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A Review of Guidance Laws Applicable to Unmanned Underwater Vehicles

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The main problem in bringing autonomy to any vehicle lies in the design of a suitable guidance law. For truly autonomous operation, the vehicle needs to have a reliable Navigation, Guidance and Control (NGC) system of which the guidance system is the key element that generates suitable trajectories to be followed. In this review paper, various guidance laws found in the literature and their relevance to autonomous underwater vehicles (AUVs) are discussed. Since existing guidance laws for underwater vehicles have emulated from tactical airborne missile systems, a number of approaches for the missile guidance systems are considered. Finally, potential guidance strategies for AUVs are proposed.

KEY WORDS

1. Guidance. 2. Command & Control. 3. Underwater Vehicles.

1. INTRODUCTION. In recent years, control systems have assumed an increasingly important role in the development and advancement of modern civilisation and technology. In particular, the burgeoning in the field of navigation, guidance and control (NGC) systems, spurred on mainly by the challenges of unsolved aerospace problems, contributed significantly to progress achieved in the development of modern systems and control theories. The success of the Soviet Union's satellite technology in the 1950s stimulated the United States to develop their own aerospace technology thus creating between the two of them new concepts in the field of control system design. The Apollo programme in the 1960s is a classical example of the translation of various NGC concepts into working systems. The early success of NGC systems soon led to advances in such diverse areas as industrial manufacturing, energy management (Lin, 1991) and underwater vehicles. Although applications of NGC in these areas have shown a profound impact in control theory in general, the majority of research and development in NGC continues to find its main application in the aerospace industry.

Navigation, guidance and control of airborne systems have been reported extensively in the literature (Cloutier *et al*., 1989; Lin and Su, 2000; Lin, 1991); however, little attention has been paid to the issue of guidance of autonomous underwater vehicles (AUVs). In light of this, the impetus behind this paper is to review a number of approaches that have been adopted for the guidance of air and sea vehicles with an emphasis on AUVs. Furthermore, it is the intention to explore ways and means of employing successful guidance strategies of air-based systems to underwater vehicles.

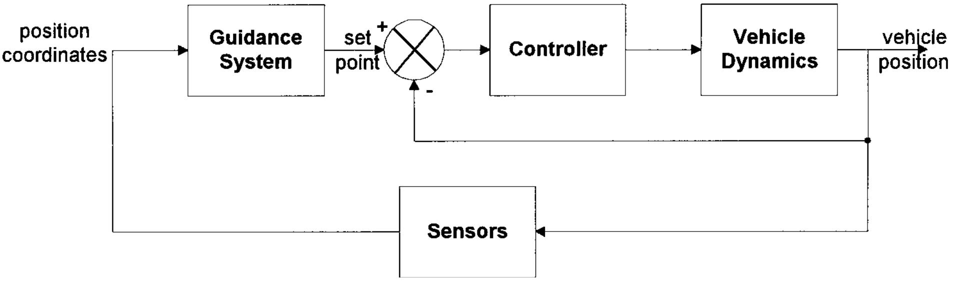

Figure 1. Guidance and Control for a Vehicle.

This would also entail certain modifications to suit the underwater mission requirement.

The paper is organised as follows. Section 2 explores the guidance problem in general. Guidance laws for the airborne missile systems are presented in Section 3, while Section 4 discusses AUVs and the guidance laws associated with them. Some modified guidance laws for underwater cable tracking problem are proposed in Section 5. Finally, concluding remarks are given in Section 6.

2. GUIDANCE.

All autonomous vehicles must have on-board NGC systems, which should work in accord with each other for proper operation. Imperfections in one system degrade the efficiency of the others. The navigation system provides information related to the target, which is processed by the guidance system to generate reference headings. The control system is responsible for keeping the vehicle on course as specified by the guidance processor. In remotely operated systems, guidance commands are sent from a ground station, while autonomous vehicles have an on-board guidance processor. In this respect, a guidance system plays the vital role in bringing autonomy to the system. Some definitions and a brief description of the elements of a guidance system are presented as follows.

> Guidance is the action of determining the course, attitude and speed of the vehicle, relative to some reference frame, to be followed by the vehicle (Fossen, 1994).

From the perspective of a control system:

> guidance is a matter of finding the appropriate compensation network to place in series with the plant in order to accomplish an intercept (Lin, 1991).

The guidance system decides the best trajectory (physical action) to be followed by a vehicle based on target location and vehicle capability.

The primary function of the elements that constitute a guidance system are sensing, information processing and correction. A rudimentary guidance and control system for a vehicle is shown in Figure 1. As shown, the guidance system receives inputs from all the sensors on-board and generates the relevant signals or set points for the control system. Guidance issues are mainly determined by the nature and location of the target and the environmental conditions. The nature of the target corresponds to the condition as to whether or not the target is stationary, moving, or manoeuvring. The target location is also imperative as it determines the heading to be followed by the vehicle; however, the accuracy of the system depends on the environmental conditions. The guidance problem is also related closely to the bandwidth of the system. It is often assumed while formulating the problem that the controller has a sufficiently large bandwidth to track the commands from the guidance subsystem (Sutton *et al.*, 2000); however, in practice, true vehicle capability can only be measured in the presence of constraints such as system dynamics and actuator limitations.

The definitions and elements of a guidance loop discussed above are quite generic and refer to all guidance mechanisms. Although widely employed in the aerospace and land vehicles, they are equally valid for underwater vehicles.

3. MISSILE GUIDANCE.

The guidance technology of missiles is a mature field with an abundance of guidance laws already implemented in real systems. Many different guidance laws have been employed exploiting various design concepts over the years. Currently, the popular terminal guidance laws involve line-of-sight (LOS) guidance, LOS rate guidance, command-to-line-of-sight (CLOS) guidance, proportional navigation (PNG) (Locke, 1955), augmented proportional navigation guidance (APNG) (Zarchan, 1994) and optimal guidance laws based on linear quadratic regulator theory (Bryson and Ho, 1969; Nazaroff, 1976), linear quadratic Gaussian theory (Potter, 1964) or linear quadratic exponential Gaussian theory (Speyer *et al.*, 1982).

Among the current techniques, guidance commands proportional to the LOS angle rate are generally used by most high-speed missiles today to correct the missile course in the guidance loop. Recently, many advance strategies have been implemented to generate different guidance laws. Rajasekhar *et al.* (2000) uses fuzzy logic to implement PNG law. The fuzzy law generates acceleration commands for the missile using closing velocity and LOS rate as input variables. The input data is fuzzified and their degree of membership to the output fuzzy sets is evaluated, which is then defuzzified to get the acceleration command. A fuzzy-based guidance law for missiles has also been proposed by Creaser *et al.* (1998) using an evolutionary computing-based approach. The proposed law uses a genetic algorithm to generate a set of rules for the missile guidance law. Menon *et al.* (1998) uses fuzzy logic weightings to blend three well-known guidance laws to obtain enhanced homing performance. The composite law evaluates the weights on each of the guidance laws to obtain a blended guidance command for the missile. Yang and Chen (2001) have implemented an H∞ based guidance law. Unlike other guidance laws, it does not require the information of target acceleration, while ensuring acceptable interceptive performance for arbitrary target with finite acceleration.

3.1. *LOS Guidance.*

LOS is the most widely used guidance strategy today. In fact, almost all guidance laws in use today have some form of LOS guidance because of its simplicity and ease of implementation. The LOS guidance employs the line of sight angle λ between the vehicle and the target which can easily be evaluated using Equation 1.

$$\lambda = \tan^{-1}\left(\frac{y_2 - y_1}{x_2 - x_1}\right), \tag{1}$$

where: (x_1, y_1), (x_2, y_2) are the missile and target position coordinates respectively.

The objective of the guidance system is to constrain the missile to lie as nearly as possible on the LOS. Since the missile ideally always lies on the line joining it to the

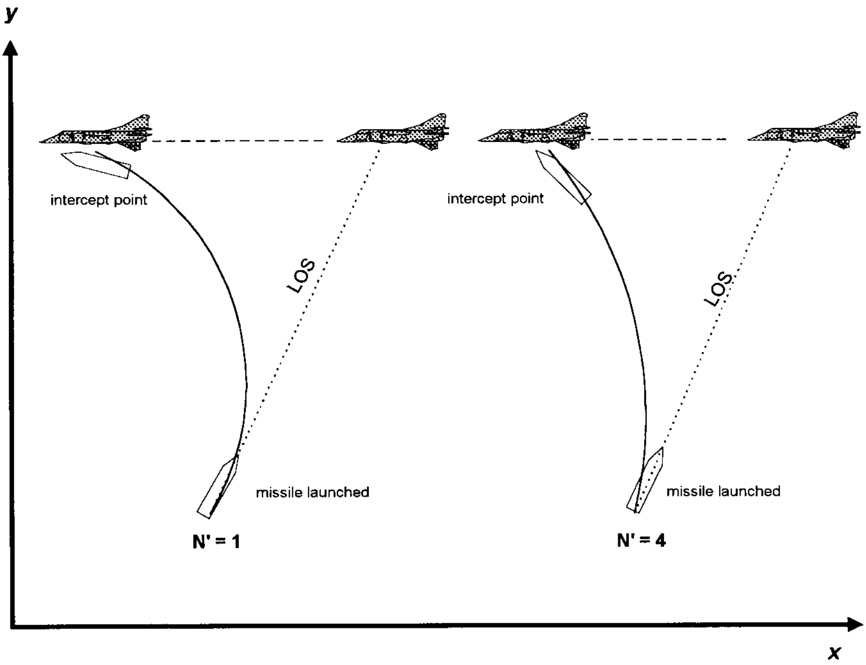

Figure 2. Proportional Navigation Guidance for a missile system.

target, the flight path will be a curved one. LOS guidance does not work well with manoeuvring targets. Also, the interception time is high, which can be abridged using different strategies as discussed in the following sections.

3.2. *Proportional Navigation Guidance (PNG) and its variants.* The Lark missile that was tested in 1950 was the first missile to use PNG. Since then, the PNG law has been used in virtually all of the world's tactical radar, infra-red and TV-guided missiles (Rajasekhar and Sreenatha, 2000). It is the most common and effective technique in case of non-manoeuvring targets that seeks to nullify the angular velocity of the LOS angle. The missile heading rate is made proportional to the LOS rate from the missile to the target. The rotation of the LOS is measured by a sensor (either onboard or from a ground station), which causes commands to be generated to turn the missile in the direction of the target. Mathematically the PNG law can be stated as:

$$\eta_c = N' V_c \dot{\lambda}, \tag{2}$$

where: η_c is the acceleration command, N' is the navigation ratio, V_c is the closing velocity and $\dot{\lambda}$ is the LOS angle rate. The advantage of using PNG over LOS guidance is that the interception time can be greatly reduced by adjusting the navigation constant as shown in Figure 2 for the case of $N'=1$ and $N'=4$. In the latter case, the missile steering commands are four times as great. As a result the missile veers off much more to the left resulting in engagement.

PNG, like LOS guidance, does not work well in the case of manoeuvring targets. However, the interception time is reduced. Augmented PNG (APNG) is a modified form of PNG to deal with target manoeuvres. Other forms of PNG are velocity compensated PNG (VCPNG), pursuit plus PNG, and dynamic lead guidance (Lin, 1991).

3.3. *Optimal Guidance Law.* Recently, great interest has been shown in using optimal control theory in the missile guidance problem. Two important mission parameters, missile target engagement time and the energy needed, can be reduced by utilising optimal control. Tsao and Lin (2000) proposed an optimal guidance law for short-range homing missiles to intercept highly manoeuvrable targets. The guidance problem that needs to be solved for the interception is to find the optimal missile trajectory such that the total time for the interception is minimised. The performance index used in the proposed optimal law is:

$$J = t_f = \int_0^{t_f} dt, \tag{3}$$

where: t_f is the interception time.

The proposed guidance law achieves the best performance in terms of the miss distance and interception time in comparison to the true proportional navigation guidance (TPNG) and APNG. However, a major disadvantage of this law is that the target's future trajectory must be known in advance, which is impossible to evaluate in a realistic environment (Tsao and Lin, 2000). A comprehensive review of optimal guidance laws is presented in (Lin, 1991).

4. AUTONOMOUS UNDERWATER VEHICLES.

AUVs are no longer engineering curiosities. They have been under development for over three decades and, in the last few years, there have been significant advances towards their use in operational missions (Millard and Griffiths, 1998). Although remotely operated vehicles (ROVs) play an important role in the offshore industry, their operational effectiveness is limited by the tethered cable and the reliance and cost of some kind of support platform. Given these limitations, developments in advance control engineering theory and the computation hardware for analysis, design and implementation, interest in the viability of employing AUVs in operational missions has been revived. The use of AUVs is increasingly being considered for applications such as cable/pipeline tracking, mines clearing operations, deep sea exploration, feature tracking etc.

The potential usage of AUVs is restricted by two main factors. The first is the limitation of battery power, which limits the use of AUVs for long duration missions. Most current vehicles use car batteries that need to be recharged every few hours, and this makes them unsuitable for long duration missions. The second limiting factor is associated with the current generation of onboard NGC systems. The vehicle must have a reliable and well-integrated NGC system of which guidance is the key element.

4.1. *Guidance Laws for AUVs.* The classical autopilots for AUVs are designed by controlling the heading or course angle in the control loop. By including an additional loop in the control system with position feedback from the sensors, an AUV guidance system can be designed. The guidance system generates reference trajectories to be followed by the vehicle utilising the data gathered by the navigation system. The following section presents some important guidance laws found in the literature.

4.1.1. *Waypoint Guidance by LOS.* Waypoint Guidance is the most widely used scheme in the field of AUVs. In the key paper by Healey and Lienard (1993), guidance is achieved between two points $[x_d(t_o), y_d(t_o)]$ and $[x_d(t_f), y_d(t_f)]$ by splitting the path between them into a number of waypoints $[x_d(k), y_d(k)]$ for $k = 1, 2, \ldots, N$ as shown in

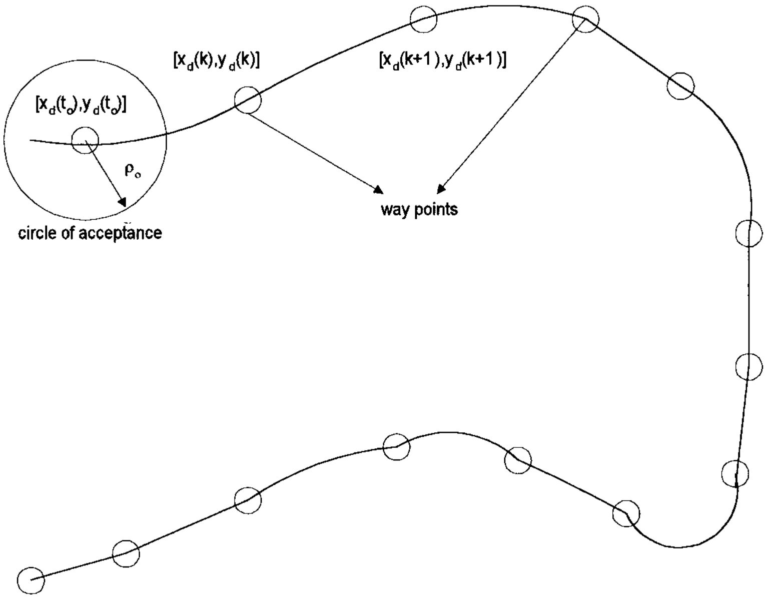

Figure 3. Way Point Guidance by LOS.

Figure 3. It is assumed that the vehicle is moving forward with speed U, then the LOS in terms of desired heading angle λ can be defined as:

$$\lambda = \tan^{-1}\left[\frac{y_d(k)-y(t)}{x_d(k)-x(t)}\right], \tag{4}$$

where: $[x(t),\ y(t)]$ is the current location of the vehicle. Care must be exercised to ensure that the heading angle λ is in the proper quadrant. Determining when the vehicle reaches the vicinity of a waypoint is achieved by checking if the AUV lies within a circle of acceptance with radius ρ_o around the waypoint $[x_d(k),\ y_d(k)]$. If the vehicle's current location $[x(t),\ y(t)]$ satisfies:

$$\rho^2 = [x_d(k)-x(t)]^2 + [y_d(k)-y(t)]^2 \leqslant \rho_o^2, \tag{5}$$

the next waypoint $[x_d(k+1),\ y_d(k+1)]$ is selected. Typically, the circle of acceptance could be taken as two times the length of the vehicle (Healey and Lienard, 1998).

If on the other hand, $d\rho/dt$ goes from negative to positive without the above condition being met, then the waypoint has not been reached. At this point, the guidance law must decide whether to keep the same destination waypoint and direct the vehicle to the circle or choose the next depending on mission planning decisions. A major disadvantage of waypoint guidance is the undesirable consumption of control energy due to possible overshoots during the change of trajectory. So, selection of the reference trajectory for tracking is important to reduce the overshoot path width and thus to decrease the control energy consumption. Yeo *et al.* (1999) employ turning simulation to determine modified waypoints to avoid overshoot. Aguiar *et al.* (1998) and others (Aguiar and Pascoal, 1997) proposed a modification in waypoint guidance to deal with the presence of ocean currents. A current compensation for the heading autopilot has been developed which aligns the total vehicle velocity direction with the heading command.

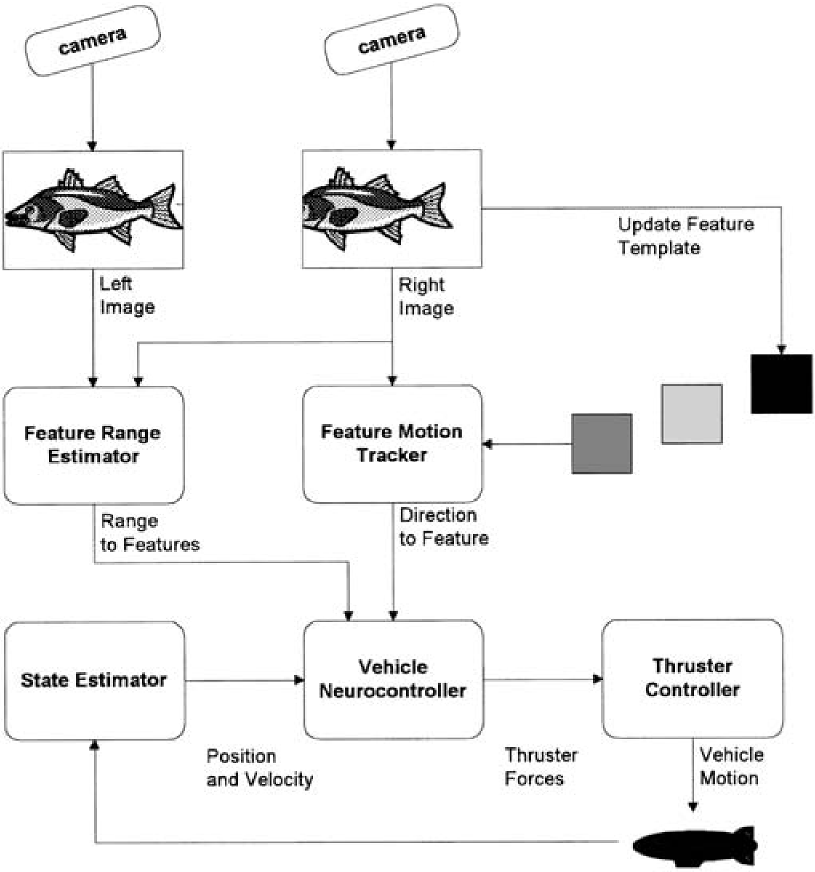

Figure 4. Vision-Based Guidance System for the Kambara AUV.

4.1.2. *Vision-Based Guidance.* The vision-based guidance technique has been inspired from the work of ROV operators, which utilise or rely on the visual information to perform tasks thus making a strong argument that visual imagery could be used to guide an AUV. Vision-based guidance has been mainly employed for cable tracking and docking problems (Gaskett *et al.*, 1999; Balasuriya and Ura, 1998; Briest *et al.*, 1997; Rock *et al.*, 1992). Briest *et al.* (1997) suggest an optical terminal guidance scheme for the docking of an AUV using a beacon. The beacon could be a light-emitting device, which can be identified using photo detectors onboard the AUV. This scheme is analogous to a heat-seeking air-to-air missile when locked on to its target. The disadvantage of using a beacon is that in shallow waters, especially during the daylight, the photo detectors can lock on to sunlight. The remedy could be to adjust the frequency of the light emitted by the beacon.

Gaskett *et al.* (1999) proposed vision-based guidance for an AUV named *Kambara* using two cameras. The authors demonstrated that guidance could be achieved by a feature tracker algorithm that requires two correlation operations within the feature tracker as shown in Figure 4. The feature motion tracker follows each feature between previous and current images from a single camera while the feature range estimator

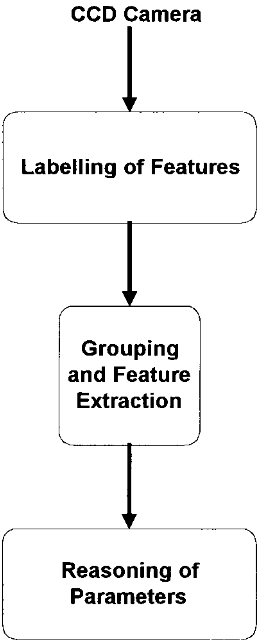

Figure 5. Vision-Based Guidance System for the Twin-Burger 2 AUV.

correlates between the left and right camera images. The feature motion tracker correlates stored feature templates to determine the image location and thus the direction to each feature. Range is determined by correlating the features in both images to find their pixel disparity. This pixel disparity is related to an absolute range using camera extrinsic and intrinsic parameters, which are determined by calibration. The direction and range to each feature is then fed to the controller, which determines a set of thruster commands. To guide the AUV, thruster commands become a function of the position of visual features.

A major drawback of using visual systems in underwater guidance is that the performance degrades in case of turbid water or when a cable is buried or there might be other similar cables appearing in the image. For such cases, a multi-sensor fusion technique has been proposed (Balasuriya and Ura, 1999a and b, 2000 and 2001). The proposed sensor fusion technique uses dead reckoning position uncertainty with a 2D-position model of the cable to predict the region of interest in the image captured by a camera mounted on an AUV. The 2D-position model of the layout of the cable is generated by taking the position co-ordinates (x_i, y_i) of a few points along the cable, which is then used to predict the most likely region of the cable in the image.

As opposed to the two camera approach, Balasuriya and Ura (1998) proposed a vision-based guidance law using a single camera. The technique has been implemented in a test-bed underwater robot, Twin-Burger 2, at the University of Tokyo for cable tracking and following a moving object. The basic idea underlying these schemes is that, the feature to be tracked introduces a particular geometric feature in the image captured by the CCD camera. The vision processor then labels these features, extract their location in the image and interprets the appearance into a guidance parameter as shown in Figure 5. For example, an underwater cable introduces a line feature in the image, and the edges of a cylinder introduce a rectangle. The vision processor derives the equation of the line representing the cable in the image plane given by Equation 6, which gives the direction 'q' and position 'r' parameters.

$$r = x\cos(q) + y\sin(q). \tag{6}$$

where: (x, y) are the co-ordinates of the straight line equation.

In the case of a cylindrical object, the co-ordinates of the centroid of the object (rectangle) in the image plane and the area A covered by the object are derived. These parameters are then fused with other sensory parameters to determine the control references for the underwater vehicle.

Rock *et al.* (1992) devised a vision-based system to track a dot of light generated by a laser. The hardware comprises two cameras, one of which is used to locate the target. The vision system works by scanning the image from the last known location of the target, or from the centre of the screen if the target was not previously in view. The pixels are examined row by row, expanding outward towards the edge. If a target is found, its angle and elevation with respect to the centre of the image is evaluated and transmitted to the vision processor, while range can be found using successive images from both cameras. The proposed law has been proved to be valid only in the case of a single distinguishable target.

4.1.3. *Lyapunov-Based Guidance.* A Lyapunov function can be considered as a generalisation of the concept of distance or energy. The Lyapunov theorem states that, if the distance of the state along any trajectory of $\dot{\mathbf{x}} = \mathbf{Ax}$ decreases with time, then $\mathbf{x}(t)$ must tend to 0 as $t \to \infty$ (Chen, 1984). Caccia *et al.* (2000) uses the concept to develop a new guidance law for unmanned underwater vehicles for testing on a prototype ROV, *Romeo*. This law is termed as a *medium range manoeuvring guidance law*. In this law, the vehicle is allowed to move from point (x, y) to (x_d, y_d) with a desired orientation Ψ_d as shown in Figure 6. By choosing the desired vehicle speeds

$$u_d = \zeta e \cos\alpha, \tag{7}$$

$$v_d = 0, \tag{8}$$

$$r_d = \mu\alpha + \zeta \frac{\cos\alpha \sin\alpha}{\alpha}(\alpha + h\theta), \tag{9}$$

(where ζ, μ and h are the tuning parameters) a Lyapunov function is suggested given by Equation 10, which makes the distance e between the two points converge to zero for increasing time.

$$V = \tfrac{1}{2}e^2 + \tfrac{1}{2}(\alpha^2 + h\theta^2), \tag{10}$$

where:

$$e = \sqrt{(x_d - x)^2 + (y_d - y)^2}, \tag{11}$$

$$\theta = \gamma - \psi_d, \quad \text{and} \tag{12}$$

$$\alpha = \gamma - \psi. \tag{13}$$

The parameters u_d, v_d and r_d are the desired vehicle's surge, sway and yaw velocities respectively. If an obstacle is detected along the way by the sensors with some

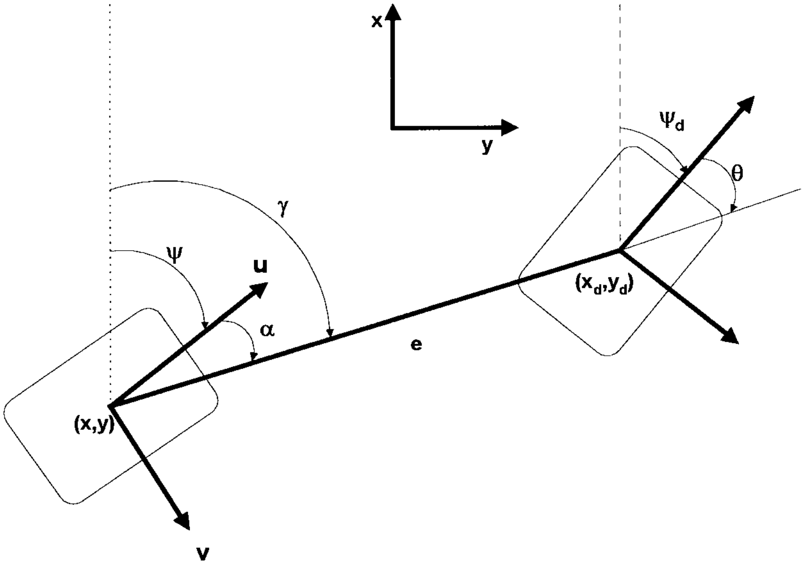

Figure 6. Medium Range Manoeuvring Guidance Law.

orientation δ and range d from the robot, the vehicle follows its profile until a suitable detaching condition is verified, and the vehicle then continues its free space manoeuvring. For feature following, the proposed law does not require control of the vehicle sway velocity while controlling the surge and yaw velocities.

4.1.4. *Guidance with Chemical Signals.* Using the fact that marine animals make extensive use of underwater chemical signals to avoid predators and to locate food sources etc., an interesting guidance scheme for AUVs using chemical signals has been proposed by Consi *et al.* (1994). The authors have built a small underwater robot, which mimics the chemical sensing abilities of a *lobster*. This class of robots is named as *biomimics* and are designed to mimic certain features of animals and act as animal substitutes in behavioral and neurobiological studies.

The goal of the research was to use the information in chemical signals to locate the source of a chemical discharge. In this respect, it has a number of scientific, environmental, commercial and defence related applications. The sensors used in the biomimic are conductivity sensors, and they are used to enable the AUV to follow a plume of saltwater in a freshwater flow-through flume. A simple gradient following algorithm is implemented to locate the source of discharge, which has the obvious disadvantage of getting trapped in local concentration minima and maxima.

4.1.5. *Proportional Navigation Guidance for AUVs.* Although PNG is widely used for missile guidance systems, Ahmad *et al.* (submitted) demonstrated that it could be tailored to work for AUVs as well. The authors propose a two-stage problem formulation to retrieve a returning AUV to the mother submarine. In the first stage, interception of the target (mother submarine) by the AUV is considered using a PNG law, which is the theme of the paper. In the second stage, the docking of the AUV is considered when in close proximity to the mother submarine and is an area of current investigation. The idea behind using PNG is that, if the AUV is made to lie on the LOS and hold there as well, a constant relative bearing between the AUV and target is ensured i.e., the LOS does not rotate and interception will occur. The PNG law

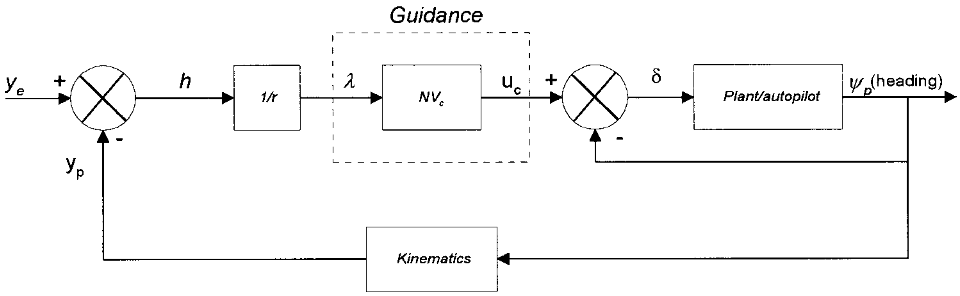

Figure 7. Proportional Navigation Guidance Loop.

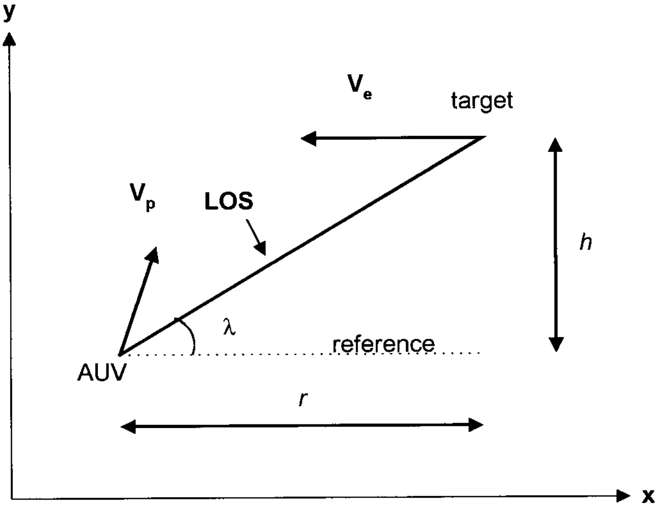

Figure 8. AUV-target engagement geometry.

can be stated as:

$$u_c \propto \lambda, \tag{14}$$

$$u_c = k\lambda, \tag{15}$$

where: k is the navigation constant, λ is the LOS angle and u_c is the command input.

The command input in this case is the heading angle ψ_c, therefore:

$$\psi_c = NV_c\lambda, \tag{16}$$

where: V_c is the closing velocity, and N is an important tuning parameter. The block diagram of the proposed guidance and control system is shown in Figure 7 and the AUV target engagement geometry is shown in Figure 8. The guidance system used is PNG, which generates commands for the control system. Different engagement scenarios have been considered. For stationary targets, the scheme is analogous to the waypoint guidance. For mobile targets, the PNG law generates suitable trajectories to be followed by the AUV for docking purposes.

4.1.6. *Guidance using Magnetometers for Cable Tracking.* The underwater cable network and its capacity are expanding very rapidly, and its installation and maintenance is becoming more important. AUVs could be a potential tool for underwater cable tracking especially in case of deep waters where human intervention is not possible. Different schemes have been proposed for underwater cable tracking. Balasuriya and Ura (1998) proposed vision-based guidance for cable/pipeline tracking as outlined in Section 4.1.2., but in the case of shallow waters, where cables are buried to avoid being damaged by fishing gear or anchors, the performance degrades. For buried electrical or telecommunications cables, the remedy is to use on-board magnetometers, which can detect the magnetic field induced from the current flowing in the cable. The data from the magnetometer is fed to a cable locator that estimates the direction, burial depth and the distance of the vehicle from the cable. The data from the cable locator is then used to guide the vehicle. The *Aqua Explorer 1000* is an example of a successful implementation of magnetometer-based guidance for underwater cable tracking (Asakawa *et al.*, 1996; Kato *et al.*, 1994; Ito *et al.*, 1994). Guidance using magnetometers has limited applications as it can only be used to guide the vehicle towards the source of the magnetic field.

4.1.7. *Electromagnetic Guidance.* A major disadvantage of using optical or visual guidance systems is that the response is only good in nonturbid, clear environments, and it is limited over a wide range of background lighting and water turbidity conditions. Also, the AUV must lie within the field of light emitted by the beacon on the cable or dock and must be oriented in such a way that the optical sensors can detect the light. Feezor *et al.* (2001) employed an electromagnetic guidance (EM) technique during the homing/docking mode of an AUV. The EM guidance system uses a magnetic field generated by the coils on the dock, which is sensed by the coils in the AUV. The guidance system provides the AUV not only the bearing to the dock, but also the angle of the AUV relative to the field lines and thus the angle relative to the dock entrance. The accuracy of the proposed system is less than 20 cm but the range is limited to 25–30 m. The proposed system is quite robust under almost all oceanographic phenomena.

5. DISCUSSION.

The following discussion presents some modifications in the guidance design for AUVs. It can be stated that the waypoint guidance, or specifically, LOS guidance is likely to remain a key feature of all present guidance systems and systems that follow. By utilising LOS, several other guidance laws can be conceptualised. For example, waypoint guidance could be utilised for a cable following problem considering several waypoints on the cable by introducing beacons at different lengths and then follow the beacons on the cable using onboard sensors. Inexpensive photodetectors could be employed to detect the light, which can be tuned to operate over different frequencies. However, the major drawback as discussed in Section 4.1.7. is that the performance degrades in case of turbid water or when there is light emanating from other sources. This approach is analogous to the heat seeking air-to-air missile.

Another strategy to accomplish a cable tracking mission is to pose the guidance as a two-stage problem i.e. using waypoint guidance while on the surface and vision-based guidance or any other existing guidance scheme while submerged. In this manner, the vehicle would have precise position co-ordinates on the surface from the Global Positioning System (GPS) so that it can accurately reach the vicinity of the area of interest. Dead reckoning could be employed to estimate the position of the AUV under

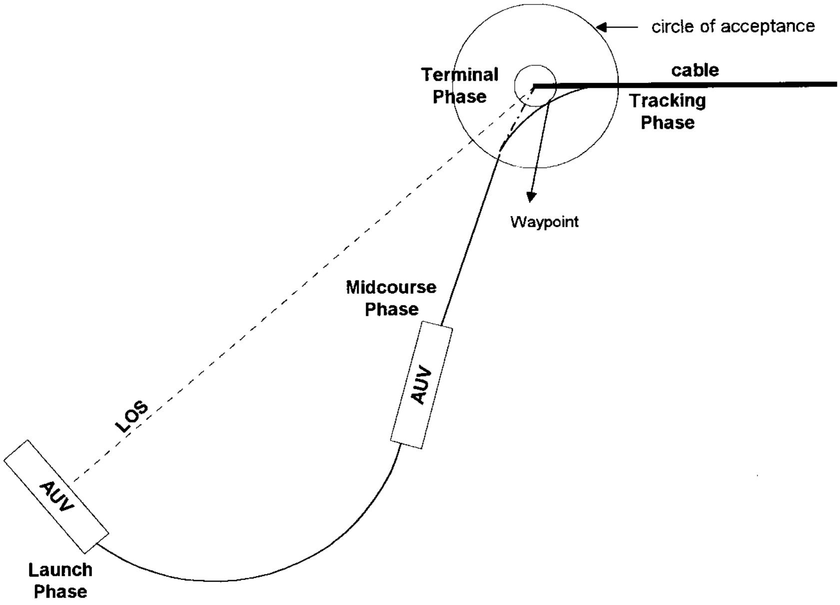

Figure 9. Planar View of the four phases of flight for cable tracking problem of an AUV.

water. A similar approach has been adopted by the Southampton Oceanography centre's AUTOSUB-1 (Mcphail and Pebody, 1998), which utilises GPS for position fixes on the surface and dead reckoning using an acoustic doppler current profiler, providing velocity measurement, while submerged.

A complete mission scenario for the underwater cable tracking problem could be to classify it into four different phases utilising different guidance laws. These are i) launch phase, ii) midcourse phase, iii) terminal phase, and iv) tracking phase as shown in Figure 9. In the first phase, called the launch phase or the boost phase, the vehicle is launched from a boat or from a mother submarine and guided in the direction of the LOS with maximum speed, using LOS guidance only. The heading command can be generated using Equation 4. Once the vehicle approaches the LOS, the midcourse phase could be invoked, in which the vehicle follows the LOS angle with maximum speed using waypoint guidance, Section 4.1.1. During this part of the operation, changes may be required to bring the vehicle onto the desired course and to make certain that it stays on that course. The midcourse guidance system is used to place the vehicle near the target area, where the system to be used in the final phase of guidance can take over. It should be noted that there is no need for the vehicle to submerge at this stage, as the objective is to approach the target area with maximum accuracy regardless of the orientation of the vehicle with respect to the cable. When the vehicle comes within the circle of acceptance, the third phase called the terminal phase is invoked. In this phase, the vehicle must be slowed down and submerged in order to line up with the cable/pipeline as shown in Figure 9. The circle of acceptance in this case, as opposed to that quoted in Healey and Lienard (1993) should be taken as at least the minimum turning radius of the vehicle in order to avoid overshoot. Finally the fourth phase, called the tracking phase, is launched utilising any existing guidance law. For example, the vehicle could use a vision-based guidance system to follow the cable outlined in Section 4.1.2. If the cable to be followed is an electrical/communication cable, then magnetometers could be used to detect the radiation from the cable and guide the vehicle in the appropriate direction.

6. CONCLUDING REMARKS.

This paper presents several guidance laws for autonomous vehicles with emphasis on AUVs. Guidance laws for airborne missile systems are also explored. It has been shown that the guidance system plays the vital role in bringing autonomy to the whole system. It is observed that most of the current AUV systems employ either the classical waypoint guidance to reach a target area or the more advanced vision-based guidance for cable/pipeline tracking. In practice, LOS guidance is the key element of all guidance systems. Some hybrid guidance schemes are also proposed based on existing airborne and underwater guidance laws.

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