Intelligent Navigation Process for Autonomous Underwater Vehicles (AUVs) Using Time-based Fuzzy Temporal Reasoning

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Abstract

This paper describes the application of a fuzzy control temporal reasoning paradigm for the development of navigation and obstacle avoidance capabilities in Autonomous Underwater Vehicles (AUVs). The ability of an AUV to undertake real-time navigation is a critical performance determinant. The objective to this paper is to employ temporal reasoning to estimate an obstacle's location within a complex underwater environment. It is expected that with the support of fuzzy temporal reasoning the control system can manage the complexity of this problem. The aim is to provide an AUV controller with robust reactive rules capable of performing real-time navigation and obstacle avoidance in a wide variety of underwater situations.

Keywords: Autonomous Underwater Vehicle, fuzzy logic, temporal reasoning, intelligent navigation.

1. Introduction

Navigation with an obstacle avoidance execution process is one of the many important capabilities and behaviours of AUVs. The real-time operation of this capability is the main requirement needed within the autonomous-vehicle's control-management system. However, there are many scenarios that may occur within a real world underwater environment that add to the complexity of the problem. The a-priori knowledge and information about underwater environment in which the AUV has to operate is often incomplete, uncertain and approximated. The information that is available to an AUV is normally supplied via a limited number of sensors that are incorporated into the AUV. The major sensor used is sonar, which will be used to control the vehicle's speed and its direction in each decision cycle. As Saffiotti [8] revealed, fuzzy logic, is a useful method in the field of robotics. This technique has been applied in a number of studies to demonstrate advanced guidance and control in a real environments and has included with obstacle avoidance, target tracking, etc. [1], [5], [6], and [7].

The obstacle avoidance functionality is a critical part of AUV's robust command and control system that can avoid collision with underwater objects even when these moving object behave in an unexpected ways. In managing AUV's underwater scenario, various steps are involved including control and evaluation of present values and variables with past states as a 'background historical tracking' process. These variables in many cases are fuzzy and can lead us to incorporate a temporal reasoning model (fuzzy temporal reasoning) within the command and control module of AUV. In this work there are number of situations that should be considered. In particular the AUV's behaviour when it is confronting an object(s) and how and AUV will manage the situation when a detected obstacle which is assumed to be at rest becomes an unrestricted moving-obstacle. Frequently the AUV's command and control system will acts based on information it possesses on the position of the object in the immediate past. However, it must be assumed that the moving object can move with variable speed and can turn with no restriction. To successfully avoid the object in this complex scenario the AUV command and control system must operate in real time and allows the autonomous-vehicle to operate with imprecise knowledge of the environment in which the AUV must operate.

2. Strategy for Obstacle Avoidance

This study is focused on the movement of an AUV in a complex dynamic environment. The scenario considered in this study is where an AUV reaches an area of interest on a path that transits through a number of intermediate obstacles while satisfying different constraints. Within the underwater environment there are fixed obstacles and/or moving-objects, which may restrict the AUV's freedom of movement and course of action. An added complexity, which is inherent in any design of an AUV, is the limited energy available to maneuver in the underwater environment. In these circumstances an AUV is limited by several variables including turn-velocity and linear-acceleration of the AUV and the range of the AUV on-board sensors to

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detect both moving-objects and obstacles at rest (see Figures 1 and 2).

It is expected that the AUV moves smoothly to a designated position and returns safely to its above-water pre-specified location. In order to avoid obstacles effectively, a system must have knowledge about the obstacle's position and likely future positions relative to the AUV. Since the information being provided by the sensors will be imperfect and there will be some uncertainty associated with this information the AUV control process unit should be capable of robustly estimating future positions of the obstacles. Since the dynamics of the obstacles may not be linear, the process models must be capable of reflecting non-linear behaviour. The uncertain information produced by the various sensors will be related to required knowledge about the obstacle by the AUV's sensor model. However, this relationship need not be linear, and may even have to be learnt by the AUV control system.

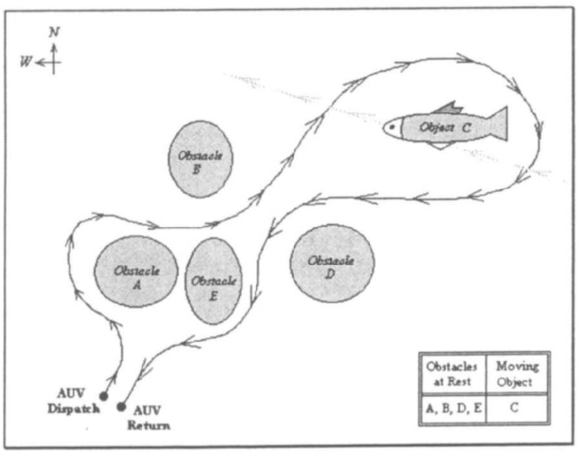

Figure 1. AUV underwater navigation process.

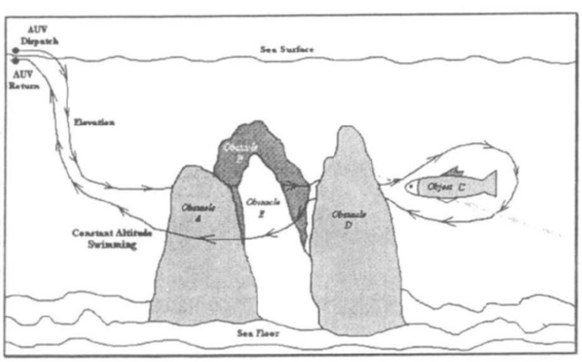

Figure 2. AUV's obstacle avoidance course.

3. The Obstacle Avoidance Technique

Let us assume *VAUV* is the velocity of AUV, *Vobject* is the velocity of the moving object, *RAUV* is the radius of the AUV and *Robject* is the radius of the moving-object as presented in Figure3. In this case the AUV's minimum radius to obstacle can be calculated as the following expression

$$R = RAUV + 2*Rsafety + Robstacle$$

and AUV's real-time velocity can be considered as follows

$$V = VAUV - Vobstacle$$

In this work *Rsafety* is assumed to be the minimum safe distance between the AUV and the moving object. The Non-Collision Guide *(NCG)* parameter is a method to evaluate the proximity of the AUV's real-time at present situation with a further collision-situation that is formulated as

$$NCG = \frac{\sin(\alpha)}{\sin|\beta|}$$

Where α is the angle between straight-line that connects AUV to the object (D_0) and the velocity vector *V*. This angle can increase clockwise (see Figure 4). Simultaneously β is the angle between the straight-line D_0 and the straight-line tangential to the radius of object's virtual sphere (object's surrounding).

The following table describes the classification index of various AUV's Non-Collision Guide values when moving towards a fixed or moving object.

Table 1. *N*on-*C*ollision *G*uide (*NCG*) parameter:

Classification	*NCG*	*Situation*
A	*IF:* $NCG > +1$	***THEN:*** AUV is going to pass before the moving object
B	*IF:* $NCG < -1$	***THEN:*** AUV has let the moving object pass
C	*IF:* $0 < NCG <= +1$	***THEN:*** AUV is going to collide with moving object on its *left hand side*
D	*IF:* $-1 <= NCG < 0$	***THEN:*** AUV is going to collide with the moving object on its *right hand side*

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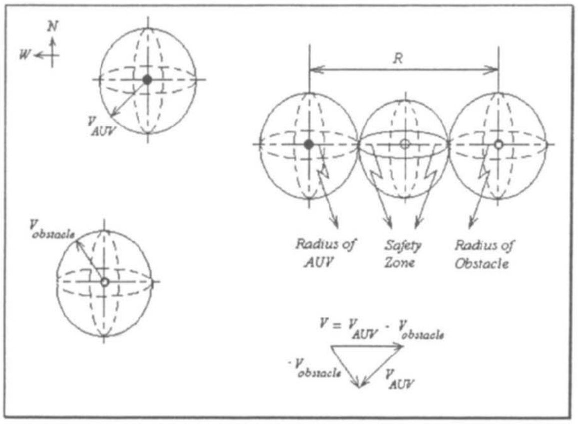

Figure 3. The AUVs and obstacle avoidance, safety-circumstances and their velocity profile.

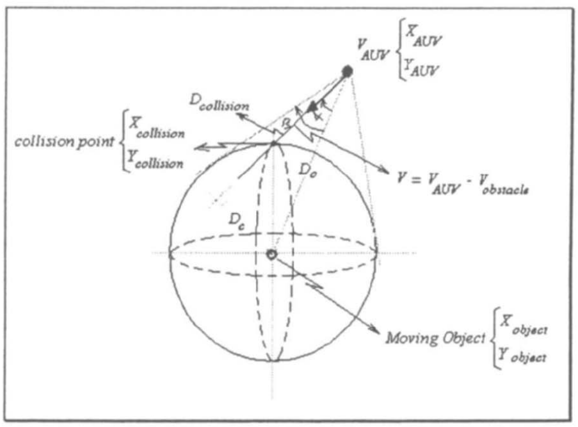

Figure 4. The process of non-collision obstacle avoidance guide.

Due to the dynamic behaviour of the obstacle there are number of variations that may occur within the *NCG* value. The *NCG* value may increase as a result of a decrease in the obstacle's velocity, or an increase in the AUV's velocity. The other possibility is that the AUV or moving-obstacle may turn to the right or left. The *NCG* value may decrease due to either a decrease in the AUV's velocity or to an increase in the moving-obstacle's velocity or to the AUV or the obstacle turning to a particular direction.

4. Temporal Reasoning Rule Method

This application is suitable in a real-time mode and there is a strong restriction on the probabilities of the reasoning mainly on the dynamics of the control system. Therefore the following formulation is proposed by Bugarin et al. [2] to model the above application:

X (linguistic variable) is *A* (linguistic value of x){in *Q* (fuzzy qualifier) of} *T* (temporal reference or entity)

In this model the temporal entity *T* represents both instants, fuzzy temporal intervals and the membership functions that are defined on a discrete set of values *t =(t0, t1, ..., tk, ..., tpresent)*, where every *tk* represents a precise instant of time, *t0* represents the origin and *tpresent* is the instant time. So the *degree of achievement* for the above proposition when

μ_A is a membership function associated with the value *A* of the proposition,

$X(t_k)$ is the value observed for the variable *X* in the instant *tk*,

μ_T is the membership function of the temporal reference

μ_Q is the membership function associated with the linguistic qualifier *Q*, and

REINT is the reinforcement of a membership function μ_T that is defined as a universe of discourse *U* and is formulated as $REIN_T = \{\frac{u \in U}{\mu_T(u)}\} > 0$.

Then to support the temporal references the following cases can be measured:

Case 1: **When** *X* (linguistic variable) is *A* (linguistic value of x) in *T* (temporal reference or entity)

Then the *Degree of Achievement* for *a non-continuous* situation = $\bigvee_{tk\varepsilon REIN_T} \mu_T(t_k) \wedge \mu_A(X(t_k))$

Case 2: **When** *X* (linguistic variable) is *A* (throughout *T* (temporal reference or entity))

Then the *Degree of Achievement* for *the continuous* situation = $\bigwedge_{tk\varepsilon REIN_T} (1-\mu_T(t_k)) \wedge \mu_A(X(t_k))$

Case 3: **When** *X* (linguistic variable) is *A* (linguistic value of x) in *Q* (linguistic counter) *T* (temporal reference or entity)

Then the *Degree of Achievement* for

$$\textit{Transitional}\text{ situation} = \mu_Q\left(\frac{\sum_{tk\varepsilon REIN_T} \mu_T(t_k) \wedge \mu_A(X(t_k))}{\sum_{tk\varepsilon REIN_T} \mu_T(t_k)}\right).$$

In the above formulas, operators $\bigvee$ represent *t*-pattern-minimum and $\bigwedge$ symbolizes *t*- pattern–maximum that appears respectively.

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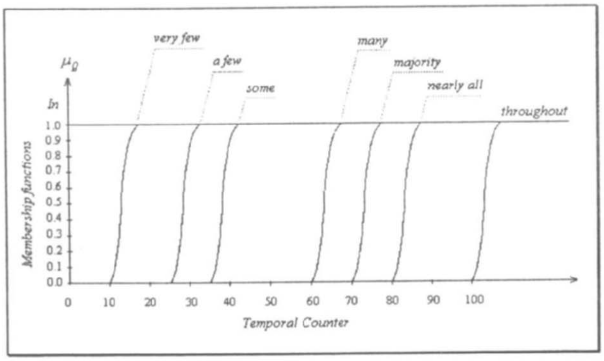

Figure 5. Definition of the membership function and its association to the temporal counter.

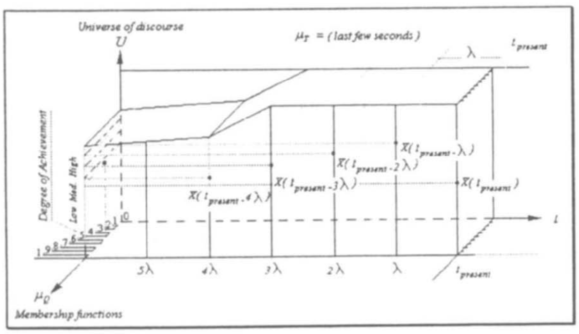

Figure 6: Estimation of degree of achievement to monitor the moving obstacle's high velocity throughout the last few seconds.

The definition of the membership function and its relation versus the temporal counter[1] is presented in Figure 5. In Figure 6 each membership degree of the variable *velocity* to the linguistic-label '*high*' for each instant *tk* is estimated. In this process '*case 2'* formula or *(continuous situation)* of type '*throughout'* would be applied and it represents the value (tpresent-4λ) as a measured temporal point with respect to degree of achievement 0.5. This estimation is also included with five membership degrees of temporal instant to support the *temporal reference or entity T*.

5. Course Evaluation of AUV Navigation

The aim of this feature is to estimate the moving-obstacle's behaviour via the AUV's control system and to enhance an AUV's capabilities when confronted with these dynamic scenarios. In this situation, to avoid collision a variable called collision-time can be calculated to identify the available time before an AUV's enters the obstacle's security-zone. The *NCG* values in two cycles can determine whether the moving object will pass first or moving object will give way to let the AUV pass through. There are three values considered for this case to be decided by AUV's control system and they are labelled '*decrease*', '*neutral'* and '*increase*'. The NCG_{trend} evaluates the moving-object behaviour within the current-state (now) and past state as well as successive differences to reduce any possible operational error.

$$NCG_{trend} = \frac{NCG(t) - NCG(t-2)}{2}$$

The outcomes will be evaluated on the bases of variables within five classes and they are as follows: '*decreases_a_lot*', '*decreases*', '*constant*', '*increases*', and '*increases_a_lot'* and ultimately they describe the trend of moving object formed as a single output [4].

6. Fuzzy Temporal Reasoning Rules

Saffiotti [8] demonstrated the advantages of fuzzy approaches to behaviour-based mobile robot control. Also Thielscher [9] described the time-based temporal reasoning process as a method to control many natural actions that may happen in a finite time interval. The combination of these two techniques can reflect the desirability of each action from the behaviour's point of view. Fuzzy behaviours can conveniently be synthesized by a set of fuzzy if-then rules together with an inference-engine (a fuzzy reasoning mechanism). Figure 7 illustrates an example describing a collision avoidance behaviour using two rules. The first rule recommends or expresses the desire to turn away from a close obstacle and the other suggests moving straightforward if the obstacle is at a safe distance. The rules are presented as follows:

Rule 1:
IF: *0 < range_to_obstacle < 50* **AND** *–90 < bearing < 90* **AND** *1.5 < AUV_speed <2*
THEN: *-60 < heading_left < 0* **OR** *0 < heading_right <60* **AND** *0.5 < AUV_speed <1*
Rule_Strength = 65

Rule 2:
IF: *0 < range_to_obstacle < 50* **AND** *–20 < bearing < 20* **AND** *0.5 < AUV_speed <1.5*
THEN: *-10 < heading_ straight < 10* **AND** *0.5 < AUV_speed <1*
Rule_Strength = 75

Using standard fuzzy inferencing, the rules are combined into a multivalued output that encodes the desirability of each action.

[1] A temporal counter represents the passage of time in the system's environment [3].

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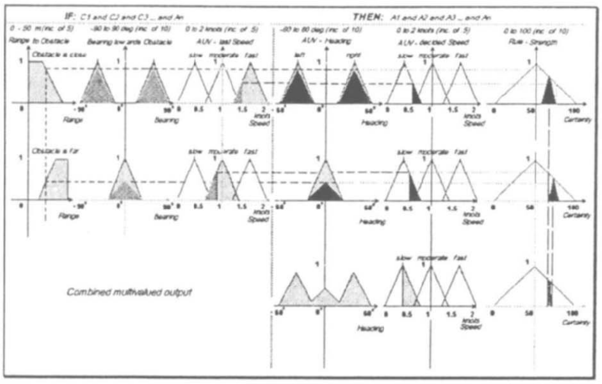

Figure 7: An example of fuzzy rule-based presenting of AUV's collision avoidance behaviour.

The following rule-types represent an example of time-based obstacle avoidance to evaluate and control the AUV's action course.

1. The example of AUV *pass_in_front*
IF: *collision_time* = short **AND** *collision_status_change* = decreased **IN** *last_seconds_collision* = 2 **AND** *NGC_trend* = constant **IN** *last_seconds_NCG* = 1

THEN: obstacle_aim is to_pass_in_front

2. The instance when obstacle *give_away* to AUV
IF: *collision_time*=medium **AND** *collision_status_change*= neutral **IN** *last_seconds_collision* =3 **AND** *NGC_trend* = increasing **IN** *last_seconds_NCG = 3*

THEN: obstacle_aim is to_give_way

3. The AUV's behaviour when the moving-obstacle is in very close vicinity to the vessel.
IF: *collision_time* = high **AND** *obstacle_trend* = give_away

THEN: *AUV_behaviour* = pass_in_front

4. The AUV's successive performance when moving-obstacle is within medium-range
time limit
IF: *AUV_behaviour*=pass_in_front **AND** *collision_time* = medium ***AND*** *AUV_ velocity* = medium **AND** *deviation* = null **AND** *incidence* = transversal

THEN: increase velocity quite a lot AND turn a little

5. The AUV is aiming to give-way to moving-obstacle as the NCG_trend is decreasing_a_lot
IF: *collision_time*=medium **AND** *collision_status_change* = neutral **IN** *last_seconds_collision* =3 **AND** *NGC_trend* = decreasing_a_lot **IN** *last_seconds_NCG =3*

THEN: *obstacle_aim* = pass_in_front

Conclusion

In this paper a fuzzy temporal control system model for the navigation and obstacle avoidance of AUVs has been described. It is assumed that obstacle is moving with no restrictions and the AUV is able to vary its velocity and its heading to choose the most suitable direction at any particular instant in time.

Fuzzy temporal reasoning explicitly handles a history of recent and past values to establish the trend and as a consequence is able to track the moving-object. This technique can be expanded as an essential tool for better obstacle avoidance tracking.

This work is contributes towards a real-time implementation of a robust AUV controller with low execution time that can handle sudden changes in trajectory and velocity of the moving object.

Acknowledgements

The author wishes to acknowledge Dr J. Riley for his valuable comments on this work.

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