \{'\text{Is young}'\}, \underset{\sim}{B} = \{'\text{Is middle-aged}'\}$ and $\underset{\sim}{C} = \{'\text{Is old}'\}$

Whereas boolean logic is restricted to truth values of one and zero. The truth value T of a fuzzy preposition P is, therefore a mapping from [0,1] to the universe T, as can be seen in 2.1 [32].

$$T : u \in U \rightarrow (0,1) \tag{2.1}$$

The truth value of proposition P is therefore given by the membership grade $\mu_{\underset{\sim}{A}}(x)$ of x in $\underset{\sim}{A}$

Many of the same operators and connectives used in classical logic, does also apply to fuzzy logic. This thesis will only present the rules necessary for the scope of the thesis, which are the following [32]:

Negation

$$T(\overline{\underset{\sim}{P}}) = 1 - T(\underset{\sim}{P})) \tag{2.2}$$

Disjunction

$$\underset{\sim}{P} \vee \underset{\sim}{Q} : x \text{ is } \underset{\sim}{A} \text{ or } \underset{\sim}{B} \quad T(\underset{\sim}{P} \vee \underset{\sim}{Q}) = max(T(\underset{\sim}{P}), T(\underset{\sim}{Q})) \tag{2.3}$$

Conjunction

$$\underset{\sim}{P} \wedge \underset{\sim}{Q} : x \text{ is } \underset{\sim}{A} \text{ and } \underset{\sim}{B} \quad T(\underset{\sim}{P} \wedge \underset{\sim}{Q}) = min(T(\underset{\sim}{P}), T(\underset{\sim}{Q})) \tag{2.4}$$

Implication

$$\underset{\sim}{P} \rightarrow \underset{\sim}{Q} : x \text{ is } \underset{\sim}{A}, \text{ then } x \text{ is } \underset{\sim}{B} \tag{2.5}$$

$$T(\underset{\sim}{P} \to \underset{\sim}{Q}) = T(\overline{\underset{\sim}{P}} \vee \underset{\sim}{Q}) = max(T(\overline{\underset{\sim}{P}}), T(\underset{\sim}{Q}))$$

Implication can also be written in rule based form

$$\underset{\sim}{P} \to \underset{\sim}{Q} \text{ is IF } x \text{ is } \underset{\sim}{A} \text{ , THEN } t \text{ is } \underset{\sim}{B}$$

$$\Leftrightarrow$$

$$R = (\underset{\sim}{A} \times \underset{\sim}{B}) \cup (\overline{\underset{\sim}{A}} \times \underset{\sim}{Y})$$

With the membership function:

$$\mu_{\underset{\sim}{R}}(x,y) = max[\mu_{\underset{\sim}{A}}(x) \wedge \mu_{\underset{\sim}{B}}(y), (1 - \mu_{\underset{\sim}{A}}(x))] \tag{2.6}$$

Equation 2.6 is equivalent to the material implication used in traditional boolean logic [34]. However, fuzzy logic has multiple implication operators [32]. The work in this thesis will use Mamdani's impication , see equation 2.7.

$$\mu_{\underset{\sim}{R}}(x,y) = min[\mu_{\underset{\sim}{A}}(x), \mu_{\underset{\sim}{B}}(x))] \tag{2.7}$$

2.4.3 Fuzzy (rule-based) systems

Fuzzy logic can be used to model complex systems described in natural language, originally written to be interpreted by humans. Such knowledge can often be written as rules in the following form [32].

$$\text{IF premise (antecedent), THEN conclusion (consequent)} \tag{2.8}$$

Combining multiple rules enables one to describe complex systems in a relatively simple structure. Rules can, furthermore, contain multiple antecedents and consequents. However, this raises the question of how multiple antecedents, as shown in rule 2.9, can be decomposed into a single antecedent and the rules aggregated into a single consequent [32].

$$\text{IF } x \text{ is } A_1 \text{ and } A_2 \ldots \text{and } A_L \text{ THEN } y \text{ is } B_s \tag{2.9}$$

Conjunctive antecedents can rewritten as a new fuzzy set

$$\underset{\sim}{A_s} = \underset{\sim}{A_1} \cap \underset{\sim}{A_2} \cap \cdots \cap \underset{\sim}{A_L}$$

with the membership function

$$\mu_{\underset{\sim}{A_S}}(x) = min \left[\mu_{\underset{\sim}{A_1}}(x), \mu_{\underset{\sim}{A_2}}(x), \ldots, \mu_{\underset{\sim}{A_3}}(x) \right]$$

Rule 2.9 can then be rewritten as

$$\text{IF } \underset{\sim}{A_S} \text{ THEN } \underset{\sim}{B_S}$$

Disjunctive antecedents can similarly be written as

$$A_s = A_1 \cup A_2 \cup \cdots \cup A_L$$

$$\mu_{A_s}(x) = max \left[\mu_{A_1}(x), \mu_{A_2}(x), \ldots, \mu_{A_3}(x) \right]$$

The same principle can be applied to find the overall consequent when multiple rules apply. Conjunctive rules where both consequents must be applied, can be found by the fuzzy intersection of all the rule consequents. Whereas disjunctive rules use the fuzzy union of the rule consequents.

3 Method

3.1 Scikit-Fuzzy

[35] [36]

A Frequently Asked Questions

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