OPERATIONS ARCHITECTURE AND VECTOR FIELD GUIDANCE FOR THE RIVERSCOUT SUBSCALE UNMANNED SURFACE VEHICLE

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ABSTRACT

Full size and sub-scale unmanned surface vehicles (USVs) are increasingly used in a variety of tasks such as surveillance, patrolling and data gathering. Sub-scale USVs in particular are attractive for operations in protected waters because of their relatively low cost, stealth due to small size and operational flexibility. Typically the USVs are tele-operated, something that can create challenges because of their susceptibility to external disturbances, such wind and currents. Similar challenges apply to the design of the guidance laws utilized when the USV operates in partial autonomy modes. In this paper we describe the architecture of the Riverscout, a sub-scale, jet-powered, V-hull USV designed for protected water operations. The paper describes the overall system design with focus on the operational modes of the craft, the basic control scheme used for the boat's auto-pilot as well as the use of guidance vector fields for implementing waypoint following and loitering. Field data is provided to demonstrate the craft's performance.

Keywords: unmanned surface vehicle, guidance vector fields, partial autonomy, teleoperation.

1. INTRODUCTION

Unmanned surface vehicles (USVs) provide significant benefits in surveillance, patrolling and data gathering tasks. Equipped with appropriate sensors, they can gather data above, at, or below the water surface (Gadre, Kragelund, et. A., 2009) and convey such data to manned surface vehicles or central command and control stations. With the advent of sensor miniaturization and the associated reduced power requirements, sub-scale USVs have become extremely attractive alternatives for such tasks because of their smaller cost relative to the full scale vehicles, as well as their natural stealth due to their reduced size. At the same time, because of their smaller size they are significantly more susceptible to external disturbances (Yu, Bao, and Nonami 2008) and have reduced ability of handling high sea states. Sub-scale vehicles however can be used in rivers, harbors and other protected waters, something that addresses these key limitations.

Whereas the technical challenges associated with the development of sub-scale USVs are similar to the full size USVs, there are some differences that create unique challenges associated specifically with the lower cost, sub-scale USVs. First, due to the small size and reduced power budget, onboard computing resources must comply with the size and power limitations. Because such vehicles are typically remotely operated, it is important to identify an appropriate blend between manual and automatic operation which can support a given mission while minimizing the task load on the operator, (Enes, Book 2010). The susceptibility to external disturbances necessitates careful attention to the guidance algorithms used during autonomous modes of operation. At the same time, because such vehicles operate in relatively constrained environments, such as when going under bridges or traversing narrow pathways, it is important that any line following behavior minimizes path deviation, even in the presence of external disturbances. Similarly, when implementing a loitering behavior, which is typically defined as the behavior or remaining within a specific radius of a target location, the vehicle cannot simply stop. Wind and currents can quickly drift the vehicle beyond its intended position and because of the non-holonomic nature of a V-hull USV remaining within the intended region can become difficult.

In this paper, we describe the operations architecture and guidance approach used in a sub-scale, V-Hull USV platform called the Riverscout. The Riverscout was designed by the Carderock division of the Naval Surface Warfare Center. The Riverscout can carry a variety of payloads while operating in protected waters and under varying levels of autonomy. The architecture provides a variety of control modes, each with a different blend of operator and autonomous control. The guidance approach is designed around a set of hierarchical controllers which at a high level use guidance vector fields while at low level utilize classical cascade PID control loops.

The remaining of this paper is organized as follows: Section 2 provides background on similar work, focusing on using vector fields for guidance. Section 3 describes the boat, the control computer as well as the modes developed to support remote operation. Section 4 describes each of these modes and the controller formulation addressing each mode's requirements. Section 5 concludes the paper.

2. BACKGROUND AND RELATED WORK

The problem of planning a path for an unmanned vehicle and then ensuring that the vehicle follows that path is of enormous importance for aerial, ground, surface and sub-surface vehicles alike. Because of its importance it has received wide range attention in the traditional robotics literature, and most recently in the autonomous vehicles research, especially for non-holonomic vehicles. In general, researchers separate the task of developing a path from the task of following the path. In this paper we focus on the latter problem, because at this point, the generation of a path is left entirely to the human operator.

Several authors have addressed the problem of guidance and control of sub-scale USVs. Yu, Bao and Nonam (2008) developed a model for a sub-scale boat's horizontal motion and designed a controller to maintain course absent a heading sensor. Indiveri, Zizzari, and Mazzotta (2007) describe an approach to following a linear path taking into account the under-actuated nature of surface vehicles. Bibuli, Bruzzone, Caccia, Indiveri and Zizzari, (2008) provide a solution to the line following problem and show its applicability to the sub-scale Charlie USV. Sonnenburg, Gadre et al., (2010) compared a variety of experimentally developed models versus actual vehicle performance for 3 sub-scale USVs, concluding that for relatively high speeds in which GPS can provide course angle, steering dynamics can be approximate by a 1st order lag models for turn rate and sideslip.

Beyond surface vehicles, there has been a tremendous amount of work on control strategies for Unmanned Aerial Vehicles (UAVs). Despite the obvious differences, there are strong similarities between aerial and surface unmanned vehicles. This is because a significant amount of the literature focuses on the two dimensional movement of a UAV, treating elevation as constant. Furthermore, a surface vehicle aiming to remain in planing mode is subject to similar constraints as an aerial vehicle, namely minimum forward speed, and turning radius limits. Another shared characteristic between sub-scale aerial and surface vehicles is their susceptibility to external disturbances. One approach that has been used extensively for guiding small UAVs is guidance vector fields. In particular, it has been shown (Frew, Lawrence, 2005, Frew, Lawrence, and Morris 2006) that Lyapunov vector fields can provide globally stable convergence when guiding UAVs. As demonstrated in Frew, Lawrence, Dixon, Elston and Pisano (2007), an on-board controller guided by vectors fields can be treated as a new dynamic system by higher layers in the control architecture which can then provide high level guidance by simply adjusting a small number of parameters defining the vector field. This is advantageous because it provides a natural means for an operator to select the level at which to interact with the remote vehicle. The authors further demonstrate how flow field equations can be manipulated to warp the basic circular shape into a racetrack. A similar approach was used by Nelson, Barber, McLain, and Beard, 2006 to develop guidance fields for circular as well as linear paths, and the authors provide an algorithm that sequences a series of waypoints and generate the appropriate vector fields to guide a UAV along the waypoints.

3. THE RIVERSCOUT PLATFORM

3.1. Craft Description

The Riverscout is a V-Hull boat measuring approximately 1.6 meters long, 0.62 meters wide, and weighs less than 40 Kgms when fully loaded. The version of the boat described in this paper is propelled by two water-jets, each powered by a 5400 Watt (7.2 HP) AC motor for a total power capacity of 10800 Watts (14.4 HP). Each motor is powered by a dedicated battery bank with a storage capacity of 30 Ah per motor. Steering is implemented by vectoring the water thrust through lateral movement of the two output nozzles. This design provides a clean underside that only requires approximately 16.5 cm (6.5 in) of water depth for operation. A reversing bucket is utilized to allow the boat movement in reverse. The boat can operate in displacement and planing mode. The two modes have distinctly different responses, both in steering as well as thrust. Figure 1 depicts the boat while operating in displacement mode.

Figure 1: Riverscout in displacement mode.

When fully loaded, the boat transitions into planing mode at approximately 4 met/sec (7.8 knots). In planing mode, maximum speed is 10.8 met/sec (21 knots). Figure 2 depicts the boat while operating in planing mode.

Figure 2: Riverscout in planing mode.

The Riverscout can be equipped with a variety of payloads, each addressing specific mission requirements. Independent of payload, the vehicle is always under the supervision of a human operator, although it can operate in varying levels of autonomy. Supervision is facilitated by a set of cameras that are part of the payload. Common to all missions are the requirements that the craft operates in an automated mode performing line following while sequentially visiting waypoints, while having the option of loitering within a specific radius and for a specific amount of time at each waypoint. Beyond the automated mode, the craft also has the requirement of operating in a manual mode in which the operator dictates a heading and desired velocity (much like an auto-pilot) and finally, the craft can also be operated in a backup mode, in which the operator can directly manipulate the control surfaces.

In order to maintain the relatively low cost of the overall system, guidance and control functions were implemented using a network of two low cost microcontrollers. One microcontroller is dedicated to interfacing to the motors and other control servos, sensing craft temperature at multiple points, monitoring battery voltage and sensing motor rotational speed. A second microcontroller is dedicated to interfacing to the on-board Ethernet network, as well as the instrument CAN bus. In addition, all guidance control and autonomy functionality is implemented on the same microcontroller.

3.2. Operator Interface

Operation of the craft is managed by a hand-held computer that provides two thumb-operated self-centering joysticks, several buttons as well as a touch screen. The computer is running a dedicated Graphical User Interface (GUI) specifically designed to support a blend of the touch-screen and hardware interfaces.

The control GUI utilizes a two state design. The initial state is focused on ensuring the orderly startup of the craft and utilizes a virtual checklist that guides the user through the startup process. Process steps are checked off automatically when possible, and explicit user input is used when it is not possible to detect if a step has been completed.

Once the startup state is completed, the control GUI allows the user to control the craft in one of three control modes: Backup, Manual, and Route. These modes are described in more details in the Guidance and Control section of the paper. Independent of the control mode, the GUI provides to the user access to multiple screens, each selected through an on-screen tab. These screens include: Planning, Monitoring, and Video.

The Planning Screen is used to set up a route for the craft to follow when in route mode and allows for waypoints to be added. Waypoints are added to the map by either clicking on the map, or taking the craft's current location. Each waypoint can be customized with how fast the craft will approach the waypoint and how long the craft will loiter at the waypoint. A zero loiter duration indicates the craft should simply cross the waypoint. A non-zero loiter duration indicates that the craft will follow a circular path around the way point, in which case the radius of the loiter circle and desired speed during loitering can also be specified.

The Craft Monitoring Screen is used to display information about the internal status and operation of the craft. This information includes the battery level, internal temperatures, control settings, sensor information etc. An error log is also provided to list any errors (communication, sensor outages etc.) that have recently occurred.

The Video Screen is used to display the on-board camera views. The interface allows the user to select how the screen will be divided (single/double/triple or quad areas) and what is displayed in each of the areas. Any of the cameras feeds or the moving map display can be selected for display in each of the areas.

The craft is controlled through hardware buttons and two joysticks. The left joystick controls speed/throttle and the right joystick controls heading/steering. As an alternative to using the throttle joystick, there are 3 hard buttons available to control the speed. The buttons are for incrementing, decrementing, and stopping the craft. Several actions can be assigned directly to hard buttons, thus allowing the user to bypass screen controls for frequent actions or actions that require quick response. For example, a button is dedicated to zero the engine thrust and set the steering to straight, independent of the operating mode or status.

4. GUIDANCE AND CONTROL

4.1. Control Formulation

The three user control modes offered to the user are implemented by a set of on-board hierarchical controllers as shown in Figure 3. There are three operating modes, Backup, Manual and Route.

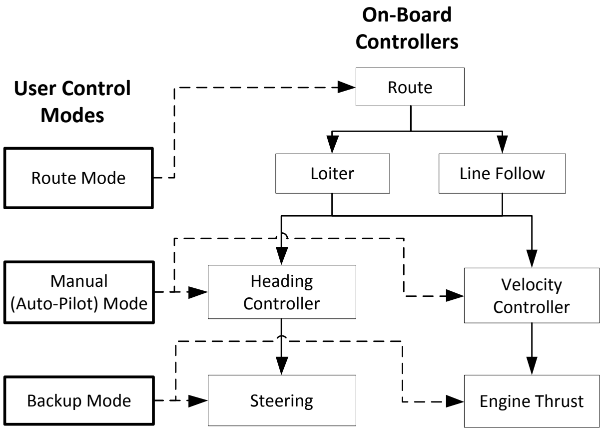

Figure 3: Heading Control Formulation.

The Backup mode is the lowest level and allows the user to directly control the actuators. The Manual mode allows the user to define a target speed and heading and uses on-board controllers to achieve the desired goal. The Route mode is the highest level mode and allows the user to specify a path to be followed. Each of these modes is further described below.

4.1.1. Backup Operating Mode

The lower level mode allows the user to directly manipulate the steering and engine thrust. Because this mode does not depend on any sensor information for feedback, it is meant to provide a backup control mode in case of sensor or navigation system failure, or for testing and diagnostics.

4.1.2. Manual Operating Mode

The Manual mode of operation allows the user to specify a desired heading and velocity without having to manage the control actuators directly. As explained in the user interface section, the hand-held control computer provides self-centering joysticks as well as discrete buttons for controlling the boat. In manual mode, discrete button clicks are used to establish the desired velocity according to pre-programmed set points. The pre-specified set points are designed to exclude a range of speed around the transition from displacement to planing mode. This range of speed is the most inefficient because the boat has not planed, yet the required thrust is significantly higher compared to slightly lower speeds when the boat is entirely in displacement mode. Whereas an operator near the boat can observe this state and increase or decrease speed appropriately, the boat can operate far enough from the operator where such observation is not possible. By eliminating this inefficient speed range, the system ensures maximum endurance even when operating far from the human operator.

The low-level velocity controller is implemented by using a feed-forward open-loop controller augmented by a classical PID portion that uses gain scheduling. The feed forward component is used to improve response and provides the majority of the controller output, whereas the PID portion compensates for smaller errors caused by disturbances and changes in battery voltage. A look-up table of engine-effort and resultant velocity values is linearly interpolated to determine the feed-forward component. The PID controller uses gain scheduling to compensate for the different response of the craft in displacement and planing mode. The topology of the velocity controller is shown in Figure 4.

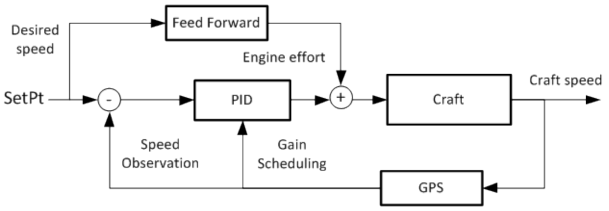

Figure 4: Velocity Control Formulation.

The performance of the velocity controller is shown in Figure 5. At speeds below 4 met/sec the boat is in displacement boat and the controller performs reasonably well both during increases and decreases in desired speed. When the speed exceeds 4.5 met/sec, the boat is in planing mode. There is a small amount of overshoot when the desired speed is set to 5.66 met/sec (11 knots) but again the controller performs adequately.

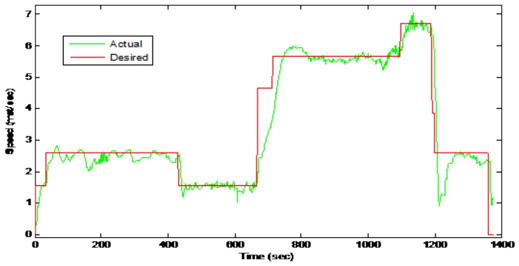

Figure 5: Velocity Tracking Performance.

A larger amount of undershoot is observed when the desired speed changes from 6.68 met/sec (13 knots) to 2.57 met/sec (5 knots). During that transition, the boat transitions from planing into displacement mode. The dynamics of that transition combined with the large discontinuity in the set point create a difficult transient. Even though this characteristic never became an issue during operational tests, we believe that additional gain calibration can significantly reduce undershoot.

The low level heading controller topology is shown in Figure 6. In Manual mode, heading is controlled through a self-centering joystick. When the joystick is centered a cascade controller topology is used; the front controller uses the heading error to derive a desired turning rate which is fed to the second controller which tracks it. When the joystick is depressed on either side, the displacement is scaled and used as direct input to the steering rate controller. The desired heading is maintained by a sample-and-hold subroutine. This subroutine monitors the release of the steering joystick at which point is samples and maintains the desired heading to be used as long as the steering joystick has no deflection.

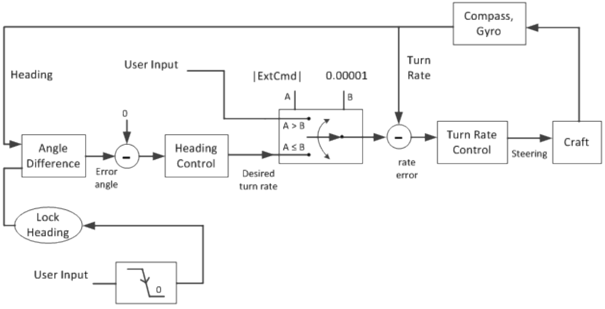

Figure 6: Heading Control Formulation.

This approach to controlling heading was found to be very natural for an operator. Simply releasing the joystick locks the boat on the current heading while moving the joystick on either side puts the boat on a best-effort constant rate turn which anecdotally has proven easier to handle for the operators.

The performance of the heading controller is shown in Figure 7. The top sub-plot shows the desired versus actual turning rate and the bottom plots shows the desired and achieved heading. This data was captured in route mode, hence the continuously adjusting desired heading.

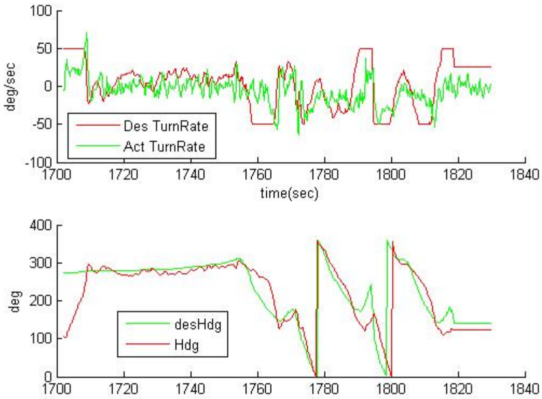

Figure 7: Steering Controller Performance

4.1.3. Route Operating Mode

In Route mode the boat follows a pre-specified route while maintaining speed constraints. The route is specified through a series of waypoints along with the desired travel speed between waypoints. At each waypoint, it is possible to specify two distinct behaviors. The default behavior is pass-through; once reaching the waypoint the boat will continue to the next waypoint. Alternatively, the boat can loiter for a pre-specified amount of time at that waypoint; once that time period has elapsed, the boat will continue to the next waypoint.

Because the Riverscout is designed to operate in relatively narrow bodies of water, it is important that the route following control strategy seeks to minimize the distance to each waypoint as it is visited but also the average distance to the line formed by successive waypoints. To achieve this goal, we utilize a strategy similar to what is described in Nelson, Barber, McLain, and Beard, 2006. This strategy utilizes a line-attracting flow field to guide the desired heading of the craft while transitioning between waypoints and a circular path flow field to guide the desired heading of the craft while loitering.

During loitering, we utilize a Lyapunov vector field as described in Frew, Lawrence et.al. 2007. For a counter-clockwise rotation, the field provides the instantaneous velocity for the boat:

$$\begin{bmatrix}\dot{x}_d \\ \dot{y}_d\end{bmatrix} = \frac{-\lambda v_0}{r(r^2+R_L^2)}\begin{bmatrix} x_r(r^2-R_L^2)+y_r 2rR_L \\ y_r(r^2-R_L^2)+x_r 2rR_L \end{bmatrix} \qquad (1)$$

In the above equation, R_L is the desired loiter radius, x_r and y_r are the x and y coordinate of the boat relative to the desired loiter center, r is the distance of the boat to the loiter center, and v_o is the desired loiter speed. The parameter λ ($\lambda > 0$) controls the gain at which the field converges to the circular path. For guiding the Riverscout, the loiter velocity is specified independently as part of the route description hence we set v_o to the value of 1 and determine the desired heading angle ϑ which is submitted to the heading controller as follows:

$$\partial = \arctan(\frac{\dot{y}_d}{\dot{x}_d}) \qquad (2)$$

Figure 8 depicts an example of the vector field generated for circular loitering. Notice that when outside the loiter circle, the vector field guides to a tangent direction that minimizes turn rate transients.

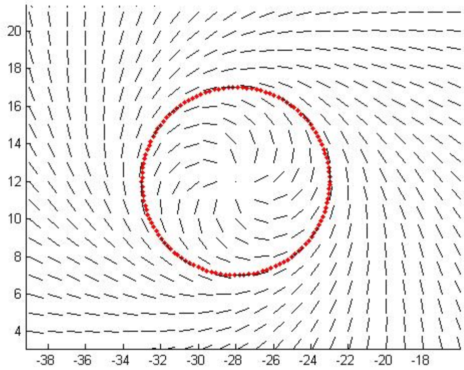

Figure 8: Loiter Vector Field.

During travel between waypoints w_1 and w_2, the vector field providing guidance to track the line (w_1, w_2) is generated by:

$$\partial = \partial_0 - \rho\theta_a(\frac{d}{\tau})^k \qquad (3)$$

where ϑ_0 is the angle of the (w_1, w_2) line, θ_a incidence angle that the boat follows when further from the line than d, which is the perpendicular distance between the boat and the line at which point the transition begins, t is the gain of the field heading transition between θ_a and ϑ_0. The value of ρ is given by

$$\rho = -sign(\overrightarrow{w_1 w_2} \times \overrightarrow{pp_p}) \qquad (4)$$

where p is the position of the boat and p_p is the projection of the boat position onto the (w_1, w_2) line.

Figure 8 depicts an example of the field generated for transitioning between waypoints, using ϑ_0= 90 deg. d = 15 and τ = 1.1.

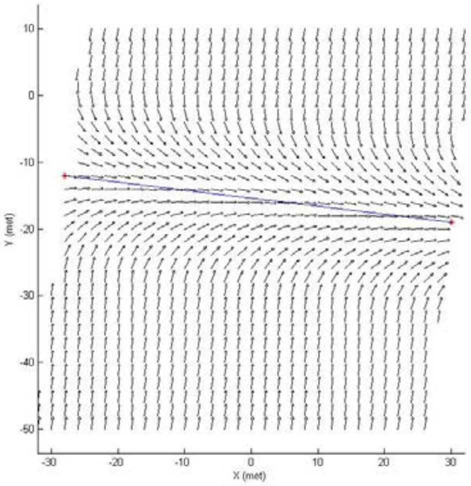

Figure 9: Line Vector Field.

To avoid situations where a large loiter radius forces the boat to deviation from the waypoint to waypoint centerline, the route guidance controller smoothly transitions from line following mode to loiter mode as the boat approaches the loiter position. Figure 10 depicts the path of boat while transitioning between two waypoints. The first waypoint is depicted by a red cross on the right side of the chart and the second waypoint and loiter radius is depicted on the left side of the chart. The wind was blowing N, NW at 15 knots during data collection, something that is affecting tracking; however the loitering pattern is clearly visible.

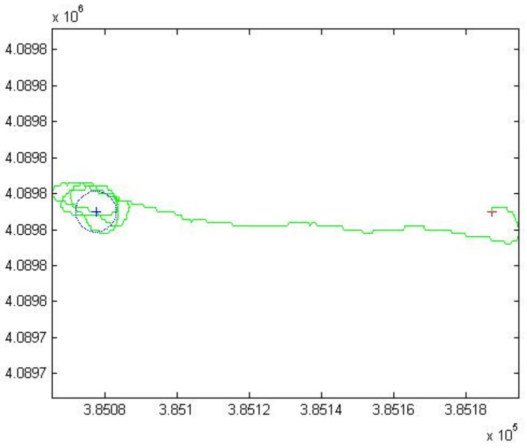

Figure 10: Line Vector Field.

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REFERENCES

Indiveri, G., Zizzari, A. A., Mazzotta, V. G., 2007. Linear Path Following Guidance Control for Underactuated Ocean Vehicles. Proceedings for the 2007 IFAC Conference on Control Applications in Marine Systems, CAMS 2007, September 2007, Bol, Croatia.

Yu, Z., Bao, X., Nonami, K. 2008. Course keeping control of an autonomous boat using low cost sensors. *Journal of System Design and Dynamics*, 2(1):389-400, November 2008.

Enes, A., Book W., 2010. Blended Shared Control of Zermelo's Navigation Problem, *American Control Conference*, June 30-July 2, Baltimore, MD, USA.

Bibuli, M., Bruzzone, G., Caccia, M., Indiveri, G., Zizzari, A.A., 2008. Line Following guidance contrl: Application to the Charlie Unmmaned Surface Vehicle, *IEEE International Conference on Intelligent Robots and Systems*, Sept 22-26, Nice, France.

Sonnenburg, C., Gadre, A., Horner, D., Kragelund, S., Marcus, A., Stilwell, D.J., Woolsey, C.A., 2010. Control-Oriented Planar Motion Modeling of Unmanned Surface Vehicles, *OCEANS* 2010, Sept 20-23, Seattle, WA, USA.

Gadre, A., Kragelund, S., Masek, T., Stilwell, D., Woolsey, C.A., Horner, D., 2009. Subsurface and surface sensing for autonomous navigation in a riverine environment. *Proceedings of the AUVSI Unmanned Systems North America*, August, Washington Dc, USA.

Nelson, D.R., Barber, D.B., McLain, T.W., Beard, R.W., 2006. Vector Field Path Following for Small Unmanned Air Vehicles, *Proceedings of the 2006 American Control Conference*, June 14-16, Minneapolis, MN, USA.

Frew, E.W., Lawrence, D.A., Dixon, C., Elston, J., Pisano, W.J., 2007. Lyapunov guidance vector fields for unmanned aircraft applications, *Proceedings for the 2007 American Control Conference*, July 11-13, New York City, NY, USA.