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NOTICE

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DTIC QUALITY INSPECTED 1

2 HIERARCHICAL TARGET INTERCEPT FUZZY CONTROLLER  
3 WITH FORBIDDEN ZONE

4 STATEMENT OF GOVERNMENT INTEREST

5 The invention described herein may be manufactured and used  
6 by or for the Government of the United States of America for  
7 governmental purposes without the payment of any royalties  
8 thereon or therefor.

9 CROSS REFERENCE TO RELATED APPLICATIONS

10 Reference is made to co-pending United States Letters Patent  
11 Application Serial No. 08/498,810 filed July 6, 1995 by Anthony  
12 F. Bessacini and Robert F. Pinkos for a Fuzzy Controller for  
13 Acoustic Vehicle Target Intercept Guidance.

14 Reference is also made to co-pending United States Letters  
15 Patent Application Serial No. 08/498,811 filed July 6, 1995 by  
16 Anthony F. Bessacini and Robert F. Pinkos for an Hierarchical  
17 Fuzzy Controller for Beam Rider Guidance.

18 BACKGROUND OF THE INVENTION

19 (1) Field of the Invention

20 This invention generally relates to a control system located  
21 at a first, or reference, site for guiding a steerable object  
22 from that site toward a second, or target, site. More

1 specifically this invention relates to such a control system that  
2 is operable even when both the control system at the first site  
3 and the target at the second site undergo independent motion.

4 (2) Description of the Prior Art

5 Real time control systems based upon sensory inputs find  
6 application in air-, land- and underwater-based vehicles. For  
7 example, with respect to underwater-based applications United  
8 States Letters Patent No. 4,323,025 to Fisher et al. (1982)  
9 describes a homing torpedo with an on-board, or autonomous,  
10 steering control system that operates in a target search phase or  
11 a target acquisition phase. In the target search phase, the  
12 control system directs the torpedo along a controlled helical  
13 search path. When the torpedo acquires a target, the control  
14 system transfers to a target pursuit phase. The control system  
15 transfers back to the target search phase whenever target  
16 acquisition is lost. It is a characteristic of control system of  
17 this type, however, that control from the submarine as a  
18 launching vehicle is lost immediately upon launch.

19 United States Letters Patent No. 5,229,541 to Will et al.  
20 (1993) discloses a variant of the foregoing on-board, or  
21 autonomous, control system in the form of a safety system that  
22 deters a homing missile from attacking its launching vehicle. In  
23 this embodiment, a tracking circuit on the launching vehicle  
24 tracks a torpedo after launch by receiving signals from a  
25 transponder on the torpedo. If the control system on the  
26 launching vehicle determines that the torpedo has reentered a

1 protective zone on a course homing on the launching vehicle, the  
2 control system generates a coded command that it transmits to the  
3 torpedo control system acoustically. The torpedo control system  
4 responds by altering its course and resuming a search for a  
5 target in a sector other than that in which it was acquiring a  
6 launching vehicle. In addition upon determining that the weapon  
7 is within an activation zone, the control system on the launching  
8 vehicle can produce a magnetic field substantially corresponding  
9 to the neutralization zone. When sensors on the torpedo enter  
10 that field, they neutralize the weapon detonator.

11           Some torpedoes and other steerable objects include acoustic  
12 or other sensory homing systems. Such homing systems have an  
13 external point in front of and along the path of the steerable  
14 object called a "guidance point". This guidance point  
15 corresponds to the centroid of the acoustic beam in the case of a  
16 torpedo with an acoustic homing device. Control systems  
17 generally must accommodate torpedoes with or without guidance  
18 points. Typically, therefore, control systems use different  
19 control modes for guiding different torpedoes toward targets. In  
20 each, the control system resides on board the submarine that  
21 constitutes a first or reference site or launching vehicle. Each  
22 control system transfers commands to and receives information  
23 from the torpedo, as a steerable object, by means of a  
24 communications link, such as a wire link.

25           If the range, course, speed and bearing of a target are  
26 known, a "target intercept" control mode can be used. In the

1 target intercept control mode, a control system predicts the  
2 trajectory of the target and directs the torpedo to an  
3 anticipated intercept point. A control system operating in a  
4 "target pursuit" mode directs the torpedo so that it always  
5 points toward the target. In a "beam rider" control mode the  
6 control system directs the torpedo along a bearing between the  
7 submarine and the target.

8 United States Letters Patent No. 5,319,556 to Bessacini  
9 (1994) discloses adaptive trajectory apparatus for selecting one  
10 of these control modes based upon information available during  
11 each update cycle for a given situation. Notwithstanding the  
12 selected control mode, once the torpedo comes within an effective  
13 range of the target, internal torpedo guidance assumes control.

14 Still other approaches for directing a steerable object from  
15 a launch site to a target involve complicated control systems.  
16 These systems are generally based on sets of differential  
17 equations and estimates of input parameters. Such systems  
18 operated in response to analytical controllers.

19 None of the control systems including those implemented in  
20 accordance with the foregoing Bessacini patent incorporate any  
21 mechanism for readily using heuristic information in establishing  
22 control, particularly information about expertise gained through  
23 past experience. Moreover, these control systems normally  
24 require an operator to determine whether to issue a particular  
25 command to a torpedo and do not automatically generate and issue  
26 guidance commands in a continuous fashion.

1           Our co-pending United States Letters Patent No. (Application  
2 Serial No. 08/498,811) discloses a beam rider control system for  
3 submarine launched torpedoes that utilizes a fuzzy controller at  
4 the submarine for generating the guidance commands transferred to  
5 the torpedo over the communications link. Such fuzzy controllers  
6 rely upon information from a torpedo model and a communications  
7 link to the torpedo. The torpedo model is a mathematical replica  
8 of the torpedo that provides position and status information for  
9 post launch guidance operation. The control mechanism utilizes  
10 measured contact information, particularly a bearing from the  
11 submarine to the target, and torpedo model information,  
12 particularly the bearing from the submarine to the guidance point  
13 of the torpedo, to generate a command sequence for maintaining  
14 the guidance point on a target bearing from the submarine to the  
15 target.

16           Such systems therefore have, as one goal, keeping the  
17 torpedo guidance point on the bearing from the launching vehicle  
18 to the target. However, the torpedo, as a source of noise, may  
19 interfere with or contaminate the signals from the target when it  
20 is on or proximate that bearing line. This interference can  
21 degrade sensed target information at the first site before the  
22 acoustic homing device in the torpedo acquires the target.  
23 Accordingly, in the system described in a co-pending application  
24 also operates with another goal of maintaining the torpedo at  
25 some distance from the bearing line from the submarine to the  
26 target. This control system, that can operate in an iterative

1 fashion, selects one of several sets of predetermined sensed  
2 linguistic variables pertaining to first and second goal sets and  
3 the control system produces a corresponding control output  
4 linguistic variable based upon the selected goal.

5 This system also includes a conditioner that constrains all  
6 command information to prevent the torpedo from traveling in a  
7 direction with a searching velocity component directed back  
8 toward the submarine. This system also conditions the commands  
9 by controlling gain, but only when the control system produces a  
10 control output in response to the other goal, namely maintaining  
11 the torpedo guidance point on the bearing line. Thus if the  
12 control system is operating to remove the torpedo from proximity  
13 to the bearing line, the conditioner operates only in response to  
14 the constraint conditions. In the target intercept mode, the  
15 conditioner operates in response to both the gain adjustment and  
16 the constraint, with gain adjustment preceding the imposition of  
17 any constraint. The gain adjustment is a function of the  
18 distance from the torpedo guidance point to the target.

19 It has been found, however, that it is not a simple matter  
20 to transfer various aspects of hierarchical beam rider control  
21 systems to target intercept control systems. First, the target  
22 intercept and beam rider modes require different sensed  
23 variables. Second, the command information, gain adjustment and  
24 velocity constraint, if directly applied, adversely effect the  
25 resulting command and trajectory so that it becomes probable that  
26 the torpedo will not intercept the target.

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SUMMARY OF THE INVENTION

Therefore it is an object of this invention to provide an improved target intercept guidance system at a first site for automatically guiding a steerable object as it moves from the first site toward a second site.

Another object of this invention is to provide a guidance system using an improved fuzzy controller that operates located at a launching vehicle in a target intercept mode for automatically guiding a steerable object toward a target wherein both the launching vehicle and target can undergo independent motion.

Still another object of this invention is to provide a guidance system using an improved fuzzy controller in a target intercept mode that operates from a launching vehicle for automatically guiding a steerable object toward a target based on competing first and second goals.

Yet another object of this invention is to provide a guidance system using an improved fuzzy controller that operates in a target intercept mode from a launching vehicle for automatically guiding a steerable object toward a target wherein both the launching vehicle and target can undergo independent motion and the fuzzy controller further limits the location of the steerable object based upon predetermined zones relative to the target bearing from the first site to the second site.

Yet still another object of this invention is to provide a guidance system using an improved fuzzy controller for

1 maintaining a guidance point of a steerable object on a target  
2 intercept trajectory through control of the steerable object.

3 Still yet another object of this invention is to provide a  
4 guidance system using an improved fuzzy controller for  
5 maintaining the guidance point of a steerable object on a target  
6 intercept trajectory while offsetting the steerable object from  
7 that trajectory.

8 Still yet another object of this invention is to provide a  
9 guidance system with an improved fuzzy controller for use with  
10 submarine launched torpedoes that prevents the torpedo from  
11 interfering with the process of maintaining a bearing to the  
12 target.

13 Still yet another object of this invention is to provide a  
14 guidance system for submarine launched torpedoes that can operate  
15 automatically and can readily accommodate diverse operating  
16 circumstances.

17 In accordance with one aspect of this invention, an  
18 iterative method and system, generate a command signal for  
19 guiding a steerable object from a launching vehicle to a target  
20 in response to any of competing sets of multiple goal control  
21 rules based upon signals from sensing means corresponding to  
22 bearings from the launching vehicle to the steerable object and  
23 to the target and from the steerable object to the target wherein  
24 the steerable object is characterized by a center point and by a  
25 guidance point externally of the steerable object and leading the  
26 steerable object as it travels toward the target. During each

1 iteration, the system generates first sensed variable signals in  
2 response to the signals from the sensing means indicating the  
3 location of the steerable object with respect to a zone about a  
4 line between the launching vehicle and the target. Second sensed  
5 variable signals are generated in response to the signals from  
6 the sensing means indicating whether the bearing from the  
7 guidance point of the steerable object to the target is varying  
8 with time. The system retrieves first and second sensed  
9 linguistic variables in response to the first and second sensed  
10 variable signals, respectively, and selects at least one control  
11 output linguistic variable from a predetermined set of control  
12 output linguistic variables in response to the selected first or  
13 second sensed linguistic variables from the first set when the  
14 first sensed variable signals indicate that the steerable object  
15 is proximate or inside the predetermined zone and in response to  
16 the second set when the sensed variable signals indicate that the  
17 steerable object is outside the predetermined zone. The  
18 iteration is completed when the system generates the command  
19 signal for controlling the steerable object in response to the  
20 control output linguistic variables selection and transfers that  
21 command signal to the steerable object.

#### 22 BRIEF DESCRIPTION OF THE DRAWINGS

23 It is intended that the appended claims particularly point  
24 out and distinctly claim the subject matter of this invention.  
25 The various objects, advantages and novel features of this

1 invention will be more fully apparent from a reading of the  
2 following detailed description in conjunction with the  
3 accompanying drawings in which like reference numerals refer to  
4 like parts, and in which:

5 FIG. 1 depicts various instantaneous relationships among a  
6 launching vehicle, a target and a steerable object that are  
7 useful in understanding this invention;

8 FIG. 2 depicts changes of positions and bearings over time  
9 for arbitrary motions of the launching vehicle, a target, a  
10 steerable object and a predetermined zone;

11 FIG. 3 is a block diagram of a guidance system constructed  
12 and operated in accordance with this invention;

13 FIGS. 4A and 4B constitute a flow diagram that depicts the  
14 operation of the guidance system in FIG. 3;

15 FIGS. 5A, 5B, 5C, 5D and 5E are graphical representations of  
16 linguistic variables and their associated membership function  
17 sets that are useful in understanding this invention;

18 FIG. 6 schematically represents a multi-goal rule based unit  
19 shown in FIG. 3;

20 FIGS. 7A, 7B and 7C represent rule based matrices  
21 incorporated in the multi-goal rule based unit of FIG. 6;

22 FIGS. 8A through 8E depict the operation of the multi-goal  
23 rule based unit in FIGS. 3 and 6 during one set of operating  
24 conditions;

1           FIGS. 9A through 9E depict the operation of the multi-goal  
2 rule based unit shown in FIGS. 3 and 6 in another set of  
3 operating conditions;

4           FIG. 10 is a block diagram of a command conditioning unit  
5 shown in FIG. 3;

6           FIGS. 11A, 11B and 11C depict the trajectory of a steerable  
7 object for a non-maneuvering target and related signals; and

8           FIGS. 12A, 12B and 12C depict the trajectory of a steerable  
9 object for a maneuvering target and related signals.

#### 10                           DESCRIPTION OF THE PREFERRED EMBODIMENT

11           FIG. 1 depicts an acoustic homing torpedo 10, as an example  
12 of a steerable object with an internal acoustic homing device,  
13 that is moving from a first site, shown as a launcher 11 or  
14 submarine, to intercept a second site, shown as a target 12, or  
15 contact at an intercept point IP. The torpedo 10 has a position  
16 ( $X_v$ ,  $Y_v$  and  $Z_v$ ), a course ( $C_v$ ) and a speed ( $S_v$ ) along a course  
17 line 10C. The launcher 11 is moving along a course  $C_0$  and at  
18 speed  $S_0$  as represented by an arrow 11C while the target is  
19 moving along an arbitrary course at an arbitrary speed, both of  
20 which are unknown and represented by an arrow 12C. Each of the  
21 course lines 10C and 11C are normally measured with respect to  
22 some reference shown by a dashed line 13 in FIG. 1, typically  
23 magnetic north.

24           In this embodiment the torpedo 10 has a homing apparatus,  
25 such as an acoustic homing apparatus. Consequently the guidance

1 control system uses measurements to a center point 14 that  
2 represents the center of the torpedo 10 and a guidance point (GP)  
3 15 that corresponds to the centroid of the acoustic beam of the  
4 internal acoustic homing device. More specifically, the system  
5 uses two bearing angles associated with the torpedo 10. One is a  
6 bearing  $B_v$  to the center point 14 of the torpedo 10; the other, a  
7 bearing  $B_{cgp}$  from the guidance point (GP) 15 to the target 12.

8 As previously indicated, it is possible that the torpedo 10  
9 will, during transit from the launcher 11 to the target 12,  
10 approach the bearing line 12A and contaminate the measurements of  
11 the sensed bearing to the target 10 from the launcher 11. To  
12 avoid this situation and as shown in FIG. 2, the control system  
13 defines a "forbidden zone" 16 around each bearing line. In FIG.  
14 2 dashed lines 17 define the boundaries of one such zone. In  
15 this particular application, the control system steers the  
16 torpedo 10 so that it does not enter this forbidden zone 16. The  
17 details of this process are described later. It will become  
18 apparent, however, that the target intercept guidance commands  
19 may direct the torpedo 10 into this forbidden zone 16 thereby  
20 producing a conflict between the goal of target intercept  
21 guidance and the goal of maintaining the torpedo at locations  
22 removed from the forbidden zone 16. It will also be apparent  
23 that the forbidden zone 16 shown in FIG. 2 is a specific example  
24 of a zone that can be located at any arbitrary position and which  
25 may, in certain circumstances, yield conflicting or competing  
26 control operations or goals.

1 Referring now to FIG. 3, a guidance system 18 constructed in  
2 accordance with this invention includes sensors 20 that measure  
3 various parameters associated with the target 12 and the launcher  
4 11. A trajectory model 21 processes data from the sensors 20 and  
5 generates a set of error functions for a hierarchical fuzzy  
6 control system 22 that classifies each of the error functions (as  
7 a plurality of sensed variables) based on competing goals into  
8 one or more goal sensed linguistic variables from corresponding  
9 sets of predetermined goal sensed linguistic variables based upon  
10 their associated goal sensed variable membership functions. This  
11 hierarchical fuzzy control system 22 logically combines the goal  
12 selected sensed linguistic variables for identifying one or more  
13 control output linguistic variables and corresponding control  
14 output membership functions from a control output membership  
15 function set. The control system 22 also converts the selected  
16 control output membership function or functions into a guidance  
17 command. A communications link 23 transfers the guidance command  
18 over a bidirectional communications channel 24, typically formed  
19 by a wire connected to the torpedo 10, to another communications  
20 link 25 and a guidance system 26 in the torpedo 10.

21 Referring to FIGS. 1 and 3, the sensors 20 include contact  
22 sensors 27 that produce a range  $R_c$  and a bearing  $B_c$  defined by  
23 the angle between the reference 13 and a line 12A to the target  
24 12. As shown in FIG. 4A, this activity occurs during step 40  
25 wherein navigation sensors 28 of FIG. 3 produce the location of  
26 the launching vehicle,  $X_0$ ,  $Y_0$  and  $Z_0$  as well as its course  $C_0$  and

1 speed  $S_0$ . In step 41 (FIG. 4A) a vehicle model 30 (FIG. 3)  
2 provides the position ( $X_v$ ,  $Y_v$  and  $Z_v$ ), course ( $C_v$ ) and speed ( $S_v$ )  
3 of the torpedo 10. This information can be obtained utilizing  
4 information supplied by the navigation sensors 28 and open loop  
5 or dead reckoning updates to the vehicle model 30 or supplemented  
6 with information from the torpedo 10. The vehicle model 30 also  
7 receives information from the torpedo 10 through the  
8 communications link 23.

9           Whatever the source of the inputs, the vehicle model 30  
10 produces two signals for a primary goal error unit 32A and a  
11 secondary goal error unit 32B. One is a  $B_v$  signal that  
12 represents the bearing relationship defined by the angle between  
13 the reference line 13 in FIG. 1 and a line from the launcher 11  
14 to the center point 14 of the torpedo 10. The second is the  $B_{cep}$   
15 signal that represents the bearing defined by the angle between  
16 (1) the reference bearing as shown by the line 13A that is  
17 parallel to line 13 and (2) a line from the guidance point 15 to  
18 the target 12. This occurs during step 42 in FIG. 4A.

19           In accordance with certain objects of this invention, it  
20 will also be assumed that the hierarchical control system is to  
21 operate in accordance with one set of rules when the torpedo 10  
22 lies within a forbidden zone 16 and in accordance with another  
23 set of rules when the torpedo 10 lies outside the forbidden zone  
24 16. A primary goal error unit 32A and a zone definition unit 31  
25 produce  $e_s$  and  $\Delta e_s$  sensed variable signals that, in this  
26 particular embodiment, represent, respectively, (a) the angular

1 measure of the amount that the torpedo 10 is inside or outside  
 2 the forbidden zone 16 and (b) the rate of change of that angular  
 3 measure. A secondary goal error unit 32B produces  $e_{gp}$  and  $\Delta e_{gp}$   
 4 sensed variable signals that, in this particular embodiment,  
 5 represent, respectively, (a) instantaneous difference between a  
 6 bearing  $B_{cgp}$  from the guidance point 15 to the target 12 relative  
 7 to the reference line 13, as shown by parallel reference line 13A  
 8 and the course  $C_v$  of the torpedo 10 and (b) the rate of change of  
 9 this difference.

10 More specifically, during step 43 of each iteration of FIG.  
 11 4A the error units 32A and 32B in FIG. 3 convert the incoming  
 12 signals into error signals representing primary and secondary  
 13 sensed variables as follows:

$$14 \quad e_s = |B_v - B_c| - \theta_s \quad (1)$$

$$15 \quad \Delta e_s = |e_s|_k - |e_s|_{k-1} \quad (2)$$

$$16 \quad e_{gp} = B_{cgp} - C_v \quad (3)$$

17 and

$$18 \quad \Delta e_{gp} = |B_{cgp} - C_v|_k - |B_{cgp_{k-1}} - C_v| \quad (4)$$

19 wherein

$$20 \quad -90^\circ \leq B_c \leq 90^\circ \quad (5)$$

$$21 \quad -90^\circ \leq B_v \leq 90^\circ \quad (6)$$

22 and wherein  $\theta_s$  is the angular measure with respect to whether the  
 23 torpedo 10 is inside or outside the forbidden zone 16 in FIG. 2.  
 24 In this particular embodiment the zone definition unit 31 in FIG.  
 25 3 defines that value according to:

$$\theta_s = \theta_m e^{-\frac{r}{c}} \quad (7)$$

1  
2 where " $\theta_m$ ", as shown in FIG. 2, represents a maximum angular  
3 separation, generally proximate the launcher 11, "r" represents  
4 the range from the launcher 11 to the torpedo 10 and "c" is a  
5 constant. It will be apparent that this constitutes but one  
6 example of a procedure for defining whether a steerable object,  
7 such as a torpedo, is inside or outside a predetermined zone.  
8 Other zones can be defined that are in reference to the bearing  
9 line or any other relative positions of the torpedo 10, launcher  
10 11 and target 12 or even with respect to an arbitrarily fixed  
11 location, such as a predetermined geographical area.

12 Steps 44 and 45 in FIG. 4A represent a preferred procedure  
13 by which the hierarchical control system 22 of FIG. 3 based on  
14 competing primary and secondary goals encodes each of either the  
15 primary or secondary error signals representing the goal sensed  
16 variables into one or more corresponding goal sensed linguistic  
17 variables based upon goal sensed variable membership functions  
18 from corresponding goal sensed variable membership function sets.  
19 In step 44 the fuzzification unit 33 selects a membership  
20 function set based upon the sensed variables. In step 45, a  
21 multi-goal rule based unit 34 monitors the selected membership  
22 function set and determines whether the primary goal or secondary  
23 goal is to be used. If those signals indicate that the guidance  
24 must proceed according to the primary goal (i.e., to steer the  
25 vehicle away from the forbidden zone), the rule based unit 34

1 returns from fuzzification unit 33 linguistic sensed variables  
2 corresponding to the sensed variable signals from the primary  
3 goal error unit 32A. If those first sensed variable signals  
4 indicate that guidance should proceed according to the secondary  
5 goal (i.e., to steer the vehicle toward the target in accordance  
6 with the target intercept mode), the rule based unit 34 returns  
7 from the fuzzification unit 33 the linguistic sensed variables  
8 corresponding to the sensed variable signals from the secondary  
9 goal error unit 32B.

10 FIG. 5A, for example, discloses an  $e_s$  sensed variable  
11 membership function set with three sensed variable membership  
12 functions and their corresponding sensed  $e_s$ , or "angular error"  
13 linguistic variables while FIG. 5B discloses three  $\Delta e_s$  sensed  
14 variable membership functions and their corresponding sensed  $\Delta e_s$ ,  
15 or "angular error rate of change" linguistic variables. FIG. 5C  
16 discloses an  $e_{gp}$  sensed variable membership function set with  
17 three sensed variable membership functions and their  
18 corresponding sensed  $e_{gp}$  "intercept angle" linguistic variables  
19 while FIG. 5D discloses an  $\Delta e_{gp}$  sensed variable membership  
20 function set with seven  $\Delta e_{gp}$  sensed variable membership functions  
21 and their corresponding sensed  $\Delta e_{gp}$  "intercept angle rate of  
22 change" linguistic variables.

23 In the following discussion the primary goal error unit 32A  
24 in FIG. 3 and the secondary goal error unit 32B produce the  
25 foregoing  $e_s$  and  $\Delta e_s$  signals as primary error signals, or first  
26 sets of sensed variable signals and the  $e_{gp}$  and  $\Delta e_{gp}$  signals as

1 secondary error signals, or second sets of sensed variable  
2 signals respectively. It will be assumed that the following  
3 relationships exist:

$$4 \quad x1 = e_{gp} \quad (8)$$

$$5 \quad x2 = \Delta e_{gp} \quad (9)$$

$$6 \quad x3 = e_s \quad (10)$$

7 and

$$8 \quad x4 = \Delta e_s \quad (11)$$

9 and that a multi-goal fuzzification unit 33 in FIG. 3 uses the  $e_s$ ,  
10 and  $\Delta e_s$  signals to select one or more of the three available  
11 "angular error" ( $e_s$ ) and "angular error rate of change" ( $\Delta e_s$ )  
12 sensed linguistic variables or uses the  $e_{gp}$  signals to select one  
13 or more of the three available "intercept angle" ( $e_{gp}$ ) sensed  
14 linguistic variables and the  $\Delta e_{gp}$  signal to select one or more of  
15 seven available "intercept angle rate of change" sensed  
16 linguistic variables. The possibilities in this particular  
17 embodiment, that includes secondary goal "intercept angle" and  
18 "intercept angle rate of change" linguistic variables  $T_{x1}$  and  $T_{x2}$   
19 respectively and the primary goal "angular error" and "angular  
20 error rate of change" linguistic variables  $T_{x3}$  and  $T_{x4}$ ,  
21 respectively can be designated as:

$$22 \quad T(x1) = (T^1_{x1}, T^2_{x1}, T^3_{x1}) \quad (12)$$
$$= (N, ZE, P)$$

$$23 \quad T(x2) = (T^1_{x2}, T^2_{x2}, T^3_{x2}, T^4_{x2}, T^5_{x2}, T^6_{x2}, T^7_{x2}) \quad (13)$$
$$= (NL, NM, NS, ZE, PS, PM, PL)$$

$$T(x3) = (T^1_{x3}, T^2_{x3}, T^3_{x3}) \quad (14)$$

$$= (N, Z, P)$$

and

$$T(x4) = (T^1_{x4}, T^2_{x4}, T^3_{x4}) \quad (15)$$

$$= (N, Z, P)$$

where "NL", "NS", "NM", "ZE", "PS", "PM", and "PL" denote Negative Large, Negative Small, Negative Medium, Zero, Positive Small, Positive Medium, and Positive Large sensed linguistic variables, respectively. "N", "Z" and "P" denote Positive, Zero and Negative sensed linguistic variables, respectively.

The specific set of membership functions  $\mu(x1)$  and  $\mu(x2)$  corresponding to inputs  $x1$  and  $x2$  and the "intercept angle" and "intercept angle rate of change" linguistic variables associated with the secondary goal and shown in FIGS. 5C and 5D, can be mathematically stated as follows:

$$\mu(x1) = (\mu^1_{x1}, \mu^2_{x1}, \mu^3_{x1}) \quad (16)$$

and

$$\mu(x2) = (\mu^1_{x2}, \mu^2_{x2}, \mu^3_{x2}, \mu^4_{x2}, \mu^5_{x2}, \mu^6_{x2}, \mu^7_{x2}) \quad (17)$$

For  $j=2$  and  $i=2,3,4,5,6$  and for  $j=1$  and  $i=2$ :

$$\mu^i_{xj} = 1 - \frac{(|xj - C^i_{xj}|)}{\delta^i_{xj}} \quad (18)$$

for

$$C^i_{xj} - \delta^i_{xj} \leq xj \leq C^i_{xj} + \delta^i_{xj} \quad (19)$$

and

$$\mu^i_{xj} = 0 \quad (20)$$

1 for

$$C^i_{xj} - \delta^i_{xj} > xj > C^i_{xj} + \delta^i_{xj} \quad (21)$$

2  
3 The end conditions,  $j=1$  and  $i=1,3$  and  $j=2$  and  $i=1,7$  are  
4 defined by the following equations:

$$\mu^i_{xj} = 1 - \frac{(|xj - C^i_{xj}|)}{\delta^i_{xj}} \quad (22)$$

6 for

$$a^i C^i_{xj} \geq a^i xj \geq a^i (C^i_{xj} - a^i \delta^i_{xj}) \quad (23)$$

8 and

$$\mu^i_{xj} = 1 \quad (24)$$

10 for

$$a^i C^i_{xj} < a^i xj \quad (25)$$

12 and

$$\mu^i_{xj} = 0 \quad (26)$$

14 for

$$a^i (C^i_{xj} - a^i \delta^i_{xj}) > a^i xj \quad (27)$$

16 where  $a^i = 1$ , except for  $i=1$  where  $a^1 = -1$ .

17 The specific set of membership functions  $\mu(x3)$  and  $\mu(x4)$   
18 corresponding to inputs  $x3$  and  $x4$  and the "angular error" and  
19 "angular error rate of change" sensed linguistic variables  
20 associated with the primary goal and shown in FIGS. 5A and 5B,  
21 can be mathematically stated as follows:

$$\mu(x3) = (\mu^1_{x3}, \mu^2_{x3}, \mu^3_{x3}) \quad (28)$$

23 and

$$\mu(x4) = (\mu^1_{x4}, \mu^2_{x4}, \mu^3_{x4}) \quad (29)$$

24

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For j=3 and i=2 and for j=4 and i=2

$$\mu^i_{xj} = 1 - \frac{(|xj - C^i_{xj}|)}{\delta^i_{xj}} \tag{30}$$

for

$$C^i_{xj} - \delta^i_{xj} \leq xj \leq C^i_{xj} + \delta^i_{xj} \tag{31}$$

and

$$\mu^i_{xj} = 0 \tag{32}$$

for

$$C^i_{xj} - \delta^i_{xj} > xj > C^i_{xj} + \delta^i_{xj} \tag{33}$$

For j=3 and i=1 and for j=4 and i=1,3:

$$\mu^i_{xj} = 1 - \frac{(|xj - C^i_{xj}|)}{\delta^i_{xj}} \tag{34}$$

for

$$a^i C^i_{xj} \geq a^i xj \geq a^i (C^i_{xj} - a^i \delta^i_{xj}) \tag{35}$$

and

$$\mu^i_{xj} = 1 \tag{36}$$

for

$$a^i C^i_{xj} < a^i xj \tag{37}$$

and

$$\mu^i_{xj} = 0 \tag{38}$$

for

$$a^i (C^i_{xj} - a^i \delta^i_{xj}) > a^i xj \tag{39}$$

where  $a^i = 1$ , except for  $i=1$  where  $a^1 = -1$ .

For j=3 and i=3

$$\mu^i_{xj} = 1 \tag{40}$$

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for

$$C^i_{xj} \leq xj \quad (41)$$

and

$$\mu^i_{xj} = 0 \quad (42)$$

for

$$C^i_{xj} > xj \quad (43)$$

FIG. 5A depicts graphically the relationship of each "angular error" linguistic variable and associated membership function in the  $e_s$  membership function set for different values of the  $e_s$  signal according to a specific set of values for  $C^i_{xj}$  and  $\delta^i_{xj}$ . FIG. 5B presents analogous information for the  $\Delta e_s$  signal. In the specific embodiment shown in FIGS. 5A and 5B certain incoming signals correspond to a single or multiple sensed "angular error" and "angular error rate" linguistic variables based upon corresponding membership functions. For example, in FIG. 5A the  $e_s$  membership function set is used to encode an  $e_s$  signal having a value 0 only into a Z linguistic sensed "angular measure error" variable whereas a value of about -0.005 is encoded into both Z and N sensed "angular error" linguistic variables by using the  $e_s$  membership function set. Likewise the "angular error rate of change" membership set in FIG. 5B encodes a signal  $\Delta e_s = 0.3$  into a P sensed "angular error rate of change" linguistic variable and a signal  $\Delta e_s = 0.1$  into both Z and P sensed "angular error rate of change" linguistic variables.

1 FIG. 5C similarly depicts graphically the relationship of  
 2 each "intercept angle" sensed linguistic variable and associated  
 3 membership function in the  $e_{gp}$  membership function set for  
 4 different values of the  $e_{gp}$  signal according to another specific  
 5 set of values for  $C_{xj}^i$  and  $\delta_{xj}^i$ . FIG. 5D presents corresponding  
 6 information for the  $\Delta e_{gp}$  signal. In the specific embodiment shown  
 7 in FIGS. 5C and 5D certain incoming signals may also correspond  
 8 to a single or multiple "intercept angle" and "intercept angle  
 9 rate of change" sensed linguistic variables based upon  
 10 corresponding membership functions.

11 Referring to step 46 in FIG. 4B, the multi-goal rule based  
 12 unit 34 in FIGS. 3 and 6 combines certain selected sensed  
 13 linguistic variables to produce one or more control output  
 14 linguistic variables in response to the hierarchical control  
 15 described in steps 44 and 45 of FIG. 4A. Each selected control  
 16 output linguistic variable corresponds to a predefined membership  
 17 function in a control output membership function set (FIG. 5E).  
 18 More specifically, each control output linguistic variable is  
 19 determined according to a set of rules defined in FIGS. 7A, 7B  
 20 and 7C. The control outputs include, in this specific  
 21 embodiment, seven control output linguistic variables defined as:

$$\begin{aligned}
 T(\Delta C) &= (T^1_{\Delta C}, T^2_{\Delta C}, T^3_{\Delta C}, T^4_{\Delta C}, T^5_{\Delta C}, T^6_{\Delta C}, T^7_{\Delta C}) \\
 &= (NL, NM, NS, ZE, PS, PM, PL) .
 \end{aligned}
 \tag{44}$$

23 The corresponding control output membership functions,  
 24  $(\mu(\Delta C))$  are:

$$\mu(\Delta C) = \{ \mu^1_{\Delta C}, \mu^2_{\Delta C}, \mu^3_{\Delta C}, \mu^4_{\Delta C}, \mu^5_{\Delta C}, \mu^6_{\Delta C}, \mu^7_{\Delta C} \}
 \tag{45}$$

1 and shown in FIG. 5E and can be defined mathematically for  
2  $i=1,2,3,4,5,6,7$  by

$$3 \quad \mu_{\Delta C}^i = 1 - \frac{(|\Delta C - C_{\Delta C}^i|)}{\delta_{\Delta C}^i} \quad (46)$$

4 for

$$5 \quad C_{\Delta C}^i - \delta_{\Delta C}^i \leq \Delta C \leq C_{\Delta C}^i + \delta_{\Delta C}^i \quad (47)$$

6 and by

$$7 \quad \mu_{\Delta C}^i = 0 \quad (48)$$

8 for

$$9 \quad C_{\Delta C}^i - \delta_{\Delta C}^i > \Delta C > C_{\Delta C}^i + \delta_{\Delta C}^i \quad (49)$$

10 Values for the various constants  $C^i$  and  $\delta^i$  are associated with  
11 different membership functions of the sensed variable and control  
12 output variable membership function sets.

13 If  $\mu(x1)$  and  $\mu(x2)$  represent the sensed variable membership  
14 function sets associated with the secondary goal error unit 32B  
15 in FIG. 3 and  $\mu(\Delta C)$  represents the output control membership  
16 function set, the following constants can also be used:

	$\mu(x_1)$		$\mu(x_2)$		$\mu(\Delta C)$		
i	$C_{x_1}^i$	$\delta_{x_1}^i$	$C_{x_2}^i$	$\delta_{x_2}^i$	$C_{\Delta C}^i$	$\delta_{\Delta C}^i$	
1							
2	1	-0.5	0.5	-0.12	0.04	-10.00	2
3	2	0.0	0.5	-0.07	0.03	-5.0	2
4	3	0.5	0.5	-0.03	0.03	-2.0	2
5	4			0	0.01	0.0	2
6	5			0.03	0.03	2.0	2
7	6			0.07	0.03	5.0	2
8	7			0.12	0.04	10.0	2

9 Similarly if  $\mu(x_3)$  and  $\mu(x_4)$  represent the sensed variable  
 10 membership function sets associated with the "angular error" and  
 11 "angular error rate of change" sensed variables for the primary  
 12 goal membership functions, a control system constructed in  
 13 accordance with this invention can operate with the following  
 14 constants:

	$\mu(x_3)$		$\mu(x_4)$		
i	$C_{x_3}^i$	$\delta_{x_3}^i$	$C_{x_4}^i$	$\delta_{x_4}^i$	
15	1	-0.01	0.01	-0.25	0.25
16	2	0	0.01	0	0.25
17	3	0.01	--	0.25	0.25

19 As previously indicated, the multi-goal rule based unit 34  
 20 of FIGS. 3 and 6 operates according to a primary set of rules

1 that are invoked whenever the torpedo 10 in FIG. 1 enters or  
2 approaches the forbidden zone 16 of FIG. 2 or according to a  
3 secondary set of rules that are invoked whenever the torpedo 10  
4 is reasonably displaced from the forbidden zone 16. Thus as the  
5 torpedo 10 begins to move close to the forbidden zone 16, the  $e_s$   
6 signal will be positive and the multi-goal fuzzification unit  
7 will select the Z linguistic variable from the  $e_s$  membership set  
8 shown in FIG. 5A and, assuming a rate of change that is greater  
9 than 0.25, will select the P linguistic variable from the  $\Delta e_s$   
10 membership set shown in FIG. 5B. Assuming the  $B_v - B_c$  is positive,  
11 the multi-goal rule based unit 34 will operate, as shown in FIG.  
12 6, with a primary goal selection, represented by the position of  
13 a goal switch GS, and use the matrix in FIG. 7A to select a ZE  
14 control output linguistic variable.

15 So long as the torpedo 10 is within the forbidden zone or  
16 close to the forbidden zone, as defined by a value of the  $e_s$   
17 sensed variable that is less than 0.01 in this specific  
18 embodiment, the multi-goal rule based unit 34 relies entirely on  
19 the matrices in FIGS. 7A and 7B to select the control output  
20 linguistic variables to be used in steering the torpedo 10 out of  
21 or away from the forbidden zone 16 in FIG. 2 associated with the  
22 current target bearing  $B_c$ . The matrix in FIG. 7A is selected  
23 when  $B_v - B_c > 0$ ; the matrix in FIG. 7B, when  $B_v - B_c < 0$ .

24 Whenever the torpedo 10 is far enough outside the forbidden  
25 zone, as represented when the  $e_s$  signal has a value greater than  
26 0.01 in this embodiment, the selection of the control output

1 linguistic variable is based on the matrix shown in FIG. 7C and  
2 rules shown in FIG. 6. For example, if the multi-goal  
3 fuzzification unit 33 classifies the  $e_s$  signal into a P  
4 linguistic variable and classifies the  $e_{gp}$  and  $\Delta e_{gp}$  signals as  
5 Negative (N) and Negative Large (NL) sensed linguistic variables,  
6 respectively, the multi-goal rule based unit 34 will generate a  
7 positive large (PL) control output linguistic variable.

8           When generating a command based upon the primary goal or  
9 secondary goal criteria, the multi-goal rule based unit 34 in  
10 FIGS. 3 and 6 utilizes either the possible combinations for the  
11 given primary or secondary set of readings based on competing  
12 primary or secondary goals to produce an output based upon the  
13 selection of one or more control output membership functions.  
14 That is, the multi-goal rule based unit 34 will use the matrices  
15 of FIGS. 7A and 7B when the torpedo 10 is in or proximate the  
16 forbidden zone 16 or the matrix of FIG. 7C when the torpedo is at  
17 any other position. More specifically, if  $e_s > 0.01$  and if  $e_{gp} =$   
18  $+0.3$  and  $\Delta e_{gp} = 0.05$ , the  $e_{gp}$  signals can be classified both as ZE  
19 and P sensed "intercept angle" linguistic variables based upon  
20 the  $x_1$  or  $e_{gp}$  membership function set of FIG. 5C while the  $\Delta e_{gp}$   
21 signal is encoded into PS and PM "intercept angle rate of change"  
22 sensed linguistic variables based upon the  $x_2$  or  $\Delta e_{gp}$  membership  
23 function set of FIG. 5D.

24           Each of the summing circuits 48P and 48S, symbolically  
25 referenced in FIG. 6, essentially combines each of the output  
26 variable membership functions corresponding to each of the

1 selected control output linguistic variables to produce an output  
2 signal as shown by steps 47 and 63 in FIG. 4B. More  
3 specifically, the summing circuits 48P and 48S in FIG. 6 combine  
4 the selected control output membership functions scaled by the  
5 various sensed variable signals as illustrated in FIGS. 8 and 9.

6 FIGS. 8A through 8E, depict the operation that occurs when  
7 the primary goal error unit 32A generates "angular error" and  
8 "angular error rate of change" signals of  $e_s = -0.005$  and  $\Delta e_s = -0.2$   
9 indicating that the torpedo is within the forbidden zone 16.  
10 During the selection of the corresponding sensed linguistic  
11 variables, the multi-goal fuzzification unit 33 correlates each  
12 of the  $e_s$  and  $\Delta e_s$  sensed variables into a particular point on any  
13 corresponding encoding sensed variable membership function as  
14 shown by FIGS. 8A through 8D. In this particular embodiment, for  
15 example, the  $e_s$  signal intersects both the Z and N membership  
16 functions shown in FIG. 5A and the  $\Delta e_s$  signal intersects the Z  
17 and N membership functions shown in FIG. 5B. The multi-goal rule  
18 based unit 34 then selects one output control linguistic variable  
19 for each possible logical combination of the sensed variable  
20 linguistic variables. In this particular example, each signal  
21 corresponds to two membership functions, so the multi-goal rule  
22 based unit 34 executes four rules and selects four control output  
23 linguistic variables. The summing unit 48P scales each selected  
24 control output membership function through the selection of the  
25 lower of the intercepts of the input signals with the

1 corresponding sensed variable membership functions incorporated  
2 in a specific rule.

3 Using FIGS. 8A through 8E as an example and assuming that  
4 the torpedo is inside the forbidden zone and that  $B_v - B_c < 0$ , the  
5 multi-goal rule based unit 34 operates according to the matrix in  
6 FIG. 7B. In FIG. 8A the  $e_s$  and  $\Delta e_s$  signals are shown as  
7 intersecting the Z linguistic variables for each so the multi-  
8 goal rule based unit 34 selects the ZE control output linguistic  
9 variable according to the rule:

10 If  $e_s$  is Z and  $\Delta e_s$  is Z THEN  $\Delta C$  is ZE

11 FIGS. 8B through 8D define the other three rules that the multi-  
12 goal rule based unit 34 invokes under the remaining three logical  
13 combinations as follows:

14 IF  $e_s$  is Z and  $\Delta e_s$  is N THEN  $\Delta C$  is NS

15 IF  $e_s$  is N and  $\Delta e_s$  is Z THEN  $\Delta C$  is NM

16 IF  $e_s$  is N and  $\Delta e_s$  is N THEN  $\Delta C$  is NS

17 FIGS. 8A through 8D also depict graphically one approach for  
18 combining the selected control output linguistic variables for  
19 producing a command signal. In Graph 8A, an intersection 47A of  
20 the  $\Delta e_s$  signal with its Z membership function is lower than an  
21 intersection 50A of the  $e_s$  signal with its selected Z membership  
22 function, so the  $\Delta e_s$  signal controls the magnitude of the  
23 selected ZE control output membership function by establishing a  
24 scaled triangular output function 51A with its peak at  
25 intersection 52A rather than the intersection 53A. In a similar  
26 fashion, the second rule depicted in Graph 8B produces a

1 triangular form 54A based upon an intersection 55A of the  $e_p$   
2 signal with the Z sensed variable membership function that is  
3 lower than an intersection 56A of the  $\Delta e_p$  signal with its  
4 corresponding N membership function. Similarly the rules  
5 depicted in Graphs 8C and 8D provide triangular forms 57A and 58A  
6 respectively based upon a lower intersection 60A of the  $\Delta e_p$   
7 signal in FIG. 8C and upon a lower intersection 61A of the  $e_p$   
8 signal in FIG. 8D.

9           Whenever the  $e_p$  primary goal error unit produces a sensed  
10 variable signal that identifies the P linguistic variable  
11 indicating that the torpedo 10 is outside the forbidden zone 16,  
12 the multi-goal rule based unit 34 operates in response to the  $e_{gp}$   
13 and  $\Delta e_p$  sensed variable signals according to the membership  
14 functions shown in FIGS. 5C and 5D and the matrix shown in FIG.  
15 7C. FIGS. 9A through 9E graphically depicts the formation of the  
16 composite control output function under these operating  
17 conditions for each of four input combinations and correlations  
18 as shown in Graphs 9A through 9D respectively, as for example,  
19 when  $e_{gp}$  has a value that identifies P and ZE membership functions  
20 and  $\Delta e_{gp}$  identifies ZE and PS membership functions.

21           The multi-goal rule based unit 34 correlates each of the  
22 possible four input combinations for the secondary goal as  
23 follows:

1 IF  $e_{gp}$  is ZE AND  $\Delta e_{gp}$  is ZE THEN  $\Delta C$  is ZE.

2 IF  $e_{gp}$  is ZE AND  $\Delta e_{gp}$  is PS THEN  $\Delta C$  is NS.

3 IF  $e_{gp}$  is P AND  $\Delta e_{gp}$  is ZE THEN  $\Delta C$  is ZE.

4 IF  $e_{gp}$  is P AND  $\Delta e_{gp}$  is PS THEN  $\Delta C$  is PS.

5 Thus in step 45 the multi-goal rule based unit 34 produces  
6 different output consequences or control output linguistic  
7 variables derived from these selected rules.

8 In the case of the first rule shown in FIG. 9A, an  
9 intersection 47B of the  $\Delta e_{gp}$  signal with ZE membership function is  
10 lower than the intersection 50B of the  $e_{gp}$  signal with its  
11 selected Z membership function, so the  $\Delta e_{gp}$  signal controls the  
12 magnitude of the selected ZE control output membership function  
13 by establishing a scaled triangular output function 51B with its  
14 peak at intersection 52B rather than the intersection 53B. In a  
15 similar fashion, the multi-goal rule based unit 34 produces  
16 triangular forms 54B, 57B and 58B respectively.

17 Stated mathematically, multi-goal rule based unit 34  
18 produces outputs for up to a maximum of four inferred control  
19 output functions from each of the identified rules. For example,  
20 these functions, for the set resulting from the operation of the  
21 secondary error unit 32B are, respectively, (1)  $\zeta_{(1)}\mu^4_{\Delta C}$ , (2)  
22  $\zeta_{(2)}\mu^3_{\Delta C}$ , (3)  $\zeta_{(3)}\mu^4_{\Delta C}$  and (4)  $\zeta_{(4)}\mu^5_{\Delta C}$  where:

23  $\zeta_{(1)}\mu^4_{\Delta C} = \mu(\Delta C)_{(1)} =$  the control output function for rule 1

24 defined by  $\mu^4_{\Delta C}$  multiplied by the value  $\zeta_{(1)}$ ; and

25  $\zeta_{(2)}\mu^3_{\Delta C} = \mu(\Delta C)_{(2)} =$  the control output function for rule 2

26 defined by  $\mu^3_{\Delta C}$  multiplied by the value  $\zeta_{(2)}$ .

1  $\zeta_{(3)}\mu_{\Delta C}^4 = \mu(\Delta C)_{(3)}$  = the control output function for rule 3  
2 defined by  $\mu_{\Delta C}^4$  multiplied by the value  $\zeta_{(3)}$ ; and

3  $\zeta_{(4)}\mu_{\Delta C}^5 = \mu(\Delta C)_{(4)}$  = the control output function for rule 4  
4 defined by  $\mu_{\Delta C}^5$  multiplied by the value  $\zeta_{(4)}$ ;

5 and

6 
$$\zeta_{(1)} = Y_{x1}^2 \wedge Y_{x2}^4 = \min(Y_{x1}^2, Y_{x2}^4) \quad (48)$$

7 
$$\zeta_{(2)} = Y_{x1}^2 \wedge Y_{x2}^5 = \min(Y_{x1}^2, Y_{x2}^5) \quad (49)$$

8 
$$\zeta_{(3)} = Y_{x1}^3 \wedge Y_{x2}^4 = \min(Y_{x1}^3, Y_{x2}^4) \quad (50)$$

9 
$$\zeta_{(4)} = Y_{x1}^3 \wedge Y_{x2}^5 = \min(Y_{x1}^3, Y_{x2}^5) \quad (51)$$

10 where  $Y_{xj}^i$  is  $\mu_{xj}^i$  evaluated at a specific sensed input  $xj(t)$  at  
11 time "t" and where " $\wedge$ " denotes a fuzzy minimum. The control  
12 output composite implication function,  $\underline{\mu}(\Delta C)$ , of the multi-goal  
13 rule based unit 34 for this example is expressed as:

14 
$$\underline{\mu}(\Delta C) = \mu(\Delta C)_{(1)} + \mu(\Delta C)_{(2)} + \mu(\Delta C)_{(3)} + \mu(\Delta C)_{(4)} \quad (52)$$

15 The inferred control output functions are generated in a  
16 similar fashion for the primary error unit example.

17 As previously indicated, the ruled based unit 34 in FIGS. 3  
18 and 6 also operates in accordance with step 63 of FIG. 4B by  
19 combining the scaled fuzzy output membership functions shown in  
20 FIG. 8E or FIG. 9E into a composite output function. A number of  
21 methods can be utilized for converting composite outputs into  
22 guidance commands in step 64. The defuzzification unit 35 for  
23 example, can use a centroid method to provide guidance commands.  
24 Mathematically the centroid is computed as follows:

$$\Delta C = \frac{\sum_k [(\zeta_{(k)} C_{\Delta C(k)}) I_{\Delta C(k)}]}{\sum_k \zeta_{(k)} I_{\Delta C(k)}} \quad (53)$$

1  
 2 where  $\Sigma_{(k)}$  is the summation over all the rules selected by the  
 3 multi-goal rule based unit 34 and  $I_{\Delta C(k)}$  and  $C_{\Delta C(k)}$  are the  
 4 respective area and centroid of the kth rule consequent set  
 5 membership function. This is represented in FIGS. 8E and 9E that  
 6 depict the superposition of the scaled control output membership  
 7 functions of FIGS. 8A through 8D and FIGS. 9A through 9D,  
 8 respectively. The resulting composite output function for either  
 9 of the selected goals is the sum of the selected scaled  
 10 individual control output functions. With reference to FIG. 8E,  
 11 this composite function includes the area under the dashed line  
 12 59A plus the sides 57A' and 51A' of the functions 57A and 51A,  
 13 respectively. Similarly, the composite function shown in FIG. 9E  
 14 includes the area under the dashed line 59B plus the sides 58B'  
 15 and 54B' of the functions 58B and 54B, respectively. The  
 16 defuzzification unit 35 calculates the centroid for either of the  
 17 composite functions of FIGS. 8E or 9E to produce a resulting  $\Delta C$   
 18 signal that is the finite signal for controlling the torpedo 10  
 19 in FIG. 1.

20 In accordance with a further aspect of this invention, the  
 21 command conditioning unit 36 modifies the output from the  
 22 defuzzification unit 35 as depicted in Step 65 of FIG. 4B  
 23 dependent upon the position of the guidance point 15 of the  
 24 torpedo 10 relative to the target 12 as shown in FIG. 1. For  
 25 example, as shown in FIG. 10, the command conditioning unit 36

1 includes a command limit unit 70 and a gain control unit 71. A  
2 switch 72 directs the output of the defuzzification unit 35 in  
3 response to the range  $R_{GD}$  from the guidance point 15 to the  
4 target 12 as a function of the distance  $GD$  from the center of  
5 gravity or turning point of the torpedo to the guidance point 15.  
6 In this specific embodiment, the switch sends commands to the  
7 limit circuit 70 when

$$8 \qquad R_{GD} \geq 1.5 GD \qquad (56)$$

9 and to gain control unit 71 when

$$10 \qquad R_{GD} < 1.5 GD \qquad (57)$$

11 so the units 70 and 71 operate on a mutually exclusive basis.

12 The limit circuit 70 operates to assure that the torpedo 10  
13 is not moved into a position whereby it has a searching velocity  
14 vector component directed back to the launcher 11. Specifically,  
15 the command limit unit 70 interrogates each control command  $\Delta C_i$   
16 from the defuzzification unit 35 routed to it through the switch  
17 to determine if this command will cause the torpedo 10 to exceed  
18 any limits that are governed by a particular circumstance. FIG.  
19 10 graphically represents one set of limits " $L_1$ " and " $L_2$ ". In  
20 terms of the specifically disclosed embodiment described above,  
21 these limits can be defined mathematically, assuming there is no  
22 initial vehicle velocity component toward the launcher, as  
23 follows:

$$24 \qquad L_1 = B_v + 90^\circ - (C_{vm})_{k-1} \qquad (54)$$

25 and

$$L_2 = B_V - 90^\circ - (C_{vm})_{k-1} \quad (55)$$

where  $(C_{vm})_{k-1}$  is the vehicle course from the last update cycle.

If the limit is defined as shown in FIG. 10 and is exceeded, only that portion of the command that will produce a torpedo trajectory perpendicular to the torpedo bearing line between the launcher 11 and torpedo 10 in FIG. 1 will be utilized. In the specific application of a torpedo launched from a submarine, these limits ensure that the trajectory of the torpedo from the addition of various system commands does not produce a velocity component toward the launcher 11 in its then current position so long as the torpedo 10 is distanced from the target contact 12 by a distance greater than 1.5 GD.

As the torpedo 10 approaches the target contact 12 and  $R_{GD} < 1.5 GD$ , the gain control unit 71 in FIG. 10 provides command conditioning by modifying the command as a function of the vehicle guidance distance (GD) and the range ( $R_{GD}$ ) from the guidance point 15 of the torpedo 10 to the target. For example, a modification could be provided according to:

$$K = f(GD, R_{GD}) = K_0 \left[ \frac{R_{GD}}{GD} \right] \left[ \frac{R_{GD}}{GD} + 1 \right] \quad (56)$$

where  $K_0$  is an arbitrary gain constant.

Stated differently, in accordance with this invention, the velocity constraint prevents any velocity component toward the launching vehicle so long as the torpedo 10 is at least 1.5 times the distance from the center point 14 to the guidance point 15 of the torpedo. Within that range, however, the constraint is

1 terminated and the gain adjustment becomes the conditioning  
2 element. Consequently the constraint and gain adjustment command  
3 conditioning units operate in a mutually exclusive fashion.  
4 Moreover, the decision is determined by the location of the  
5 torpedo relative to the target, rather than on which of the  
6 competing rules are in force.

7 After the control system 22 generates its command signal  
8 subject to the command conditioning unit 36, the communications  
9 link 23 transfers the command signal over the communications  
10 channel 24 to the communications link 25 in step 66 of FIG. 4B.  
11 The guidance system 26 responds to any command requiring a course  
12 alteration by changing the path of the torpedo 10.

13 FIG. 11A depicts a sample trajectory for a torpedo when a  
14 launcher 11 and target 12 move along parallel courses 80 and 81  
15 respectively at the same speed. Initially the launcher 11 starts  
16 the torpedo along a path 82 for a predetermined time, as known.  
17 When that time expires at point 83, the control system of FIG. 3  
18 takes control. In this example, at point 83 the  $e_s$  signal is  
19 negative and indicates that the torpedo 10 is in the forbidden  
20 zone. Since the bearing to the torpedo,  $B_v$ , minus the bearing to  
21 the contact,  $B_c$ , is negative, the multi-goal rule based unit 34  
22 uses the matrix of FIG. 7B for the primary goal. Negative course  
23 commands are issued moving the torpedo 10 away from the bearing  
24 line until it exits the forbidden zone at point 84 at the time of  
25 the positive-going zero crossing of the  $e_s$  signal.

1           Beginning at point 84 the transition of the  $e_s$  signal to a  
2 positive value enables control to transfer to the matrix of FIG.  
3 7C for the secondary goal (i.e., guidance according to the target  
4 intercept method). Consequently, according to the matrix of FIG.  
5 7C the multi-goal rule based unit 34 selects control output  
6 membership functions to place the guidance point 15 of the  
7 torpedo 10 on a target intercept trajectory.

8           At 87 the torpedo crosses back into the forbidden zone, so  
9 the  $e_s$  signal changes to a negative value. This transition  
10 causes the hierarchical fuzzy control system 22 to operate  
11 according to the primary goal to move the torpedo out of the  
12 forbidden zone.

13           As shown in FIG. 11B, the hierarchical fuzzy control system  
14 22 oscillates between the primary goal and secondary goal over an  
15 interval 88 until the motion of the contact bearing line, the  
16 size of the guidance distance, the orientation of the torpedo 10  
17 and the decreasing boundary separation angle with increasing  
18 vehicle range result in a geometry that allows the vehicle to  
19 maintain a course for the guidance point intercept without  
20 reentering the forbidden zone for the remainder of the run. This  
21 operation begins at point 90 in FIGS. 11A through 11C.

22           FIGS. 12A, 12B and 12C depict the trajectory of a target 12  
23 and torpedo and the excursions of the  $e_s$  and  $\Delta e_{gp}$  signals in a  
24 situation in which the target takes evasive action. In this case  
25 reference number 100 indicates the position of the launching  
26 vehicle 11, that is assumed to be stationary, and the target 12

1 at the time the torpedo is launched along a path to a point 101  
2 when the control system in FIG. 3 becomes active. When control  
3 over the torpedo begins, it is in the forbidden zone as indicated  
4 by the negative excursion of the  $e_s$  signal. In this particular  
5 configuration the  $(B_v - B_c)$  value is greater than 0. The primary  
6 control is selected and positive commands are issued. The  
7 resulting commands steer the torpedo outside the zone at point  
8 102 where the value of the  $e_s$  signal becomes positive.

9 With this transition, the control system in FIG. 3 shifts  
10 from primary to secondary goal control and begins to impose  
11 target intercept guidance parameters on the torpedo. During the  
12 interval from point 103 to point 104 the torpedo remains outside  
13 the forbidden zone and under secondary control. At point 104,  
14 the  $e_s$  signal becomes negative indicating that the torpedo is  
15 within the forbidden zone and control reverts back to the primary  
16 mode. At point 105 the contact maneuvers. The control system in  
17 FIG. 3 oscillates between the primary and secondary goals over  
18 the interval from point 105 to point 106 when the intercept angle  
19 rate of change signal,  $\Delta e_{gp}$ , goes to zero placing the guidance  
20 point 15 on an updated intercept trajectory with the maneuvered  
21 contact. As shown in FIG. 12B after point 106, the  $e_s$  signal  
22 continues to increase in a positive direction and target  
23 intercept or secondary control continues with the torpedo  
24 guidance point obtaining an intercept with target at an intercept  
25 point IP.

1           If the maneuvering shown in FIG. 12A is considered for a  
2 control system that does not include competing goals, but relies  
3 merely upon the target intercept guidance system, the oscillating  
4 portions between points 104 and 106 do not appear. In fact the  
5 e, signal smoothly varies throughout the trajectory. Moreover  
6 the guidance point trajectory for entire contact maneuver remains  
7 smooth. However, it is the activity between points 104 and 106  
8 in FIGS. 12A through 12C that assures the positioning of the  
9 torpedo outside the zone where it cannot impair the signals being  
10 received from the target by the launching vehicle. The interval  
11 between reference points 104 and 106 in FIG. 12B, for example,  
12 represents a significant time interval during which degradation  
13 could cause the control system to fail to recognize the maneuvers  
14 of the target.

15           Thus in accordance with this invention, a control system 22  
16 as shown in FIG. 3 combines a contact bearing, a forbidden zone  
17 angular separation and a torpedo bearing and a target bearing  
18 measured from a torpedo guidance point and torpedo course to form  
19 a plurality of error functions and derivatives thereof. The  
20 hierarchical structure of the control system with its primary and  
21 secondary goals enables the control system to mediate between two  
22 competing goals, namely: maintaining the torpedo outside a  
23 predetermined zone along the bearing from the launching vehicle  
24 and the target and maintaining the position of the torpedo along  
25 a target intercept trajectory.

1           A control system constructed in accordance with this  
2 invention emulates operations that reflect heuristic  
3 considerations through the utilization of a rule based expert  
4 system that includes a knowledge base that reflects the thinking  
5 process of a human. Moreover, the control system has the  
6 capability of mediating between two competing goals and  
7 automatically generating and issuing control commands.

8           More specifically, various signals are sampled on a regular  
9 iterative basis, so data from two successive sets of signals also  
10 provides the rate of change of any angle these signals represent.  
11 The fuzzification unit 33 uses corresponding sensed variable  
12 membership functions to encode the inputs obtained during one  
13 iteration into one or more sensed linguistic variables based on a  
14 hierarchial structure by which a primary goal is met in one set  
15 of operating conditions and a secondary goal is met in other  
16 operating conditions. The multi-goal rule based unit 34 converts  
17 these selected sensed linguistic variables into one or more  
18 control output linguistic variables. The control system selects  
19 control output membership functions of a control output  
20 membership function set that then can be combined by diverse  
21 procedures to obtain a control signal. Command conditioning  
22 prevents the control unit 22 from directing the objects such as a  
23 torpedo in an inappropriate direction and, in certain operating  
24 conditions, provides a gain or other modification to the command  
25 signal necessary to obtain good control with different tactical  
26 parameters.



2  
3 HIERARCHICAL TARGET INTERCEPT FUZZY CONTROLLER  
4 WITH FORBIDDEN ZONE

5  
6 ABSTRACT OF THE DISCLOSURE

7 A target intercept guidance system for directing a steerable  
8 object, such as a torpedo with a guidance point. The guidance  
9 system is located at a launching vehicle and senses the bearings  
10 from the launching vehicle to a target and to the steerable  
11 object as it moves toward the target. Various error signals are  
12 then generated and classified into sensed linguistic variables  
13 using membership functions of corresponding sensed variable  
14 membership function sets based upon primary and secondary goals  
15 to become fuzzy inputs that produce fuzzy control output  
16 membership functions from a control output membership function  
17 set based upon logical manipulation of the fuzzy inputs. The  
18 control system performs this classification and selection  
19 according to sometimes competing goals of excluding the torpedo  
20 from a particular operating zone while guiding the torpedo in  
21 response to variations in a target bearing relative to the  
22 guidance point. The selected fuzzy control output membership  
23 functions are converted into an output having an appropriate form  
24 for control, subject to optional conditioning to prevent unwanted  
25 effects and assure good behavior for different tactical  
26 parameters.