Heading control and shoreline detection for river navigation using autonomous surface vessel

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Heading control scheme and shoreline detection play a significant role to vision-based navigation system in riverine environment. In this paper, side-line heading and center-line heading control for an Autonomous Surface Vessel (ASV) that capable of maneuvering along the river are presented. The ASV is equipped with propeller and rudder to control the speed and heading direction, respectively. Continuous stream of images are captured by camera that mounted on ASV and sent to the base station over network in low latency. An image segmentation algorithm based on Hough Transform technique is implemented for waterline detection. The purpose of using Hough Transform is to perform visual based navigation that track along with the river. Besides, a high accuracy GPS receiver is installed on the ASV to provide the latitude and longitude coordinates. Proportional control is designed as heading controller in order to stabilize the unstable process. Data logger system helps to save the data and important information for further analysis and processing. The optical flow algorithm is implemented to detect and avoid obstacle. The ASV’s navigation, control and task specific vision have been evaluated through experiments with results presented to demonstrate its capabilities.

[Keywords: Heading control scheme, shoreline detection, Autonomous Surface Vessel (ASV), image segmentation, Hough Transform]

Introduction

Autonomous surface vessel (ASV) also known as unmanned surface vehicle (USV) is a robotic boat that operates on the surface of the water. ASV is designed to traverse and explore unstructured and unknown environments sufficiently in order to construct a complete map. It also accomplishes a challenging task with minimum human interference. Hence, the uses of ASV with absence of human will reduce the risk in dangerous situation due to unpredictable impacts on the environment.¹,³

ASV technology has been developed and being researched since 1993³. ASV can be used for wide variety of applications such as navigation, mapping, military, observation, measurement, environmental monitoring and collecting data⁵. Scientist and researchers can also collect data on the ocean using satellite systems and floating buoys. However, the data collection is limited due to the cost of satellite systems. Hence, ASV can solve the problem to help collecting environmental data.

ASV can be used for river environment exploration and perform river navigation. Mapping of a river provides information to help in understanding the topology and health of river environment⁶. Rivers are important sources of food and fresh water for humans since the beginning of history. Nowadays, humans use the river for transportation, international trade, agriculture and energy. Hence, river mapping plays a significant role in helping humans to use the rivers for those purposes.

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Navigation system is important to allow ASV to navigate to a specific location. Global Positioning System (GPS) navigation technique is widely used in ASV. The onboard sensors mostly contain GPS together with compass and Inertial Measurement Unit (IMU).\textsuperscript{7,9} The ASV that is equipped with GPS, compass and IMU may increase the efficiency of navigation system. However, it is challenging that ASV need to perform navigation on riverine environment due to complex and unstructured environment. Sometimes, the GPS signal may be loss or blocked by thick and high canopy\textsuperscript{10}. Hence, vision-based navigation is another technique that can be used in ASV.

Vision system can perform an autonomous navigation and obstacle avoidance.\textsuperscript{11,12} The system is capable of detecting obstacles, bridge and ships. There are many sensors that have been used on vision system such as infra-red (IR) sensor, ultraviolet sensor, laser and camera. IR sensor is the common sensor in market and it is easy to use for autonomous robot to detect the obstacle. However, the range of infra-red sensor and ultrasonic sensor are short as compared to camera. This is because a digital camera sensor can capture a wide range of brightness value.

The main objective of this project is to develop an algorithm to perform an autonomous navigation along the river. A computer vision sensor guidance system is developed to locate and guide the ASV to navigate along the river autonomously. A real time navigation system requires software integration, hardware interfacing, control system and robotics. The control system is utilized in all hardware and software such as heading control, network communication and signal conditioning. One of the computer vision fields is image analysis which involves processing an image, information extraction and statistical analysis.

The remaining of the paper is organized as follow. In approach and methods section, the heading control scheme, the hardware implementation, the power support system, shoreline detection and obstacle avoidance technique are discussed. Next the simulation and experimental result are shown to verify the ASV navigation system. Finally, the conclusion is made to summarize the paper.

**Approach and Methods**

*Heading Control Scheme*

In this approach, two methods are used to control the heading of ASV: side-line heading and center-line heading. Side-line heading is a simplest method for ASV expecting to navigate along the river by keeping the distance between ASV and shoreline. In order to keep the ASV to travel along the edge of the shoreline, the ASV heading is controlled by comparing the $d_i$, the desired distance. As shown in Figure 1(a), $d$ is a distance of riverbank to port of the ASV. On the other hand, center-line heading is controlled by comparing the two distances between the shorelines and ASV as to keep ASV to travel in the center line of the river\textsuperscript{13}. As shown in Figure 1(b), $dL$ and $dR$ are distances of shoreline to port and starboard of the ASV, respectively. The position of riverbank is detected as straight line by lateral camera. It is computed by pixels to control the heading of ASV. The condition to control the position or orientation of ASV is shown in Table 1.

<table>
<thead>
<tr>
<th>Heading Control</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side-line heading</td>
<td>1. If $d &gt; d_i$, then the orientation of ASV is turned to left.</td>
</tr>
<tr>
<td></td>
<td>2. If $d &lt; d_i$, then the orientation of ASV is turned to right.</td>
</tr>
<tr>
<td></td>
<td>3. If $d = d_i$, then the ASV travels along the edge of shoreline.</td>
</tr>
<tr>
<td>Center-line heading</td>
<td>1. If $dL &gt; dR$, then the orientation of ASV is turned to left.</td>
</tr>
<tr>
<td></td>
<td>2. If $dL &lt; dR$, then the orientation of ASV is turned to right.</td>
</tr>
<tr>
<td></td>
<td>3. If $dL = dR$, then the ASV travels in the center of river.</td>
</tr>
</tbody>
</table>

![Fig. 1 – Illustration of ASV navigation on river](image-url)
The Hardware Implementation and Power Support System

According to Figure 2, the hardware is built around the system in microcontroller. It is used as the main control unit for the ASV. Arduino Uno will receive the data from GPS module and send to microcontroller for data logging. Two microcontrollers are connected to the router for wireless communication. The speed of brushless motor and position of servomotor are controlled by microcontroller via GPIO signal. The components such as rudder and propeller are installed at the back of the ASV. The proposed system is designed to provide a real-time vision-based navigation system.

There are two parts in the power support system that are used in ASV. The first part is two rechargeable batteries which are used for devices that require high voltage. The second part is one 20000 mAh USB mobile charger (power bank) which is used to power the two microcontrollers through USB port. The mobile charger provides power for the microcontroller to support its decoding, wireless communication and video streaming from camera. The Li-Po batteries can keep the motor running for approximately 3 hours. The router is powered by a three cell Li-Po battery, producing over 12 volts to turn on the wireless connection between two microcontrollers and laptop.

![Image](image.png)

**Fig. 2 – Structure of hardware control system**

Shoreline Detection

Shoreline detection plays a key role in vision based safe navigation for autonomous surface vessel. Shoreline always changes as a result of the dynamic nature of the coastal zone due to physical impact and climate change. For example, sea level rise, flooding and removal of sediments can cause the shoreline erosion along the river. Investigation over the shoreline change is very important as the information can be used for monitoring and data analysis.

River surface segmentation and surface line detection are vision systems used to detect the shoreline for measuring the distances from ASV. Thresholding is the simplest image segmentation process. Thresholding can be used to create binary images from a grey-scale image. Many objects or image regions are characterized by constant reflectivity or light absorption of their surfaces. Then, a brightness constant or threshold can be determined to segment objects and background.

In addition, the environment is constantly changing due to time or light condition which causes reflection to appear on water surface. Hence, the color information of the vegetation and river can be taken initially before conducting the image segmentation process. Image segmentation which is based on color is to classify each pixel in a given image as either having a color in the specified range or not. Two sets of pixels in the image with black and white are coded to produce a binary segmented image. Color is represented in the hue channel. During the color segmentation, a rectangular region that contains samples of color is chosen to segment out of the color image. The mean and the standard deviation of the hue values of pixels that contained within the rectangle are computed. Then, each point is coded as 1 if it is inside the range of values, otherwise as 0.

Another method to detect the shoreline is corner detection. It is an indirect method for the segmentation. There are 3 ways to detect the corner such as minimum eigenvalue, local intensity comparison and Harris corner detection method. Shoreline can be detected through edge features but it is sensitive due to changing of illuminating condition. The vegetation is rich in corner information whereas river and sky region are poor in corner information unless there is a strong reflection on water surface.

The flowchart for the algorithm to segment and detect the shoreline is shown in Figure 3. A continual stream of frames is captured by camera. Each jpeg frame is extracted from network stream and taken as byte stream. The byte stream is decoded into readable matrix format for image processing. Each frame is converted to grayscale image in which the colors are shaded with gray color. The grayscale image is threshold to separate out the building and water. The threshold image is applied for morphology and canny edge detection to extract the water boundary.
Morphology operation is used to remove imperfections introduced during segmentation. In mathematical morphology, closing is used for noise removal such as pepper noise. Canny edge detection algorithm is used for accurate edge detection.

Lastly, Hough Transform is used to detect the shoreline and the straight line is drawn. Hough transform is a technique for shape positioning in image for extracting lines, circles and ellipses. In this paper, Hough line transform is used to determine the corresponding parameters such as \( m \), slope and \( c \), intercepts for line. Assume two or more straight line pass through the point \((x', y')\) in an image, it forms (1) for varying \( m \) and \( c \). This equation can be written as in (2) for each point in image space.

\[
y' = mx' + c \tag{1}
\]
\[
c = -x'm + y' \tag{2}
\]

However, a straight line will breakdown for the vertical line when the slope \( m \) becomes infinite. Consequently, it would be an unbounded value. Richard Duda and Peter Hart used polar coordinates \( r \) and \( \theta \) in order to avoid this problem\(^7\). The parametric form is shown in (3). The point \((r, \theta)\) in parameter space is corresponding to the straight line as shown in Figure 4. The number of point \((x', y')\) in image space on the line will determine the number of votes to detect the minimum line.

\[
r = x_c \cos \theta + y_c \sin \theta \tag{3}
\]

**Closed-loop System**

In designing a closed-loop control system, two types of input variables such as perpendicular distance and yaw angle are taken for measurement to control the heading of ASV. Perpendicular distance represents the distance between the camera that is mounted on the ASV and the shoreline. This distance is calculated in pixel after segmentation. Besides that, in ASV maneuvering system, only horizontal plane motion (in this case, yaw control) is considered. Thus, the perpendicular distance and yaw angle are measured to control the position and orientation (yaw) of ASV respectively. Both perpendicular distances, \( d \) and yaw angle, \( \Psi \) are taken from the center at the bottom of image captured by camera as shown in Figure 5. The yaw angle is the angle of perpendicular line of the green line relative to the bottom of image frame. It tends to keep the heading of the ASV to pointing towards straight.

Field of View (FOV) is the object area that is focused by the lens onto the image sensor.
Proportional control is a simple and widely used method for various types of control systems. The step input is set to the desired threshold value required for ASV to keep the distance between ASV and the shoreline. The error signal is the difference between the desired input signal and the feedback signal. The larger the error, the larger the control signal to drive the servomotor. Two proportional gains of $K_{p1}$ and $K_{p2}$ are chosen for perpendicular distance and yaw angle, respectively. The servomotor is used to drive the rudder and control the position of ASV. The desired position is set in order to keep a reference position of the ASV. P-controller for side-line heading and center-line heading are illustrated as shown in Figure 6(a) and Figure 6(b), respectively.

![Diagram of P-controller of ASV](image)

(a) Side-line heading, (b) Center-line heading.

The main aim of the control system is to maintain the reference position and the yaw angle of the ASV. The system is usually being designed in such a way that the ASV can move forward with constant speed, while the position is controlled by correction of rudder angle, $\delta$. The output from the system represents the desired direction of motion of ASV. Hence, the heading control is developed and used to make sure that the ASV is following the side-line or center-line.

**Obstacle Avoidance**

Most autonomous robots rely on range data for obstacle avoidance. The goal of the obstacle avoidance algorithms is to avoid collisions with obstacles. Optical flow is one of the techniques of feature tracking in image processing. It tracks the motion of features in a set of image frames. The current frame and previous frame are taken from the video to detect the feature change.

The gradient-based algorithms such as Lucas-Kanade algorithm, Horn-Schunk algorithm, and Image Interpolation algorithm (I2A) have been used a lot in motion estimation. In this paper, Lucas-Kanade algorithm is applied to the image sequences. This method assumes the displacement of the image contents between current frame and previous frame are small and it is constant within a neighborhood of the point $p$. Assume $3 \times 3$ windows of brightness value around the current pixels and all pixels are hold within the windows which is centered at $p$. Next, 9 equations are set up as in (4).

$$
\begin{bmatrix}
I_x(p_1) & I_y(p_1) \\
I_x(p_2) & I_y(p_2) \\
\vdots & \vdots \\
I_x(p_9) & I_y(p_9)
\end{bmatrix}
\begin{bmatrix}
V_x \\
V_y
\end{bmatrix}
= 
\begin{bmatrix}
I_x(p_1) \\
I_x(p_2) \\
\vdots \\
I_x(p_9)
\end{bmatrix}
$$

where $I_x$ and $I_y$ are the spatial derivative across the first image with respect to position $x$ and $y$, $I_t$ is the derivative between images over time, $V_x$ and $V_y$ are the velocity vector.

The equation is simplified into matrix form as $AV = b$ and the least squares principle is used to obtain the solution as in (5). Finally, the equation is computed as in (6).

$$
AV = b
$$

$$
V = (A^T A)^{-1} A^T b
$$

$$
\begin{bmatrix}
V_x \\
V_y
\end{bmatrix} = 
\begin{bmatrix}
\sum_{i=1}^{9} I_x(p_i) I_x(p_i) & \sum_{i=1}^{9} I_x(p_i) I_y(p_i) \\
\sum_{i=1}^{9} I_y(p_i) I_x(p_i) & \sum_{i=1}^{9} I_y(p_i) I_y(p_i)
\end{bmatrix}^{-1}
\begin{bmatrix}
\sum_{i=1}^{9} I_x(p_i) \\
\sum_{i=1}^{9} I_y(p_i)
\end{bmatrix}
$$

(6)
Lucas-Kanade algorithm for optical flow measurement is a fast calculation algorithm with accurate time derivative. Hence, a vision based algorithm is developed to detect the obstacles from image captured by the camera. The relative motion between the camera and the screen cause the change in structure intensities of an image. The larger the change in structure intensities, the nearer the obstacle is detected on the screen.

**Result**

*Simulation Result of Shoreline Detection and Obstacle Avoidance Algorithms*

The shoreline detection algorithm is tested on the set of 10 videos. The video is recorded from the Kerian River that is located in Nibong Tebal, Penang. There are 4 different types of algorithms that are tested and the results of the test are shown in Figure 7. The result shows that all of the images are able to detect the shoreline perfectly except for 4th image from Figure 7(c) due to the strong wave of water surface.

![Fig. 7 – Simulation results of shoreline detection.](image)

(a) Simplest thresholding, (b) Color segmentation, (c) Corner detection, (d) Adaptive water segmentation

**Optical flow** is applied to the video as shown in Figure 8. Each image is divided into 3 segments as right, left and center. Green color arrow is the difference between the current frame and previous frame. Figure 9(a) shows the result that the obstacle is detected at right side. It gives the comment that the boat need to turn left. Figure 9(b) shows the result that the obstacle is detected at the left side from a distance. So, it gives the comment for boat to stay at center due to less obstacle is detected at the center. The result of optical detection algorithm is operated correctly.

![Fig. 8 – Simulation result of obstacle detection.](image)

(a) Obstacle on the right, (b) Obstacle on the left

**Experimental Result of Heading Control Scheme**

According to Figure 10(a), the perpendicular distance, \( d \) is smaller than the desired input value. The result shows that rudder is able to rotate 45º and the ASV has moved to the right towards the desired value. Figure 10(b) shows that the perpendicular distance, \( d \) is larger than the desired input value. The rudder is able to rotate -45º and ASV has moved to the left towards the desired value. Figure 10(c) illustrates the ASV is moved in straight since there is no steady-state error.
According to Figure 11(a), the yaw angle, $\Psi$ is less than 90º. The result shows that ASV is turned left to capture the heading angle towards 0º. Figure 11(b) shows that the yaw angle, $\Psi$ is more than 90º. ASV is turned right to capture the heading angle towards 0º. Figure 11(c) illustrates the ASV is moved in straight line since the heading angle is 0º.

Experimental Result of ASV Travel along the Pool Side

The navigation process is carried out autonomously at the swimming pool located at the Universiti Sains Malaysia (Main Campus) by using ASV as shown in Figure 12. The starting points of the three tasks are A, B and C, respectively. Purple line represents the slope of the desired line. This line was estimated for ASV to navigate along the pool. The distance travelled from initial position to final position is around 20 meters. The overall process from starting point A to final destination is shown in Figure 13.
Fig. 13 – ASV is travelled along the pool side from (a) to (h)

The GPS location is obtained from GPS module. These data are sent to the microcontroller. The latitude and longitude coordinate are plotted by using Google Earth. These points are displayed on the google map as shown in Figure 14. The result verified that ASV is able to navigate along the pool side. Figure 15 shows the motion parameters of starting points A, B and C. The motion parameter of starting point, A is corresponded to Figure 14. The heading controller is able to guide the ASV to travel through the desired line. There is still an oscillation occurred during testing due to the short distance travelled.

Fig. 14 – Mapping location (side-line heading)

Fig. 15 – Motion parameters. (a) Plot of longitude versus latitude, (b) Graph of perpendicular distance against time, (c) Graph of heading direction against time, (d) Graph of rudder angle against time
Experimental Result of ASV Travel at the Center Line

The process is carried out at diving pool similar to one shown in Figure 8. However, ASV is operated by using center-line heading controller instead of side-line heading. Two lateral cameras are mounted onboard of ASV to detect both side of pool-line. Both sides of perpendicular distance are compared by center-line heading control to keep the center tracking in pool. Figure 16(a) and 16(b) are shoreline detection to port and starboard of the ASV at starting point. ASV is taken 30 seconds to reach the end of the pool as shown in Figure 16(i) and 16(j). Figure 17 shows the ASV can navigate through the center-line of pool.

Experimental Result of Obstacle Detection

The USB camera is connected on microcontroller and it is mounted in front of ASV. It captured frames continuously and it is undergone optical flow algorithm. Practically, the algorithm is operated correctly. However, there is a difficulty to apply this algorithm since the pool is narrow. In addition, the bottom of diving pool has several black lines that are considered motion of features when applying the algorithm. All of view in front of camera is detected as obstacles as shown in Figure 18(a). This makes algorithm difficult to give a decision in order to avoid the obstacle. It needs to apply filter and eliminate the black line in order to track the obstacle as shown in Figure 18(b) and Figure 18(c).

Discussion

A Wi-Fi module is an additional feature to allow code editing, live video stream and autonomous control of the ASV. Interfacing of Wi-Fi module and microcontroller board has been done. It is installed on the ASV and added to the system to transmit and receive the signal. It sends the information for operation control like rudder and propeller control. Thus, a Wi-Fi router is utilized to handle wireless communication between ASV and laptop.

Algorithms are developed to reliably detect the shoreline as well as obstacle. During the algorithm development stage, the algorithm is tested to make sure it is implemented correctly. In simulation result, it clearly shows that the shoreline detection algorithm and the obstacle
avoidance algorithm are working successfully to perform the task. The shoreline and obstacle can be detected correctly throughout the videos. Since the water color distribution and light reflection on the river may introduce disturbance to the system, the algorithm might need to be further improved to identify the shoreline as well as detecting the obstacles.

P-controller with closed-loop system is tested and operated correctly. Rudder controller is implemented to change the ASV’s heading. This makes the ASV to travel at the constant speed in desired line. The ASV able to complete the desired lap on short duration while keeping the error to minimum. Hence, a fast response of the feedback control system is achieved using P-controller.

The data logging system as a computer application is developed on microcontroller board. The application is successfully developed with real time sensors reading. These data could be logged over a long period of time. Heading and position information can be obtained from data that is collected since ASV’s heading is the most significant of all the navigation parameters. The location of GPS is recorded and displayed on the Google Map.

The experimental results from image analysis and motion parameters demonstrated that the proposed method can guide the ASV to travel along the pool side and center line correctly. Hence, the ASV is able to navigate along the diving pool.

Conclusion

It can be concluded that the navigation system has proven to be a success in diving pool by detecting the waterline. The ASV can travel along the pool side and center line without false triggering by detecting the false waterline. The concept of the system can be applied to ASV with better accuracy of GPS system and better obstacle avoidance system. The outcome from this research able to provide a proof of concept for ASV river navigation system and it can be further improved by time.

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