Mamdani type fuzzy inference failures in navigation

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Abstract—This paper proposes a methodology to overcome failures on Mamdani rule based fuzzy inferences in navigation. The fuzzy inference failures are observed in three situations: Intersected contradictory decision boundaries, improper transition region between the inference boundaries of non-intersected contradictory decisions and contradictory decision accumulation. In order to solve the problems, it is proposed to insert a smooth transition region between intersected contradictory decision inference boundaries, to determine the size limitations between non-intersected contradictory decisions inference regions, and finally to integrate a “multi-level” process. The proposed solutions are applied to a decision making process of ocean navigation and successful simulation results are shown in this study.

I. INTRODUCTION

The use of Mamdani type fuzzy rule based inference in navigational/steering systems has been previously proposed and extensively applied. However, this solution exhibits several problems that might become critical when applied in real world systems and that have been overlooked in recent studies. These problems arise in three different situations that can be categorized as: Intersected contradictory decision boundaries failures; improper transition region between the inference boundaries of non-intersected contradictory decisions failures; and Contradictory decision accumulation failures.

A. Intersected Contradictory Decision Boundaries

Figure 1 shows a pictorial example of a possible situation, where a two vessel navigation situation is illustrated. The own vessel, the vessel that is equipped with the Mamdani type fuzzy rule based inference system, is located in the point \(O(k)\) \((x_o(k), y_o(k))\), at the \(k^{th}\) time instant. The \(i^{th}\) target vessel, the vessel that needs to be avoided, is located at point \(P_i(k)\) \((x_i(k), y_i(k))\). As presented in the figure, the following fuzzy rule inferences are assigned: the Own vessel should steer to port \((\delta\psi_o<0)\) and maintain its speed \((\delta V_o=0)\) when target vessel is in Region VIII, and should steer to starboard \((\delta\psi_o>0)\) and maintain speed \((\delta V_o=0)\) when target vessel is in Region I. If the target vessel is located in the region where Regions I and VIII intersect (fuzzy region in Figure 1), the defuzzified inference result will be “No Action” due to the cancellation of the two contradictory decisions (Steer starboard \(\delta\psi_o>0\) and steer port \(\delta\psi_o<0\)) when the centroid defuzzification method is applied. This decision would possibly lead to a catastrophic system failure. The way rules are defined generates contradictory decisions due to the inherent Mamdani inference mechanism.

B. Improper Transition Region between the Inference Boundaries of Non-Intersected Contradictory Decisions

Figure 2 shows a pictorial example of a possible navigation situation. Assume that in this case, the region X exists as a smooth transition region between regions IX and I, and that this region avoids the problem of intersected contradictory decision boundaries (section A) by stating No steering change \((\delta\psi_o=0)\) and speed decrease \((\delta V_o<0)\) while target vessel is in region X. These actions will make the target vessel move into one of the non-conflict regions I or IX. However, if the target vessel assumes the relative trajectory depicted in Figure 2, the following situation failures can occur: if Region X is “improper”, i.e., not wide enough, it is possible for the navigation system to jump between two contradictory decisions in consecutive (or relatively close) instants leading to an erratic trajectory and/or to implement two contradictory decisions on the same trajectory. These situations are also possible catastrophic failures since the target vessel might not be avoided. Therefore, the selection of a proper fuzzy smooth region is an important part of the designing process of the Mamdani type fuzzy rule based inference system.

C. Contradictory Decision Accumulation

While observing the navigation situation presented in Figure 3, it is easy to see that the presence of multiple decisions under Mamdani type fuzzy rule based inference systems can generate catastrophic failures on a navigation system. As presented in the figure, the following fuzzy rule inferences are assigned to a two vessel collision situation: the Own vessel should steer to starboard ($\delta \psi_o > 0$) and maintain speed ($\delta v_o = 0$) when target vessel is in Region I, and should steer to port ($\delta \psi_o < 0$) and maintain speed ($\delta v_o = 0$) when target vessel is in Region IV. The accumulation of these two contradictory decisions would once again lead to a No Action/decision, and the own vessel would eventually crash into the target vessel in region I. This situation is categorized as a failure due to contradictory decision accumulation situation due to multiple decision making conditions, and can occur in “single-level” Mamdani type fuzzy rule based inference in navigation systems.

II. PREVIOUS RELATED WORK

Fuzzy logic based systems have been developed in research and commercial applications to fulfill the technological requirements inspired by human behavior in decision making processes [1]. A fuzzy target based soft decision for mobile vehicle in dynamic environment is proposed in [2], where a navigation trajectory is selected from all possible via-points learned based on final destination. Similarly, a fuzzy logic algorithm for a path selection in autonomous vehicle navigation is proposed in [3]. The drawbacks of the above methods come from the fact that they were implemented in limited and constrained environmental models, causing the decision making process to be less effective and time consuming in larger navigation spaces.

Seraji and Howard present in [4] a fuzzy logic approach to a behavior-based robot navigation on challenging terrain. Seraji [5] also presented a study for autonomous navigation of planetary rovers using a fuzzy logic framework. These systems consist of multiple behavior capabilities: goal-seeking, terrain-traversing, and collision avoidance. Fatmi et al. propose a similar approach of fuzzy logic for mobile robot navigation in [6]. Fuzzy-logic based navigation controllers for a mobile robot where the input and output fuzzy membership functions (FMFs) for steering and speed commands are expressed by linguistic values are proposed and implemented in [7] and [8]. All the mentioned systems were implemented under limited obstacle behavior and/or stationary environmental conditions as well.

Fuzzy decision making processes in mobile robot navigation under dynamic environmental conditions are presented in [9] and [10]. The fuzzy decision making process consists of two algorithms for “obstacles avoidance” and ”target following”. The drawback in this approach is that it is vulnerable to the fuzzy inference failures described in section I.

Usually fuzzy rule based systems are formalized assuming a single-level system. However, it is possible to formulate the multiple identities within a system using different set of rules, as proposed in [11], and a multiple behavior based fuzzy control system for sonar-based obstacle avoidance of a mobile robot is presented in [12]. Even though this study facilitated a multiple behavior based fuzzy control approach, they still suffer from the accumulated decision cancellation situations between non-intersected contradictory decisions inference regions of a “single-level” fuzzy logic based system, as further discussed in this study.

An automatic ship collision avoidance system using fuzzy logic based control is proposed by Hasegawa in [13]. Ignorance of the IMO rules and regulations and expert knowledge in ocean navigation (i.e. crash stopping
maneuvers) are two of the drawbacks in this study.

A study of collision avoidance in ocean navigation based on fuzzy sets for optimizing the distance to the closest point approach (DCPA) is proposed by Zhao in [14]. Two drawbacks are observed in this implementation: the proposed study is limited to two vessel collision situations; the system inputs and outputs are directly related by fuzzy rules (single-level systems). Therefore, the system capabilities to overcome complex multi-vessel collision situations are limited.

III. SOLUTIONS AND ITS LIMITATIONS

This paper proposes and describes several general requirements that can be applied to overcome the above situations in order to prevent the inherent system failures in navigation:

1. The navigation system should be equipped with a minimum of two fuzzy output decisions (e.g. Steering and Speed changes);
2. Proper formulation of decisions in the input and output linguistic terms and the respective fuzzy membership functions (FMFs): common boundary points or regions between contradictory decisions should be avoided in both input and output FMFs;
3. If a common boundary between regions that indicate contradictory decisions is unavoidable, then a smooth transition region should be inserted;
4. When a smooth transition region between common boundary points or regions of contradictory decisions is necessary, then its proper size should be analyzed in order to prevent the second situation failures, i.e., an improper transition region between the inference boundaries of non-intersected contradictory decisions.
5. A “multi-level” decisions/actions process should be used to avoid the third situation failures, i.e., contradictory decision accumulation.

The paper illustrates the previously discussed three types of inference rule failures and the solutions to be implemented on ocean navigation to improve safety by avoiding collision situations. Therefore, the solutions are categorized as: Fuzzy Smooth Region Insertion, Proper Sizing of Fuzzy Smooth Regions and Multi-step Decision/Action Formulations.

A. Fuzzy Smooth Region Insertion

The usual solution to solve the problem of Intersected Contradictory Decision Boundaries consists in using a higher-level decision process to override one of the conflicting decisions. However, usually there is not a simple universal solution, and therefore one must consider and prepare the decision process for every single possible rule base failure case.

Here one proposes a more elegant and simple solution that basically consists on the insertion of a fuzzy smooth transition region on the boundary of the regions that have contradictory decisions. The decisions in this smooth region must not contradict any of the decisions in the original regions. As a result of these proactive actions, the relative position of the target vehicle will automatically be redirected into either one of the original regions, hence eliminating conflict.

Consider the mathematical formulation of vessel navigation presented in Figure 4. The figure shows the navigation decisions, Steering Decisions (D<sub>δψ</sub>(k)) and Speed Decisions (D<sub>δV</sub>(k)) for High risk collision situations for fuzzy bearing regions I to X, and for the ranges R<sub>a</sub> to R<sub>b</sub> and R<sub>c</sub> to R<sub>d</sub> in each fuzzy bearing region.

The decisions on fuzzy bearing region I are formulated as steer to starboard (δψ<sub>a</sub>&gt;0) and no speed change (δV<sub>a</sub>=0); in region II, the decisions are steer to starboard (δψ<sub>b</sub>&gt;0) and decrease speed (δV<sub>b</sub>&lt;0). Therefore, there are no contradictory decisions in the intersection of both regions. In region IV, the decisions are steer to port (δψ<sub>d</sub>&lt;0) and decrease speed (δV<sub>d</sub>&lt;0). Region III was introduced as a smooth transition region between regions II and IV with decisions no steer change (δψ<sub>c</sub>=0) and decrease speed (δV<sub>c</sub>&lt;0).

In region V, range R<sub>c</sub> to R<sub>h</sub>, the decisions are steer to port (δψ<sub>e</sub>&lt;0) and no speed change (δV<sub>e</sub>=0), and in range R<sub>h</sub> to R<sub>c</sub> the decisions are no steer change (δψ<sub>f</sub>=0) and no speed change (δV<sub>f</sub>=0). With the insertion of fuzzy smooth region III, all the navigation decision transitions in the right half of the decision space are smooth and no contradictory decisions exist. A similar approach was followed in the left half of the decision space, where regions VI, VIII and X were introduced as smoothing regions. Figure 4 contains all the details regarding the used fuzzy decisions.

B. Proper Sizing of Fuzzy Smooth transition Regions

Even though smooth transition regions are proposed to overcome rule inference failures in the intersected

contradictory decision inference boundaries, the behavior of the navigation system should nevertheless be analyzed to observe any further failure situations, especially those where the size limitation of the transition region may effect the overall system performance. Therefore, this problem is referred to as “improper transition region between non-intersected contradictory decisions inference boundaries of the FMFs”.

The rule inference failures of a fuzzy logic based navigation system can be observed by creating all possible relative trajectories of the Target vessel with respect to the Own vessel. One should note that the interception of the Own vessel initial position, near zero relative minimum distance between two vessel, by the relative trajectories of the Target vessel represents a collision situation.

In general, the smaller the size of the smooth transition regions, the better the decision transition, as it facilitates the system transition into a better decision making region. However one must note that contradictory decision inference boundaries should not exist in the same process in this situation, and smaller regions can cause system decisions to jump between two contradictory decisions in the same navigation process.

In order to understand the process of designing a proper smooth region, one should be aware that generally, if no avoidance measures are taken, when the Target vessel is coming from the right end of a head-on situation, the relative navigation trajectory converges towards the Own vessel domain if there is a collision risk between vessels, and the relative trajectory diverges from the Target vessel domain when there is no collision risk.

An example of this situation is presented in Figure 4. As shown in Figure 4, line O(k)B(k) separates regions I and X, and line O(k)D(k) separates regions X and IX. The line O(k)D(k) intercepts the Own vessel domain at point C(k). There is a collision risk if any relative trajectories of the Target vessel starting from region I converge into the Own vessel domain. The straight line B(k)E(k) represents the left-end relative navigation trajectory starting from region I that neither converges nor diverges from the Own vessel domain. Hence all the relative navigational trajectories of the Target vessel in the region I with collision risk stay on the left side of line B(k)E(k). The line B(k)E(k) intercepts the Own vessel domain at point E(k). Hence this line should be used as a guideline regarding whether the collision risk increases or decreases in a collision situation in region I.

In order to ensure that the relative trajectories starting from region I never enter region IX (preventing two contradictory decisions in the same obstacle avoidance process), the line B(k)E(k) should never cross region IX in the $R_a$ to $R_e$ range. This is achieved if point C(k) is always to the left of point E(k). Hence the minimum size of region X should be given by $C(k)=E(k)$.

These conditions can be formulated into geometrical relationships among regions I, IX and X. Considering the triangle of $O(k)B(k)E(k)$ with $C(k)=E(k)$, the sine rule can be written as:

$$\frac{R_e}{\sin \left(\frac{\theta^0}{2} - \kappa_s - \kappa_7\right)} = \frac{R_a}{\sin (\kappa_7)}$$

(1)

Since $E(k)B(k)$ is a straight line parallel to the $Y_o$ axis and angle $\kappa_7$ is symmetric around the $Y_o$ axis, the angle condition $\kappa_7 = \kappa_2/2$ and (1) becomes:

$$\kappa_s = 180 - \sin^{-1}\left(\frac{R_a}{R_a + \sin (\kappa_2/2)}\right) - \frac{\kappa_2}{2}$$

(2)

Hence the minimum size requirement for a proper smooth transition region X in (2) is related to the size of the contradictory decision regions I and IX that motivated the creation of proper smooth region X. . The fuzzy logic based decision making system is further described in [15].

C. Multi-step Decision/Action Formulations

The decision making process in “single-level” fuzzy rule based systems should be associated with a “secondary-level” that can automatically overcome rule inference failures due to multiple interactive situations (see Figure 3).

Therefore, in order to overcome the accumulated decision failures, the system is formulated into a “multi-level” decision-action process that composed of; the fuzzy logic based Parallel Decision Making (PDM) module and those decisions are formulated into actions by the Bayesian network based Sequential Actions Formulation (SAF) module.

In the proposed solution, the Bayesian network based Sequential Action Formulation (SAF) module is illustrated as a “second-level” process that overcomes failures due to contradictory decision accumulation in multiple target scenarios. The main objective of the SAF module is to transform the parallel navigation decisions that are generated by PDM module into sequential actions that can be executed in the Own vessel navigation system while eliminating the mentioned failures. This can be achieved by collecting from the PDM module the multiple navigation decisions for the $k^{th}$ time instant, $D_i(k) \equiv (D_{psi}(k), D_{psi}(k))$, and evaluating them with respect to proper time to execute each actions. Hence the
final navigational decisions are arranged as sequential formation of actions, \( A_i(k) = (A_{\delta\psi_i}(k), A_{\delta V_i}(k)) \) involving the steer and speed actions at given time instants \((T_{\delta\psi_i}(k), T_{\delta V_i}(k))\). Figure 5 gives an example of the process of sequential steer and speed action execution. \( D_{\delta\psi_i}(k), D_{\delta V_i}(k) \) and \( A_{\delta\psi_i}(k), A_{\delta V_i}(k) \) represent the steer and speed change decisions and actions at \( k \)th time instant respectively. This approach eliminates the cancelation of contradictory decisions due to accumulation.

The block diagram of the SAF module is presented in Figure 6. The SAF module consists of a continuous Bayesian Network that is formulated to update the parallel navigation decisions into sequential actions that will execute at appropriate time instants. A Bayesian Network approach is proposed as the inference media between navigation decisions and navigation actions.

The continuous Bayesian Network module that is formulated to update the parallel navigation decisions into the sequential actions consists of four nodes: Collision Time Estimation, Collision Risk, Actions Delay and Collision Avoidance Actions. The inputs of the Bayesian network are the Collision Decisions, \( D_i(k) \), and Time until Collision, \( T_i(k) \), which generated respectively by the system. The main objective of the Collision Time Estimation node is to estimate the Time until Collision, \( T_i(k) \), between the Own vessel and each of the Target vessels. The node Collision Risk inferences the collision risk with respect to each Target vessel considering the Collision Time Estimation. The Actions Delay node is designed to formulate the appropriate time to take navigation actions. The Actions Delay node, the Collision Risk node, and the Collision Decisions node are use to infer the Collision Avoidance Action node. The Bayesian network nodes, inferences and their associated functions are further described in [16].

IV. COMPUTATIONAL SIMULATIONS

The ocean navigation system is implemented on the MATLAB software platform. The computational simulations for a multi-vessel collision situation are presented in Figures 7 to 10. All startup and final positions of the Own and Target vessels are represented by vessel shape icons at the \( k \)th time instant. It is assumed that the Target vessels are moving in constant steering and speed conditions and do not honor any navigational rules or regulations of the sea. The collision risk assessment is formulated by a Gaussian distribution and presented in the \( x = -8000 \)m axis. Similarly, the navigation actions for the steer and speed changes formulated by the Gaussian distributions are presented in the \( x = -6000 \)m and \( x = -4000 \)m axis respectively. The scaled Time axis (Actual
This paper introduces Mamdani type fuzzy inference failures, applicable solutions and limitations on those solutions with respect to ocean navigation. As presented in computational simulations, the proposed solutions of insertion of a smooth transition region between intersected contradictory decision inference boundaries, determination of its proper size limitations between non-intersected contradictory decisions inference regions and introduction of a “secondary-level” decision/action formulation module can overcome “single-level” based rule inference failures. Even though these solutions are developed for collision avoidance in ocean navigation, this could be implemented on any Mamdani type of fuzzy logic based system that suffers from similar rule inference failures.

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