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Fuzzy Collision Avoidance Autopilot

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ABSTRACT
USV Unmanned Surface Vessel is a new generation of marine vessels, Falco is the first commercial version of USV, it was produced by Rolls Royce, and began tested on December 2018, USV consist of many systems as autopilot, path tracking, collision avoidance…, etc.
In this research a fuzzy collision system and fuzzy autopilot was combined in one system, the proposed system was designed and simulated and tested in Matlab.
Keywords* :— *Fuzzy, Autopilot, Collision Avoidance, Human Expert.

I. INTRODUCTION

Many techniques are introduced to design the collision avoidance systems (CASs). An algorithm using fuzzy logic was proposed to take the suitable decision for changing the path of a water robot, that was succeeded in overcoming obstacles [1]. A decision-making mechanism for collision avoidance based on fuzzy logic was built using autonomous navigation and guidance systems [3]. In [2], it was created a cloud-based decision model based on the rules of the International Maritime Organization (IMO) based on Global Organization for Collision Prevention (COLREGs) to avoid collision. Another Collision avoidance system was designed based on COLREGs rules using the dynamic window algorithm, where it is possible to avoid collisions against fixed and moving obstacles [4]. An adjustable collision avoidance system was designed, which takes the collision avoidance measures according to human experience [5]. Another collision avoidance system was proposed taking into account the target hazard indicator, it succeeded in avoiding collision and improved the safety distances in the dangerous situations [6].

Autopilot is an important part of ships; one of its advantages is to guide the ship into the demanded path. Two autopilots were designed to control a ship with four degrees of freedom, the first one was PID autopilot and the other was fuzzy autopilot [7]. A combination of these two autopilots was proposed in [8].

These studies interested in marine autopilot apart from the collision avoidance system, and vice versa. The idea of integrating the marine autopilot with the collision avoidance system (CAS) in one system has not been discussed previously, that may be for commercial reasons where the ships may have to purchase the two systems; or due to the differences between these two systems in working concept and installation position in the ship. The output of CAS is the autopilot input.

In this research an adjustable fuzzy CAS Autopilot was proposed, where the target hazard system based on the CAS presented in [6] emerged with the fuzzy autopilot in [7]. Modelling and simulation and testing of the proposed system were conducted using MATLAB.

II. BLOCK DIAGRAM OF PROPOSED CAS AUTOPILOT SYSTEM

Fig. 1 shows the general block diagram of the Marine Vehicle's control system. The inputs of the collision avoidance system (CAS) are the ship parameters that are location, current heading, and velocity; and the target parameters that are speed, relative direction, distance, and route. The CAS assess the relationship between the ship and the target and calculates the required speed and course of the vessel to navigate in this case. The required course goes to the autopilot to calculate the rudder angle, both of the rudder angle and ship velocity go to the ship to modify its course to correct the current course.

In this paper, a modification on the block diagram in Fig. 1 was proposed, by integrating both the autopilot and the collision avoidance system as shown in Fig. 2. The current parameters of the ship that are course, velocity, and location; which are measured by special sensors such as the gyroscope compass and GPS. As well, the target parameters that are the velocity, bearing, range, and course; which are measured using a navigational radar; are the inputs of CAS. The system output is the velocity and rudder angle to steer the vessel to its target and avoid collisions.

Fig. 2 shows that the integration of the CAS system and the autopilot will reduce the ship on board equipment and connections. The autopilot is designed in [7] and the CAS system is proposed in [6].

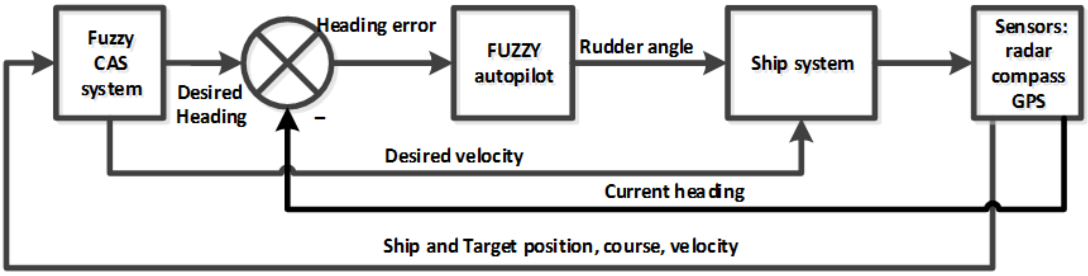

Fig. 1 General block diagram of marine vehicle control system [7].

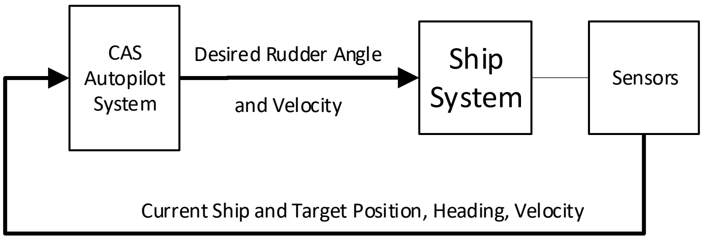

Fig. 2 The proposed block diagram of CAS Autopilot system.

III. THE PROPOSED FUZZY CAS AUTOPILOT SYSTEM ALGORITHM

Fig. 3 shows the proposed Fuzzy CAS Autopilot algorithm. Before sailing, the sea state and the ship length and sailing ship velocity should be provided to the system. These parameters are inputs to the three zone determining system [9]. Its outputs are the diameters of the forbidden, danger, and safe zones, which are the inputs of the fuzzy CAS Autopilot system. The target hazard calculation system generation system which build both of target hazard calculation system [6] and the Fuzzy CAS Autopilot system, the inputs of fuzzy CAS autopilot are the target parameters that are: range, bearing, relative course, relative velocity, and hazard; and the ship heading error and heading rate. The output of this system is addcourse which is the input of the desired course calculation system which is an input to the comparator to compare with the measured current course to produce the heading error. The heading error is the input of the proposed CAS Autopilot system. The second output of the proposed system is addspeed, and the third one is the rudder angle. These outputs are the inputs of the ship system to control its movement and to correct its course and change it avoiding the collision if there is any collision danger.

The target parameter calculation system received the target parameter that are: range, bearing, course, and velocity; which can be got from the radar; and ship parameter that are: location and velocity measured by GPS, and the current course measured by GYROCOMPSS, to calculate the relative coordinate of the target. The output of the target parameter calculation is an input to the target hazard calculation system[6] to produce the target hazard which goes with the output of target parameter calculation system to the CAS Autopilot system. The heading rate that could be measured by the GYROCOMPASS is also the input of the CAS autopilot system.

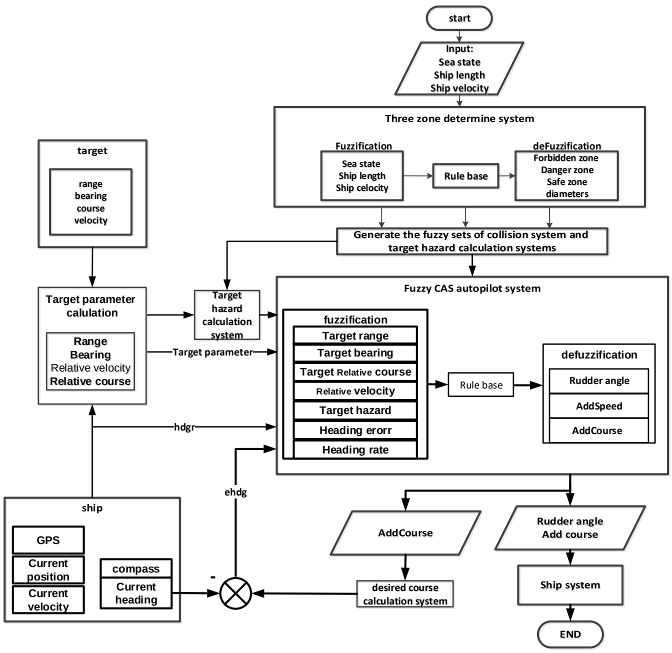

Fig. 3 Fuzzy CAS Autopilot algorithm.

IV. THE PROPOSED FUZZY CAS AUTOPILOT SYSTEM

The proposed CAS autopilot system is built using Fuzzy Mamdani FIS system. The system, as shown in Fig. 4, has seven inputs: target ranges [Nmile], relative velocity, target bearing [deg], target relative course [deg], target hazard, ship-heading error [deg], and ship heading rate [m/s]. The CAS autopilot system has three outputs. The first one is the addcourse [deg] that is the needed course to prevent the collision. The second one is the addspeed [knot] that is the needed speed to prevent the collision. While the third output is the rudder angle [deg] that is the needed rudder angle to modify the ship heading for correcting or changing its route to avoid the collision. Rule Base of this system consists from 442 IF…THEN rules.

The first input target range [Nmile] has divided into three trapezoid fuzzy sets as depicted Fig. 5, ranges of these sets determined by the three zone determine system [9]:

1. The first set is cas represents the safe zone around the ship.
2. The second set is danger represents the danger zone around the ship.
3. The third set is forb represents the forbidden zone around the ship.

The second input **v_t/v_o** relative velocity has divided into three trapezoid fuzzy sets Fig. 56:

1. The first set is S represents that the speed of own ship is more than target speed; its range is [0-0.6].
2. The second set is M represents that the speed of own ship is equal to target speed; its range is [0.4-2.6].
3. The third set is B represents that the speed of own ship is less than target speed; its range is [2.4-50].

The third input is target bearing [deg], it has been divided into 10 trapezoid fuzzy sets, its range is [0-360], which is represents the ship contour, each set named by a number represents the number of the region and a letter represents the name of this region as marine named it (Fig. 7).

The fourth input is target relative course [deg], it has been divided into 8 trapezoid fuzzy sets, its range is [0-360], which is represents the target motion direction each set named by letters [a,b,c…,h] represents the name of this region (Fig. 8).

The fifth input is target hazard that has divided into 2 trapezoid fuzzy sets, its range is [0-1], which is represents the target hazard (Fig. 9):

1. The first set is LOW represents the low risk of target; its range is [0-0.8].
2. The second set is HIGH represents the high risk of target; its range is [0.7-1].

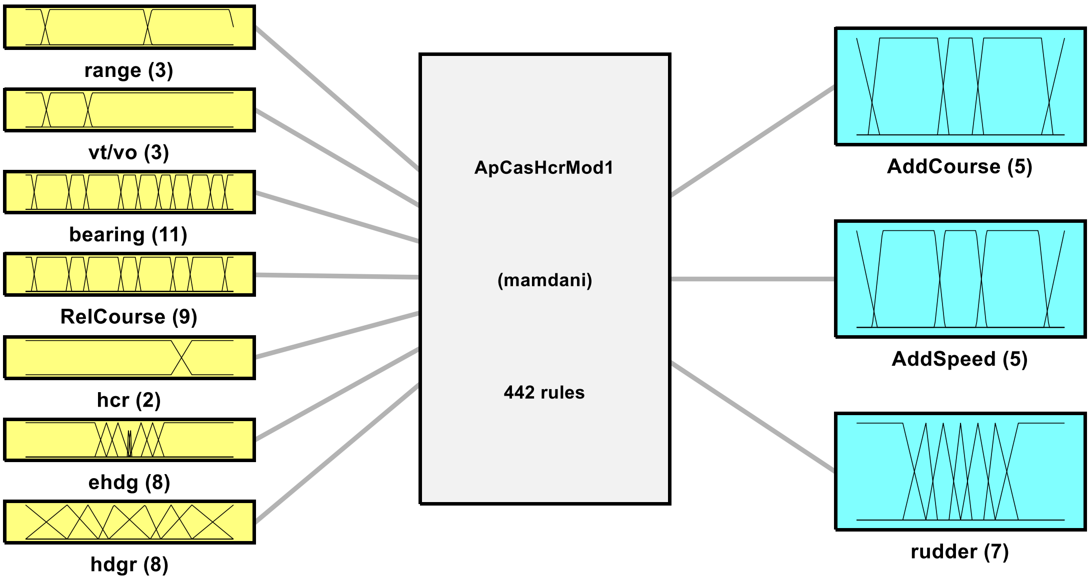

Fig. 4 Adjustable Fuzzy CAS autopilot with target hazard.

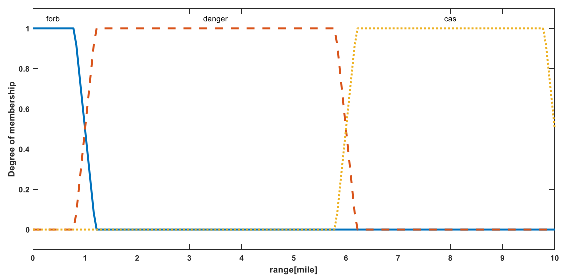

Fig. 5 Target range fuzzy sets.

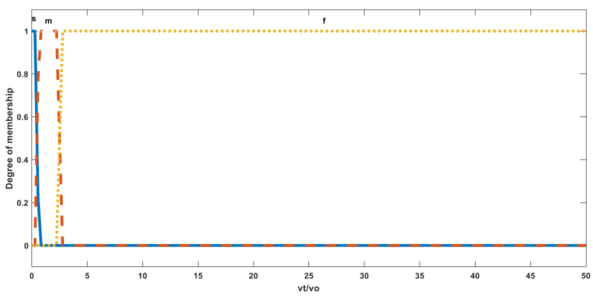

Fig. 6 Relative velocity fuzzy sets.

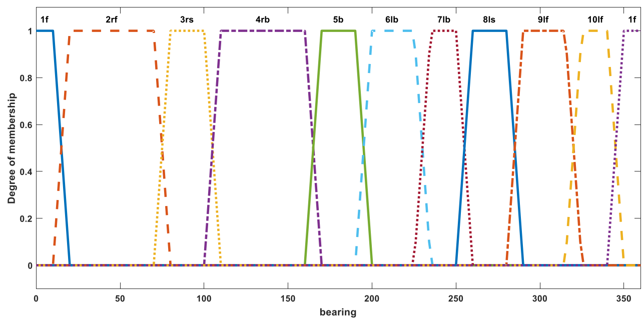

Fig. 7 Target bearing fuzzy sets.

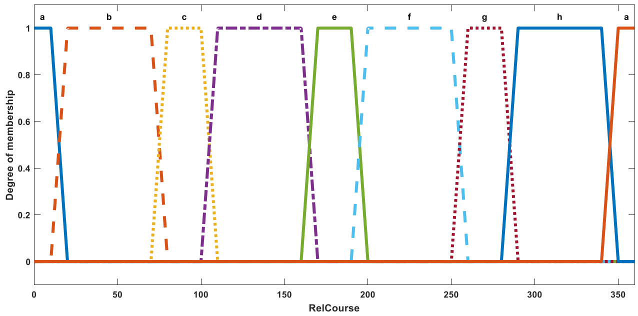

Fig. 8 Target relative course fuzzy sets.

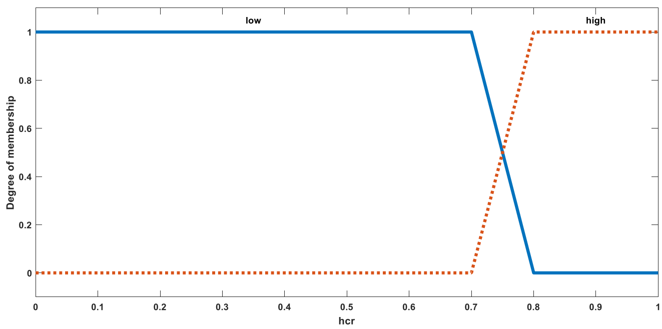

Fig. 9 Target hazard fuzzy sets.

The sixth input is ‘ehdg’ ship error heading, that has been divided into 8 fuzzy sets (6 sets are triangle, and 2 sets are trapezoid), its range is [-180, +180] which represents the ship drift from its desired course. The name of these sets has two letters. The first one is n (negative) that means left of the ship (ship port) or p (positive) that means right of the ship starboard. The second letter represents the value of the error t (for tiny), s (for small), m (for middle), b (for big). All of these names are related to the marines (Fig. 10).

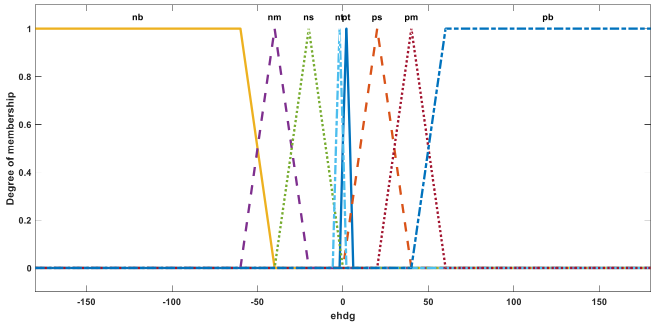

Fig. 10 Heading error fuzzy sets.

The seventh input is ‘hdgr’ ship heading rate [m/s] that has divided into 8 triangle fuzzy sets, its range is [-5 - +5] which is represents the ship angular velocity of the heading motion of the ship. The name of this set has two letters. The first one is n (negative) that means left of the ship (ship port) or p (positive) which means the right of the ship starboard. The second letter represents the value of the error t (for tiny), s (for small), m (for middle), b (for big) (Fig. 11.)

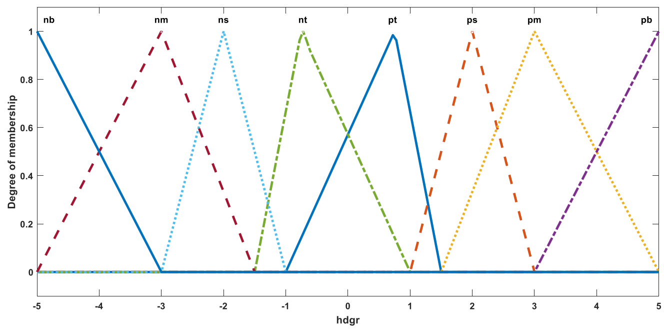

Fig. 11 Heading rate fuzzy sets.

The first output ‘AddCourse’ [deg] means the needed course to be added to the current course to prevent the collision; it has divided into five fuzzy sets (Fig. 12):

1. The first set is d2 represents decreasing the course with a big angle, its range is [-35 - -50].
2. The second set is d1 represents decreasing the course with a small angle, its range is [-5 - -35].
3. The third set is zero represents that there is no need to change the course, its range is [-5-+5].
4. The fourth set is in1 represents increasing the course with a small angle, its range is [+5 - +35].
5. The fifth set is in2 represents increasing the course with a big angle, its range is [+35 - +50].

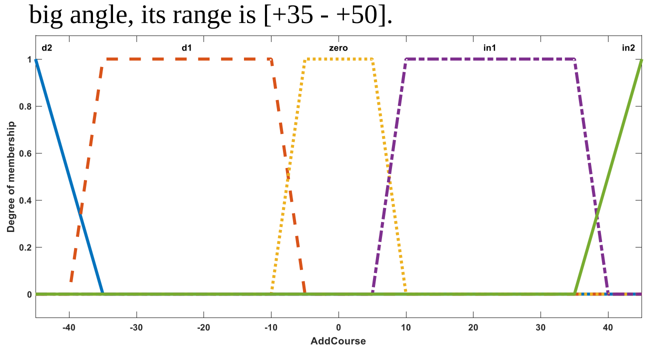

Fig. 12 ‘AddCourse’ output fuzzy sets.

The second output 'AddSpeed' [knot] which means the speed needed to be added to the current ship velocity to prevent the collision; it has divided into five fuzzy sets (Fig. 13):

1. The first set is 'd2' represents decreasing the velocity with a big value, its range is [-1 - -0.8].
2. The second set is 'd1' represents decreasing the velocity with a small value, its range is [-0.85 - -0.15].
3. The third set is 'zero' represents that there is no need to change the velocity; its range is [-0.25-+0.25].
4. The fourth set is 'in1' represents increasing the velocity with a small value, its range is [+0.15 - +0.85].
5. The fifth set is 'in2' represents increasing the velocity with a big value, its range is [+0.8- +1].

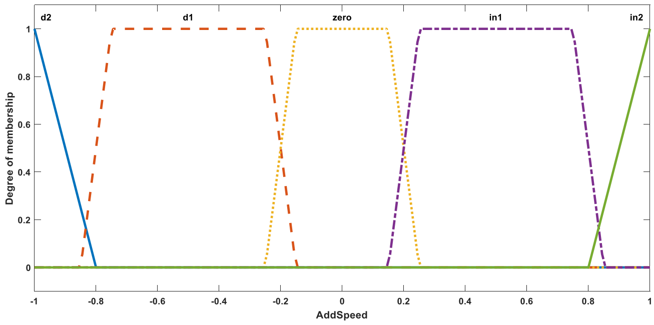

Fig. 13 'AddSpeed' output fuzzy sets.

The third output rudder [deg] that means the angle of the ship rudder. It has divided into seven fuzzy sets (Fig. 14):

1. The first set is 'nb' represents negative big angle of the rudder to the left; its range is [-50 - -15].
2. The second set is 'nm' represents negative middle angle of the rudder to the left; its range is [-25 - -10].
3. The third set is 'ns' represents negative small angle of the rudder to the left; its range is [-15 - 0].
4. The fourth set is 'z' represents zero angle of the rudder; its range is [-5 - +5].
5. The fifth set is 'ps' represents positive small angle of the rudder to the right; its range is [0 - +15].
6. The sixth set is 'pm' represents positive middle angle of the rudder to the right; its range is [+10 - +25].
7. The seventh set is 'pb' represents positive big angle of the rudder to the right; its range is [+15 - +50].

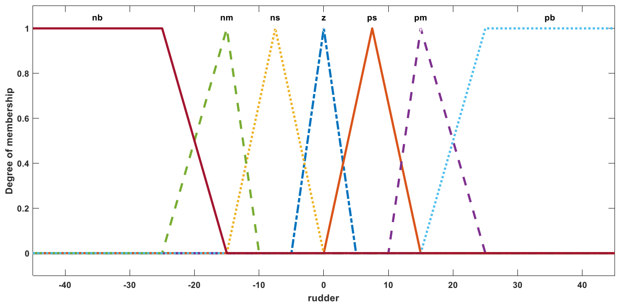

Fig. 14 Rudder angle output fuzzy sets.

The if...then expressions was used to build the Rule base of the system which is designed depended on human expert. Some of these rules shown in Table 1:

TABLE 1

SOME OF THE RULES OF THE PROPOSED SYSTEM

1. If (range is danger) and (vt/vo is s) and (bearing is 1f) and (RelCourse is e) and (hcr is low) then (AddCourse is in2)
2. If (range is cas) and (vt/vo is s) and (bearing is 1f) and (RelCourse is e) and (hcr is low) then (AddCourse is in1)
3. If (range is danger) and (vt/vo is m) and (bearing is 1f) and (RelCourse is e) and (hcr is low) then (AddCourse is in2)
4. If (range is cas) and (vt/vo is m) and (bearing is 1f) and (RelCourse is e) and (hcr is low) then (AddCourse is in1)
5. If (range is danger) and (vt/vo is f) and (bearing is 1f) and (RelCourse is e) and (hcr is low) then (AddCourse is in2)
. . .
438. If (ehdg is pb) and (hdgr is nt) then (rudder is pb)
439. If (ehdg is pb) and (hdgr is pt) then (rudder is pb)
440. If (ehdg is pb) and (hdgr is ps) then (rudder is pb)
441. If (ehdg is pb) and (hdgr is pm) then (rudder is pb)
442. If (ehdg is pb) and (hdgr is pb) then (rudder is pb)

V. RESULTS

In this research, a fuzzy adjustable collision avoidance with target hazard indicator autopilot system was designed based on the algorithm depicted in Fig. 3. The proposed system consist of three subsystems: the three zone determination system [9], target hazard calculation system [6], and the proposed CAS autopilot system. All of these systems were designed depending on the human experts. The system has been tested by using MATLAB with the following parameters:

1. Ship length is 160m.
2. Sea state is 6 bal.
3. The relative speed is 0.5, ship velocity is v_o=10 knot, and the target velocity is v_t= 20 knot.
4. Ship initial position is x=0, y=0.
5. Ship heading is to the North (e.g. heading=0).
6. The target will move from different positions with different heading.
7. The collision point is at x=0, y=5.

The following four scenarios is done to test the proposed system. The scenarios are:

1- the target is in front and to left of the ship.
2- the target is at left of the ship and moves toward it.
3- the target is behind and to left of the ship and moves toward it.
4- the target is to the right of the ship and moves toward it

A. The target is in front and to left of the ship

In this scenario, the ship has the road right. The target is in the overtaking situation, and it has to manoeuvre to avoid the collision, but it does not do. Relaying on the COLREGS, the ship has to take an action to avoid the collision, the result shown in fig. 15. Without the system the dcpa (distant to closest point of approach) is 0.12Nm at x=0, y=4.96, that means a collision will happen if there is no any collision avoidance procedure happens. While with the proposed CAS autopilot system, after the target enter its danger zone, the ship begins a manoeuvre to prevent the collision and the dcpa becomes 0.87Nm.

B. The target is to the left of the ship and moves toward it

In this scenario, the ship has the road right and the target in the overtaking situation and it has to manoeuvre to avoid the collision, but it does not do. So, relaying on the COLREGS, the ship has to take an action to avoid the collision. The result shown in Fig. 16. Without the proposed system, the dcpa is 0 Nm at x=0, y=5, that means a collision will happen if there no any collision avoidance procedure happens. However, with the proposed CAS Autopilot system, after the target enter its danger zone the ship begins a manoeuvre to prevent the collision and the dcpa becomes 0.97Nm.

C. The target is behind and to left of the ship

In this scenario, the ship has the road right and the target in the overtaking situation and it has to manoeuvre to avoid the collision, but it does not do the manoeuvre. So, relaying on the COLREGS the ship has to take an action to avoid the collision. The results are shown in Fig. 17. Without the proposed system, the dcpa is 0.1 Nm at x=0, y=4.9, that means a collision will happen if there is no collision avoidance procedure happens. While with the proposed CAS autopilot system, the ship begins a manoeuvre to prevent the collision after the target enter its danger zone, and the dcpa becomes 1Nm.

D. The target is to the right of the ship and moves toward it

In this scenario, the target has the road right and the ship in the overtaking situation and it has to manoeuvre to avoid the collision. The result is shown in Fig. 18. Without the proposed system, the dcpa is 0 Nm at x=0, y=5, that means a collision will happen if there is no any collision avoidance procedure happens. However, with the proposed CAS autopilot system, the ship begins a manoeuvre to prevent the collision, and the dcpa becomes 2.5Nm.

VI. CONCLUSIONS

Most of studies concerned with designing an autopilot system and CAS system as two systems. However, this research companied these two systems with one system that is the proposed adjustable Fuzzy CAS Autopilot with target hazard. The integration of the two systems produces one system have more than one task: preventing collision and tracking the desired course to arrive to its destination. This integration will decrease the complexity of the devices on the ship, and so the connection between them.

The system is a MIMO (Multi Input Multi Output) system, with seven inputs: target range, target bearing, relative speed, target relative course, target hazard, ship heading error, and ship heading rate; and three outputs: added course, added speed, rudder angle. Therefore, this system will control the ship to keep its course or change it to prevent any collision.

The proposed system was tested and it took the suitable procedure of its tasks to prevent collision and keep course. The proposed system is designed taking into consideration the marine expertise and the maritime rules.

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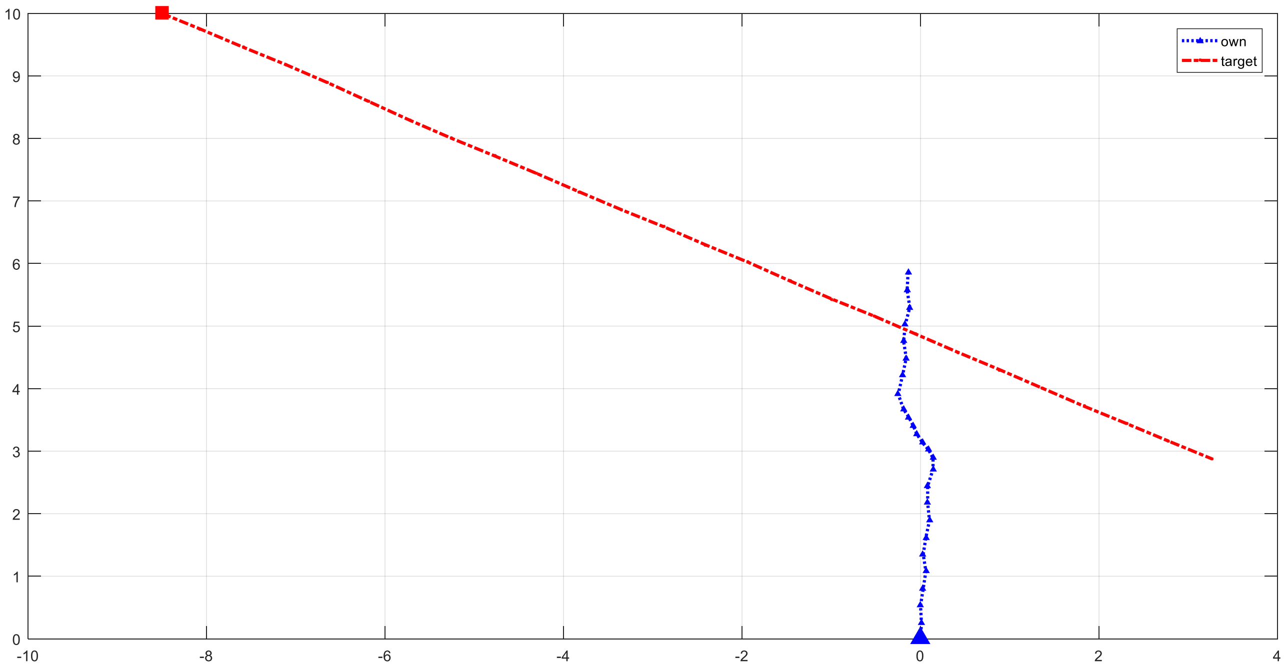

Fig. 15 the first scenario result of the proposed CAS autopilot system

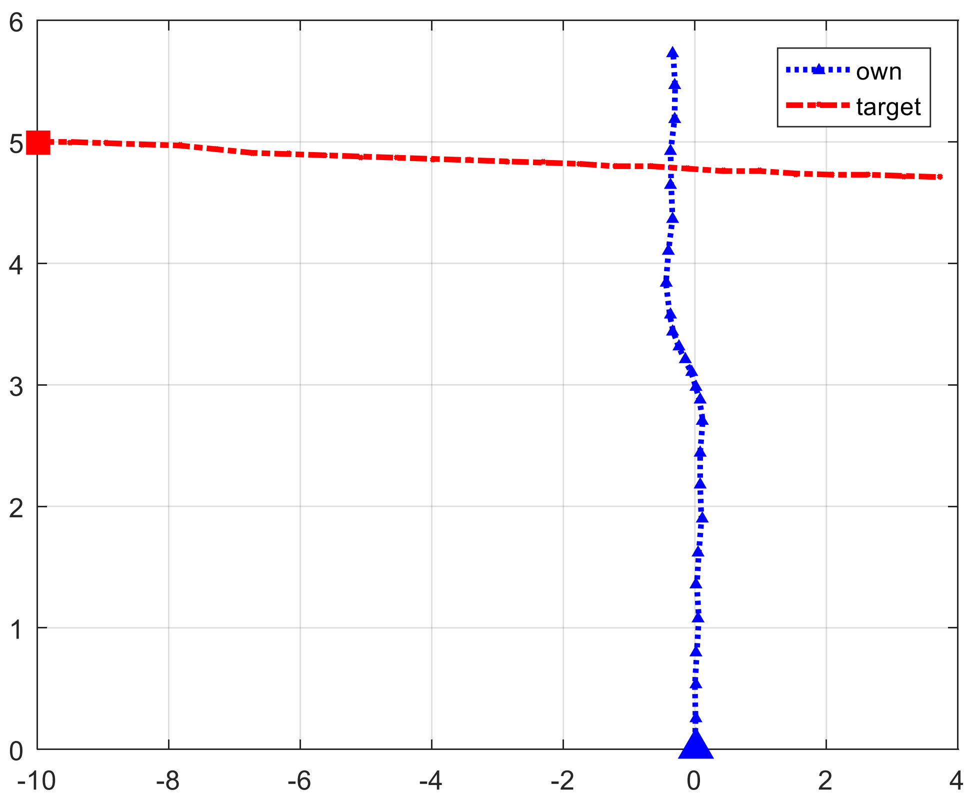

Fig. 16 the second scenario result of the proposed CAS autopilot system

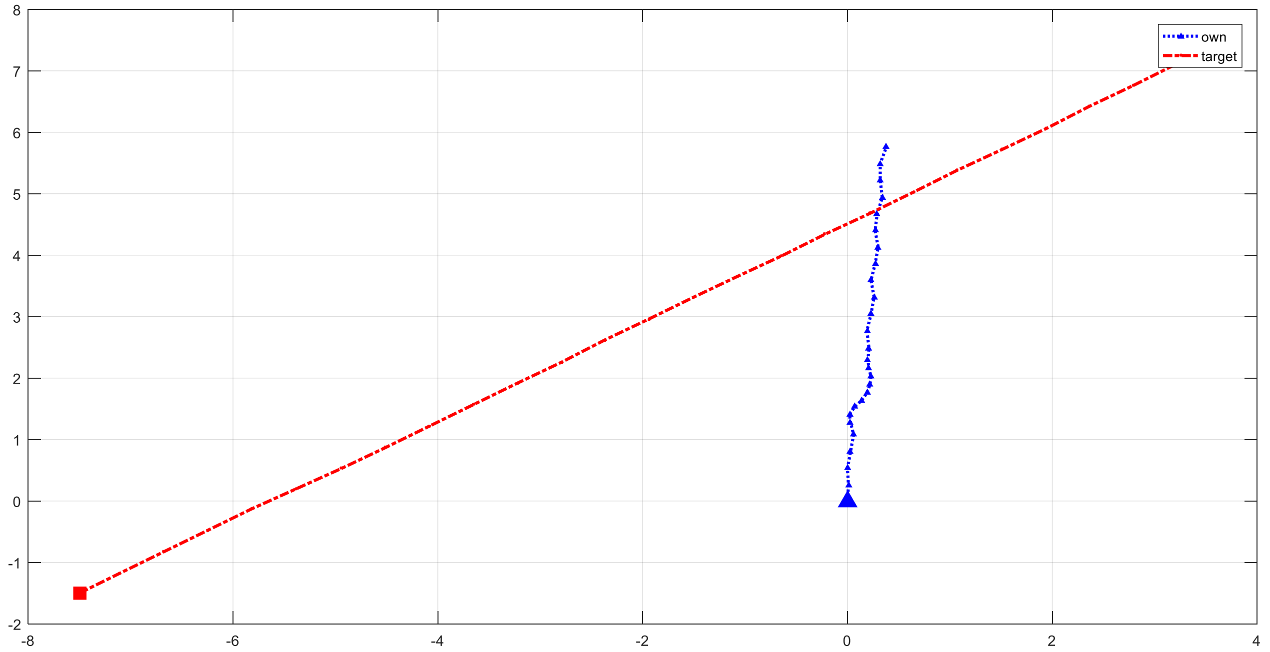

Fig. 17 the third scenario result of the prorposed CAS autopilot system

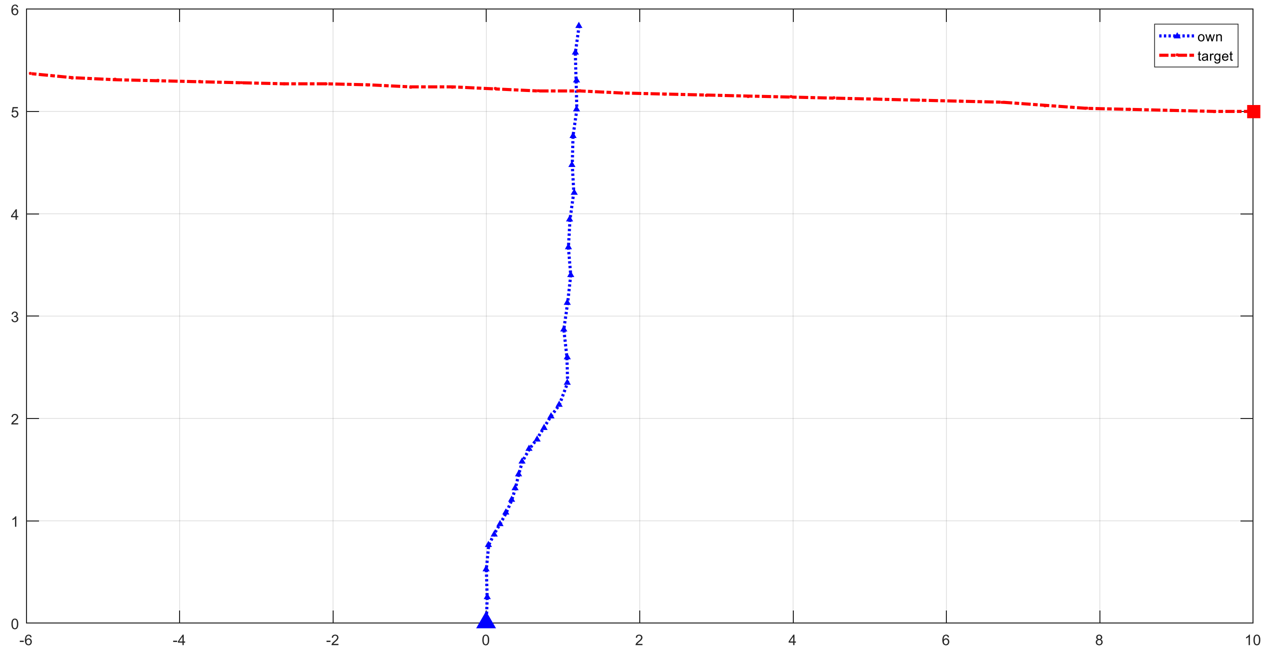

Fig. 18 the fourth scenario result of the prorposed CAS autopilot system