

Obstacle Avoidance While Bottom Following for the REMUS Autonomous Underwater Vehicle

Anthony J. Healey
Distinguished Professor,
Dept. of Mechanical and Astronautical Engineering
Center for Autonomous Underwater Research
Naval Postgraduate School
Monterey, CA

Abstract- Future Naval operations necessitate the incorporation of autonomous underwater vehicles into a collaborative network. In future complex missions, a forward look capability will also be required to map and avoid obstacles such as sunken ships and reefs. Following previous work on steering control, this work examines collision avoidance behaviors in bottom following using a hypothetical forward-looking sonar for the autonomous underwater vehicle REMUS. Hydrodynamic coefficients are used to develop diving equations that model REMUS behaviors. A two-dimensional forward-looking sonar model with a 20° vertical scan and a 40 meter radial range is modeled for obstacle detection. Sonar mappings from geographic range-bearing coordinates are developed for implementation in MATLAB simulations. REMUS is a highly responsive vehicle and care has taken to balance pitch and heave response to keep the obstacle to be avoided in sight during the response behavior.

1. INTRODUCTION

The Naval Postgraduate School Center for Autonomous Underwater Vehicle (AUV) Research has been building, operating and researching underwater vehicles since 1987. The Center currently operates two small vehicles, the ARIES and the REMUS. Coordination of underwater vehicles for collaborative network applications requires increased operational capabilities in these vehicles. One capability is to move around and avoid locally detected obstacles.

While most underwater vehicles can solve the problems of localization and maneuvering to some degree of accuracy, many do not possess the capability to avoid obstacles that arise in their programmed path, specifically in unmapped areas near the littorals where mine-like objects or other potential hazards are prevalent. Land robots and crawling vehicles are capable of obstacle and collision avoidance using forward look sensors – even video cameras – and a “stop-back-turn” principle while most swimming vehicles cannot stop and hover [2]. In some recent exercises, particularly in areas where coral outcrops and reefs occur, it is becoming clear that some form of look ahead capability is desirable through which

altitude above bottom can be increased rapidly to avoid undesirable grounding. As opposed to previous work in [12,13], which dealt with steering avoidance, this paper will present a study of a proposed obstacle avoidance capability incorporated into the bottom following control design of the REMUS AUV. This is a more difficulty problem since vehicle pitch response is directly coupled with altitude response and obstacle avoidance sonars located on the vehicle are not image stabilized.

2. VEHICLE DESCRIPTION

The REMUS AUV is designed to perform hydrographic reconnaissance in the Very Shallow Water (VSW) zone from 40 to 100 feet. As seen in Figure 1, it is 62 inches long and 7.5 inches in diameter. It weighs 80 pounds in air and can operate in depths up to 328 feet, but typically operates between 10 and 66 feet. REMUS is capable of speeds up to 5.6 knots. Its four fins, two horizontal and two vertical on either side and just forward of the propeller, allow pitch and yaw motions for maneuvering.



Figure 1. REMUS [1], Taken from (<http://www.whoi.edu/science/AOPE/dept/OSL/remus.html>)

REMUS can operate in a maximum sea state of 2 in very shallow water for up to 20 hours at 3 knots or 9 hours at 5 knots.

3. OBSTACLE AVOIDANCE METHODS

The obstacle avoidance problem has been under research since the advent of underwater vehicle technology. Several approaches have been used to solve this problem for underwater robots. One approach for horizontal plane avoidance is that of wall-following or obstacle contour following [3] in which obstacle boundaries are utilized to

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE 2004		2. REPORT TYPE		3. DATES COVERED -	
4. TITLE AND SUBTITLE Obstacle Avoidance While Bottom Following for the REMUS Autonomous Underwater Vehicle				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School, Center for AUV Research, Monterey, CA, 93943-5000				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT Future Naval operations necessitate the incorporation of autonomous underwater vehicles into a collaborative network. In future complex missions, a forward look capability will also be required to map and avoid obstacles such as sunken ships and reefs. Following previous work on steering control, this work examines collision avoidance behaviors in bottom following using a hypothetical forward-looking sonar for the autonomous underwater vehicle REMUS. Hydrodynamic coefficients are used to develop diving equations that model REMUS behaviors. A two-dimensional forward-looking sonar model with a 20° vertical scan and a 40 meter radial range is modeled for obstacle detection. Sonar mappings from geographic range-bearing coordinates are developed for implementation in MATLAB simulations. REMUS is a highly responsive vehicle and care has taken to balance pitch and heave response to keep the obstacle to be avoided in sight during the response behavior.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

determine a close proximity path around the obstacle. The vehicle follows this path until reaching a position on the obstacle boundary where it can break away and return to course. Experimental results using Kamon's wall following algorithm show that this technique produces minimal path distances around obstacles.

Moitie and Suebe [4] use an obstacle avoidance system consisting of four subsystems: a digital terrain manager used to estimate the sea floor altitude, a global planner used to generate waypoints to guide the AUV to a given target, a reflex planner to check the trajectories of the global planner, and an obstacle avoidance sonar for environmental mapping. All of these subsystems are used to determine a viable area of the state space from which a viable (or escape) trajectory can be used. While all this may be needed at some point, this paper looks at the simple problem of avoiding an obstacle reflexively.

4. PATH PLANNING METHODS

Path planning is a tool used for devising collision free trajectories for robot vehicles in a structured world where mission specifications and environmental models are known. Path planning commonly occurs prior to mission execution for the existing environmental constraints. Environmental data allows path planners to design paths around known physical obstacles such as trees and pillars or hazardous environments such as rough terrain or high turbulence areas. Path planning differs from obstacle avoidance in that obstacle avoidance is performed in a non-structured world that is initially assumed to be free of obstructions. However, due to the unpredictable nature of an underwater environment, path planning alone is insufficient to allow for safe vehicle navigation. Obstacle avoidance is a necessary tool for in situ response to unknown environmental conditions and hazards.

Several path planning techniques have been developed for both land based and subsurface robots. One that has received the most attention in recent years is the potential field approach in which an artificial potential field is defined to reflect the structure of the space around the vehicle [5,6]. A repulsive field pushes the vehicle away from an indicated obstacle while an attractive field pulls a vehicle toward a goal. The path to the goal is minimized through the space. It is configured to have a global minimum at the desired terminal state of the vehicle. The main drawback to this approach lies in the fact that local minima may entrap the robot trajectory.

A second approach considered by Latrobe [7] is that of cell decomposition in which the workspace is divided into non-overlapping cells represented by nodes. The space is then searched from starting point to the end node using a graph search algorithm to determine the path of free cells.

Further progress has been made to incorporate path planning and obstacle avoidance in a single program.

Stentz [8] develops a path planning algorithm known as D* for partially known environments in which a sensor is also available to supplement a map of the environment. It combines what is known of the global environment prior to mission with acquired local environmental data during missions. The D* technique uses a cost based approach in which a directed graph of arcs is generated prior to mission with each arc having an associated cost. The robot's sensor can then measure arc costs in its local vicinity and generate known and estimated arc values that compromise a map.

Lane [9] uses an approach using dynamic programming. This method considers a modular system that handles different needs of the environment while the robot is in motion. These modules consist of a segmentation module that identifies regions of the sonar image containing obstacles, a feature extraction module, a tracking module that provides a dynamic model of the obstacle, a workspace representation that builds a symbolic representation of the vehicle's surroundings, and finally a path planning module that represents each obstacle as a constraint. The maneuvering solution is then based on minimizing the path length to the goal.

While several of the path planning techniques described above are designed for land robots vice underwater robots and involve much simpler dynamic motions, the challenge of underwater robot technology is in the difficulty of ceasing or changing a forward motion given a short notice sonar return. There is not enough time for a planning system to work when rapid increases in altitude above bottom are needed.

5. CONTROL AND DYNAMICS

The REMUS vertical plane model uses autopilot controls for maneuvering based on a dynamic model using hydrodynamic coefficients and mass parameters appropriately modified from [11].

From [11], which has attempted to provide data for REMUS, certain modifications to the hydrodynamic coefficients had to be made so that realistic response rates could be accurately simulated. The stability derivatives are calculated from hydrodynamic added mass effects, lift and cross flow drag effects. The individual component effects are summed, but often provide canceling evaluations giving the net result as the difference between large numbers. The net values are therefore highly uncertain. However, experimental responses of the REMUS vehicle have been obtained from several in water exercises and validated with a modified set of coefficients to produce a realistic set of values for horizontal and vertical plane maneuvering. In particular, the turn and rise rates established by the vehicle have to be correctly represented in order for realistic obstacle avoidance results to be obtained.

In all, with the modifications to the values in [11], the following set of coefficients were determined to be valid.

Table 1 REMUS Hydrodynamic Coefficients

Z_{w_r}	$-6.66 e^1 \text{ kg/s}$
$Z_{\dot{w}_r}$	$-3.55 e^1 \text{ kg}$
Z_q	-9.67 kg m/s
$Z_{\dot{q}}$	-1.93 kg m
M_{w_r}	$+3.07 e^1 \text{ kg m/s}$
$M_{\dot{w}_r}$	-1.93 kg m
M_d	-34.6 Nm/rad
Z_d	-50.6 N/rad
M_q	$-6.87 \text{ kg m}^2/\text{s}$
$M_{\dot{q}}$	-4.88 kg m^2

$$m = 30.48 \text{ kg} \quad I_{zz} = 3.45 \text{ kg m}^2/\text{rad}, \quad B = 306 \text{ N}, \\ W = 299 \text{ N}, \quad z_g = 1.96 e^{-2} \text{ m}.$$

Table of Hydrodynamic and Inertial Parameters for REMUS Steering Dynamics (C Churan, MS Thesis, [14])
Notation is Standard from [10].

These parameters are used in a linearized diving response model, [10],

$$\begin{bmatrix} (m - Z_{\dot{w}_r}) & -Z_q & 0 & 0 \\ -M_{\dot{w}_r} & I_y - M_{\dot{q}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{w}_r \\ \dot{q} \\ Z \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} Z_{w_r} & (Z_q + mU) & 0 & 0 \\ M_{w_r} & M_q & -z_g W & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & -U & 0 \end{bmatrix} \begin{bmatrix} w_r \\ q \\ \dot{q} \\ Z \end{bmatrix} + \begin{bmatrix} Z_d \\ M_d \\ 0 \\ 0 \end{bmatrix} \mathbf{d}(t) = \begin{bmatrix} (W - B) \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

6. ALTITUDE CONTROL

Depth and altitude control may be accomplished using many methods. Here, a sliding mode control is used in which the sliding surface is a linear combination of state errors. For depth control, the surface is described by,

$$\mathbf{s}(t) = s_1 q(t) + s_0 w_r(t) + s_2 (\mathbf{q}_{com} - \mathbf{q}(t)) + s_3 (Z_{com} - Z(t))$$

while for altitude control, it may be noted that the depth rate and altitude rate are simply of opposite sign, everything else being equal, so it follows that the surface may be modified to

$$\mathbf{s}(t) = s_1 q(t) + s_0 w_r(t) + s_2 (\mathbf{q}_{com} - \mathbf{q}(t)) - s_3 (h_{com} - h(t))$$

The control law for the autopilot then becomes,

$$\mathbf{d}(t) = -k * \mathbf{x}(t) - ? * \tanh((s(t)/f))$$

where the linear feedback gain is found by pole placement and the switching term's parameters \mathbf{h} , and \mathbf{f} , are tunable.

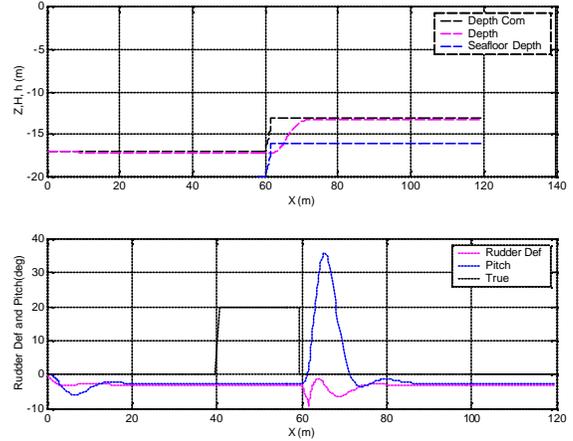


Figure 2. Vehicle Vertical Response (Z) Comes Too Late with Sudden 4 m. Jump in Seafloor (H). Note Pitch Response Peaks at over 30 Degrees)

The results shown in Figure 2, indicate advanced notice is required in order to overcome a large 4 m. rise in the seafloor. While a forward looking sonar could see the obstacle within 20m. (indicated by the True response), if no action is taken, a simple collision occurs. To achieve the forward look benefit, early response may be obtained. A reflexive response to objects seen within 20m of the vehicle is simulated using the concept of a range and bearing evaluated threat estimation using weighting functions based on range and bearing computations from the sonar returns.

7. SONAR MODEL

To begin with, we have noted that the forward look sonar image must be stabilized for pitch of the vehicle otherwise unstable responses will result called pitch banging in which the bottom is alternately seen by the sonar, not seen, then seen again causing bang-bang behavior in control. With a pitch stabilized image, it is not always guaranteed that stable heave response can be achieved either. Image processing non-linearities make the analysis difficult but amenable to simulation.

Figure 3 shows the sonar model based on ray tracing in which each range bin on each sonar beam bearing is thresholded to indicate a return presence / absence.

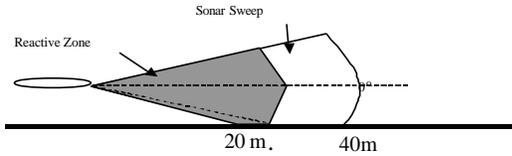


Figure 3 Sonar Model Vertical Plane

The simulation breaks the seabottom into a finite number of nodes, each of which can be computed a range and bearing in the forward look sonar space. If $rs(i)$ is the sonar range to the i th seabottom element, and $bs(i)$ is its corresponding bearing,

$$rs(i,t) = \text{sqrt}((Xb(i) - X(t))^2 + (H(i) - Z(t))^2),$$

$$bs(i,t) = \text{asin}((H(i) - Z(t))/rs(i,t)); i=1 \dots n, Xb(i) > X(t)$$

Only elements in front of the vehicle are counted. The threat level is computed as a weighted sum of each range bearing pixel that has a countable return.

$$Threat(t) = \sum_{i=1}^n W_r(rs(i,t))W_b(bs(i,t));$$

The translation of threat into added altitude command is additive to the nominal altitude of 3 meters. A is a sonar gain parameter tied to the design of the weighting functions W_r and W_b .

$$h_{com}(t) = 3 + a * Threat(t);$$

The range and bearing weight functions used are shown below which have to return to zero for range and bearings outside the reaction zone, but increase as they both tend to zero. The bearing weight must be equal for both positive and negative bearings.

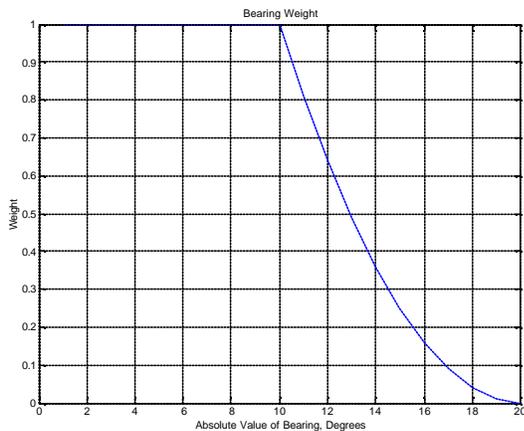


Figure 4. Bearing Weight Function

In simulation, large angle responses for the vehicle's progression over ground are used so that the equations of dynamics including weight – buoyancy mismatch and currents are;

$$\begin{bmatrix} m - Z_{w_r} & -Z_q & 0 \\ -M_{w_r} & I_y - M_q & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{w}_r \\ \dot{q} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} Z_{w_r} & (Z_q + mU) & 0 \\ M_{w_r} & M_q & -z_G W \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} w_r \\ q \\ q \end{bmatrix} + \begin{bmatrix} Z_d \\ M_d \\ 0 \end{bmatrix} \mathbf{d}(t) + \begin{bmatrix} (W - B) \\ 0 \\ 0 \end{bmatrix}$$

$$\dot{X} = U \cos(q) + w_r \sin(q) + U_{cx}$$

$$\dot{Z} = -U \sin(q) + w_r \cos(q) + U_{cz}$$

The seabottom is modeled by $H(X(t))$ above a known datum, as interpreted by discrete nodes $H(i)$.

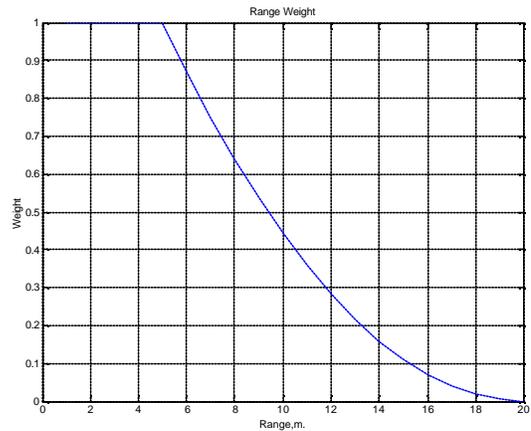


Figure 5. Range Weighting Function Used in Threat Assessment.

Using a Threat gain of 3.0, the following responses in Figure 6 are found. The Threat is well established before the sudden rise in seabottom is reached so there is a chance for the vehicle to rise in time to avoid collision. Once the sea rise has been reached, the avoidance response is not needed and as the Threat goes away (shown in Figure 7), normal altitude following occurs.

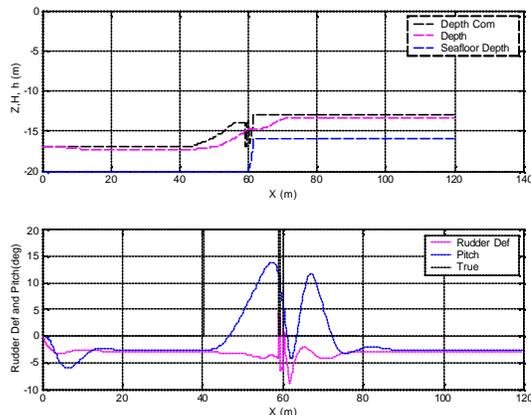


Figure 6. Avoidance Response with $a = 3$ for a 4.m. Sudden Rise in Seabottom.

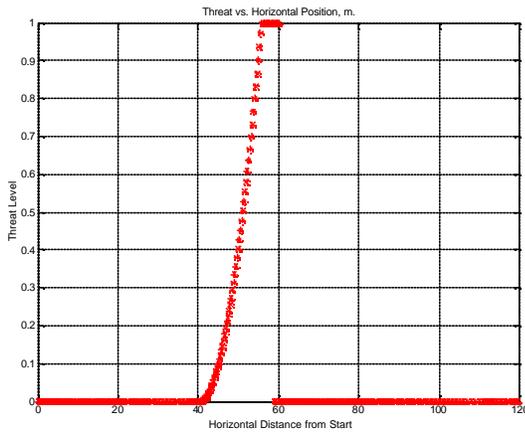


Figure 7. Threat Response, $a = 3$ for a 4.m. Sudden Rise in Seabottom. Threat Goes Away After Rise is Negotiated.

As an example of the sonar returns during this process, each nearest return on every bearing is noted for each time during the simulation. As time proceeds, the nearest return and the bearing beam in which it is seen are plotted as in Figure 8. The result of the avoidance response is that the range is reducing with time because of the vehicle's forward motion, but the bearing beam in which the first return is seen increases due to vehicle rise. It also increases with vehicle pitch, but this has no impact of the algorithm since the image is pitch stabilized.

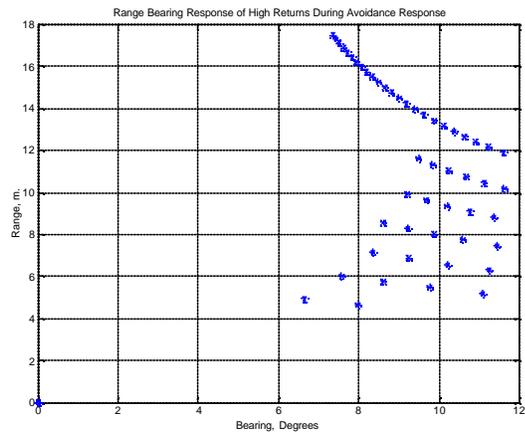


Figure 8, Plot Of Significant Return From Sonar In Range Bearing Space, $rs(i,t)$ vs $bs(i,t)$ For t During Time Period Of The Vehicle Rise Response. As t Increases, Range Reduces And Bearing Increases Due To Vehicle Rise.

There are values of threat gain, a , for which the altitude following control becomes unstable. These should be avoided. Probably in water experimentation will finalize the values used, but simulation can at least expose the anticipated problem. For example with $a = 7$, we note the following response.

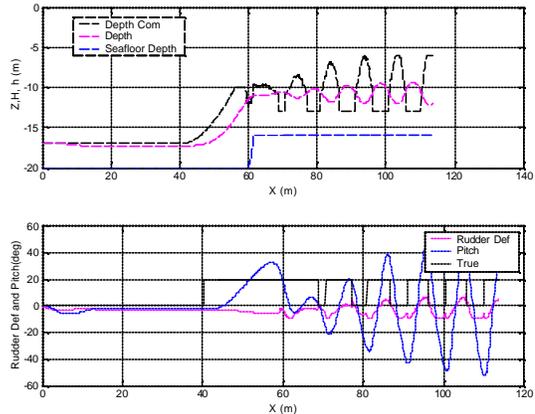


Figure 9 Unstable Vertical Plane Response with High Threat Gain, $a = 7$.

8. CONCLUSIONS

The problem of autonomous underwater vehicle obstacle avoidance has been examined. The sudden rise in Sea-Bottom constitutes an obstacle into which the vehicle would otherwise collide. The collision response avoidance is enables using a small forward looking sonar with which high returns are thresholded and observed in the sonar range and bearing space. A threat response has been formulated using range and bearing weighting functions and an added threat response forcing an early rise in vehicle altitude. The image must be pitch stabilized, and even so, too high a threat gain leads to vehicle bang-bang instability.

9. ACKNOWLEDGEMENT

The authors wish to thank the Office of Naval Research and Drs. Tom Swean and Charles Loeffler for funding this work under Contract # N0001402AF00002.

10 REFERENCES

[1] REMUS <http://www.whoi.edu/science/AOPE/dept/OSL/remus.html>, Jan 2003
 [2] Healey, A. J., Kim, J., "Control And Random Searching With Multiple Robots", *Proceedings IEEE CDC Conference 2000, Sydney Australia*, Nov. 2000 paper No INV-2303.

<http://web.nps.navy.mil/~me/healey/papers/Random2000.PDF>

[3] Kamon, I. And Rivlin, E., "Sensory-based motion planning with global proofs", *IEEE Transaction on Robotics and Automation*, Vol 13, no. 6, 1997.

[4] Moitie, R. and Seube, N., "Guidance Algorithms for UUVs Obstacle Avoidance Systems", OCEANS 2000, Brest, France.

[5] Thorpe, C. F., "Path Relaxation: Path Planning for a Mobile Robot", *Carnegie-Mellon University Robotics Institute, Mobile Robots Laboratory, Autonomous Mobile Robots, Annual Report*, Sep 1986, pp. 12-19.

[6] Krogh, B. H. and Thorpe, C. E., "Integrated Path Planning and Dynamic Steering Control for Autonomous Vehicles", *Proceedings of the 1986 IEEE International Conference on Robotics and Automation*, Apr, 1986, pp. 1664-1669.

[7] Latrobe, J. C., "Robot Motion Planning", Kluwer Academic Publishers, Norwell, MA, 1991.

[8] Stentz, Anthony, "Optimal and Efficient Path Planning for Partially-Known Environments", *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '94)*, Vol. 4, May, 1994, pp. 3310 - 3317.

[9] Lane, David M., Petillot, Yvan, and Ruiz, Ioseba Tena, "Underwater Vehicle Obstacle Avoidance and Path Planning Using a Multi-Beam Forward Looking Sonar," *IEEE Journal of Oceanic Engineering*, Vol. 26, n. 1 Apr 2001.

[10] Healey, A. J., Marco, D. B., "Command, Control and Navigation: Experimental Results with the NPS ARIES AUV" *IEEE Journal of Oceanic Engineering, Special Issue on Autonomous Ocean Sampling Networks*, vol.26, n.4, Oct.2001, pp.466-477.
http://web.nps.navy.mil/~me/healey/papers/IEEE_Marco_Healey.pdf

[11] Prestero, Timothy, "Verification of a Six-Degree of Freedom Simulation Model for the REMUS Autonomous Underwater Vehicle," M.S. Thesis Massachusetts Institute of Technology, Sep 2001.

[12] Fodrea, L. R., "Obstacle Avoidance Control for the REMUS Autonomous Underwater Vehicle", MSME Thesis, Naval Postgraduate School, Dec. 2001
http://www.cs.nps.navy.mil/research/auv/theses/fodrea/Lynn_Fodrea/

[13] Fodrea, L.,R., Healey, A. J., "Obstacle Avoidance Considerations for the REMUS Autonomous Underwater Vehicle", Proceedings of the ASME OMAE Conference, 2003, Cancun, Mexico, June 2003

[14] Churan, C "Obstacle Avoidance Control For The REMUS Autonomous Underwater Vehicle" MSME Thesis Naval Postgraduate School, Monterey, Ca. Sept. 2003