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MODELING AND MOTION CONTROL OF A RIVERINE AUTONOMOUS SURFACE VEHICLE (ASV) WITH DIFFERENTIAL THRUST

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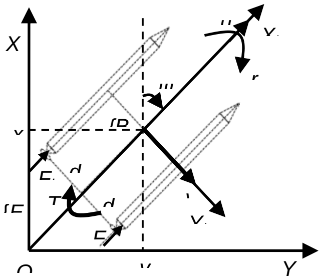
Graphical abstract



Abstract

It is challenging that *Autonomous Surface Vehicle* (ASV) navigated in the riverine environment since the unknown and unstructured waterway, and the non-uniform riverbanks makes the waterway tracking difficult. This paper presents a catamaran type Autonomous Surface vessel (ASV) for autonomous bathymetry survey and environmental monitoring at riverine areas. The ASV is equipped without rudder, thus it is driven by differential thrust to control the speed and heading. The theoretical 3 DOF model of ASV and differential thrust steering dynamics is discussed. The aim is to perform the visual navigation that track along with the river by keeping in the center of river. Meanwhile, the speed is required to vary with the width of river to avoid collision. In order to perform the control aims, a balance control scheme is designed. The results indicate that the proposed control scheme is successful for the navigation task.

Keywords: Riverine Aunonomous surface vessel, differential thrust, model of ASV, balance control

Abstrak

Adalah agak mencabar untuk *Autonomous Surface Vehicle* (ASV) bernavigasi dalam persekitaran sungai kerana jalan air yang tidak diketahui dan tidak berstruktur dan tebing sungai yang tidak seragam menjadikan penjejakan jalan air susah. Kertas kerja ini mempersembahkan jenis calamaran Autonomous Surface Vehicle (ASV) untuk kajiselidik batimetri autonomi dan pengawasan persekitaran pada kawasan sungai. ASV dilengkapkan tanpa kemudi, jadi ia digerakkan oleh tujahan perbedaan untuk mengawal kelajuan dan arah. Model 3 DOF ASV dan dinamik tujahan perbezaan arah dibincangkan. Tujuan ialah untuk menjalankan navigasi visual yang menjejak sungai dengan memastikan ianya di tengah sungai. Kelajuan diperlukan untuk berubah dengan lebar sungai untuk mengelak perlanggaran. Untuk mencapai tujuan kawalan, skema kawalan seimbang telah direka. Hasil menunjukkan kawalan yang dicadangkan berjaya untuk tugas navigasi.

Kata kunci: *Autonomous Surface Vehicle*, tujahan perbezaan, model ASV, kawalan seimbang

1.0 INTRODUCTION

In general, riverine environment is poorly known and unstructured, with restricted and narrow waterways, non-uniform riverbanks, depths and currents, floating debris (Stilwell & Woolsey, 2011) [1]. All these factors make the autonomy of ASV challenging. The traditional GPS+INS system is not able to achieve the navigation in complex riverine environment thus vision based navigation is needed.

Visual cues such as color, texture, optical flow etc. are used for unmanned system navigation [2]. In addition, marine craft based on standardised rules, COLREGs are also designed as compliant obstacle avoidance system [3]. Han Wang [4] developed a real time vision system to detect and locate multiple obstacles on the sea surface by using both the monocular and stereo vision methods. The sea-sky line was detected to identify the sea surface as background. Then the color and texture cues were used to extract the objects. Kalman filter was used to estimate the trajectory of objects. Michael T. Wolf [5] used an omnidirectional camera to realize the 360 degree central perception and situation awareness system and performed other vessels tracking. Terry Huntsberger [6] used Hammerhead vision system as stereo vision to detect objects and generate grid-based hazard maps and discrete contact lists. Static obstacle avoidance and dynamic target following were achieved by a R4SA control system.

This paper presents a catamaran ASV developed by URRG (Underwater Robotic Research Group, Universiti Sains Malaysia) for autonomous bathymetry survey and environmental monitoring at riverine areas. It is based on the previous work reported in [7]. This ASV is equipped with GPS and vision system for heading and speed control, and sensors for depth mapping and environmental monitoring. As shown in Figure 1, two lateral cameras are mounted on ASV as vision system to detect the left and right side positions of riverbanks as the distances from ASV. This ASV is required to track along with the river by keeping in the center of river. This navigation purpose is achieved by a designed balance control scheme to control the heading and speed with the changing position of riverbanks.

In Figure 1, D_L' and D_R' is the left and right distances from riverbank to ASV respectively. The ASV heading is controlled by comparing the two distances to keep the ASV travelling in the center of river. For instance, if $D_L' > D_R'$, then turn the orientation of ASV to left, and vice versa. The speed is controlled by width of river, if $(D_L' + D_R')$ is becoming greater, the ASV speed will increase, otherwise it will decrease.

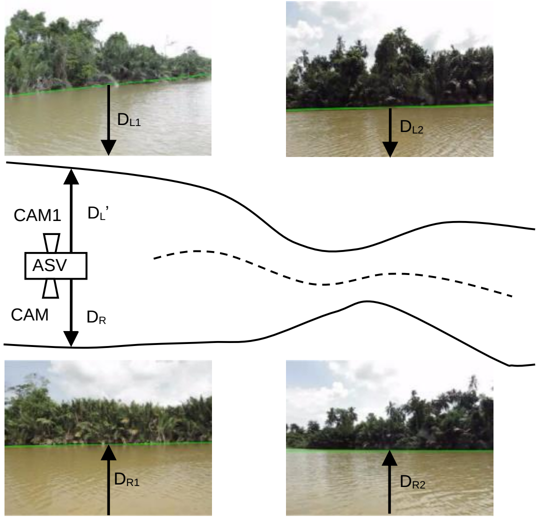


Figure 1 Illustration of ASV navigation in river

The riverbank is detected as straight line in the image which has been completed in previous work [7]. Since the control objective is to keep the ASV in the center, the distances from left and right side riverbank are compared without accurate measurement. In this case, the distances D_L' and D_R' are represented by height of D_L (D_{L1}, D_{L2}) and D_R (D_{R1}, D_{R2}) respectively in Figure 1. Particularly, the height of D_L and D_R are not measurements of D_L and D_R, but are monotonically increasing with D_L' and D_R'. Hence D_L and D_R are computed by pixels and used to control the heading of ASV.

The organization of the paper is as follows. Section 2 presents the 3 DOF planar model of ASV and the differential thrust dynamics. And the specifications of the developed ASV are listed. Whilst Section 3 addresses the balance control scheme for the navigation objects. The simulation results for the proposed method are presented in Section 4 followed by the conclusion in Section 5.

2.0 THREE DOF MODEL OF ASV AND DIFFERENTIAL THRUST DYNAMICS

Most of the ASVs are equipped without transverse propeller, thus the autopilots are performed by forward propeller and rudder. This means that the only two control variables are used to control a 3 DOF motion, heading and position (x, y) of ASV.

2.1 Three DOF Model of ASV

With the assumption that,

(1) The hull is symmetrical on $O_b X_b Z_b$ planar.

(2) The environment disturbances are considered to be slowly time-varied process.

Then 3 degrees of freedom model is indicated as follows,

$$\begin{cases} \dot{\eta} = J(\eta)\nu \\ M\nu + C(\nu)\nu + D(\nu)\nu = \tau \end{cases} \qquad (1)$$

where matrices $J(\eta)$ is the transformation matrix for converting from body-fixed frame to earth-fixed frame; M is a mass matrix; $C(\nu)$ is a Coriolis matrix; and $D(\nu)$ is the summation of linear and nonlinear drag matrices, $D(\nu) = D + D_n$. The expression and detailed calculation of these matrices could be introduced in [8].

2.2 Differential Thrust Steering Dynamics

In Equation (1), τ is a vector that contains the sum of all other forces and moments acting on the ASV.

$$\tau = \begin{bmatrix} (F_l + F_r) \\ 0 \\ (F_l - F_r) * d \end{bmatrix} \tag{2}$$

where F_l and F_r are the port and starboard forces respectively, which are provided by differential thrust. d is the side hull separation (from hull centerline to ASV centerline) [9].

From Figure 2 we can see that the steering of ASV is based on differential thrust. If $F_l = F_r$, the ASV will move in a straight line. If F_l and F_r are not equal, it will cause a heading change of ASV. In some cases, the ASV is required to maintain a constant speed. Therefore, the force F_l and F_r could be decomposed into,

$$F_l = F + \Delta F / 2 \tag{3}$$

$$F_r = F - \Delta F / 2 \tag{4}$$

where F and ΔF are magnitudes of the collective thrust differential thrust respectively. In this case, F is to control speed and ΔF is to control the heading.

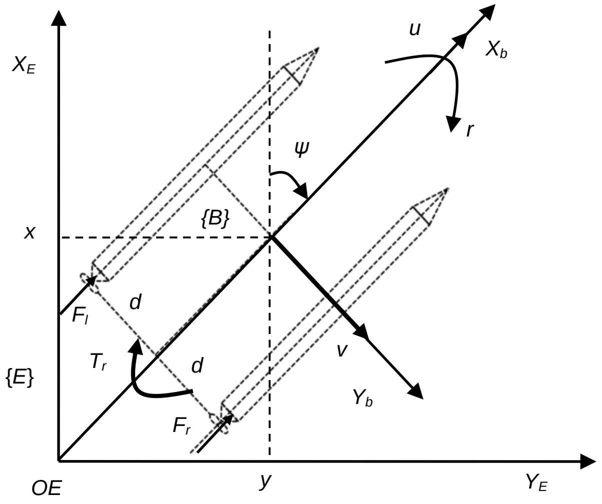


Figure 2 Planar model of the ASV with differential thrust

3.0 HEADING AND SPEED CONTROL SCHEME

ASV in this paper is expected track along the river by keeping center of river. Thus the heading should be changed with the position of both sides of riverbanks. Since the river environment is unstructured, the distance of left and right side riverbank should be equal to make sure the ASV is on the centerline of river. As shown in Figure 2, the position of riverbank is detected as straight line by lateral CAMs. The distance from riverbank to ASV is represented as height of detected riverbank line (D_L, D_R) in image. This work has been competed in [7]. In addition, the forward speed is controlled by width of river which means that speed is varied with ($D_L + D_R$). The balance control scheme is designed for heading and speed control, as shown in Figure 3.

3.1 Heading Control

(D_L - D_R) in Figure 3 is the value difference of left and right distances from riverbank. This is to control orientation to make sure the ASV is travelling in the centre of river. When $D_L > D_R$, means that the ASV is nearer to right side riverbank, so the heading controller will control the rudder to turn left. When $D_L < D_R$ means that the ASV is nearer to left side riverbank, then the heading controller will control the rudder to turn right. When $D_L = D_R$, means that the ASV is moving in centre of river, then keep the heading.

Thus a PD controller is designed as heading controller:

$$\delta = K_p \times (D_L - D_R) + T_d \times r \tag{5}$$

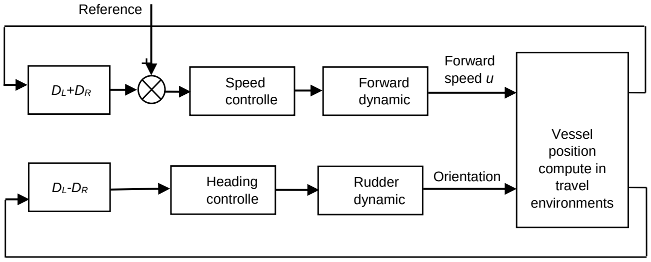


Figure 3 Balance control scheme of ASV

where δ is angle input for heading control; K_p is proportional gain and T_d is differential gain of heading controller; r is yaw rate of ASV.

3.2 Speed Control

Since the width of river is changing in practical environment. Thus the speed should be controlled to avoid collision with riverbank when the river is very narrow. In Figure 3, the ASV speed varies with respect to width of river ($D_L + D_R$). When value of ($D_L + D_R$) is greater, which means that the river is wider as demonstrated in the left part of Figure 2, the ASV will move at higher speed. Similarly, the ASV will move at lower speed when the river is narrower to decrease the risk of collision to the riverbank. For instance, in left part of Figure 2 the distance value ($D_{L1}+D_{R1}$) > (D_{L2}+ D_{R2}), which can be seen that the right part of river is narrower than left part. Thus the ASV will move slower when it travels from left part to right part.

A specified value of river width is set as reference to determine a specified speed. Here the reference width is 40m, and the corresponding speed is 2m/s. When ($D_L'+D_R'$) =40m, the ASV will keep the speed of 2m/s; when ($D_L'+D_R'$)>40m, the speed of ASV will increase; when ($D_L'+D_R'$) <40m, the speed of ASV will decrease.

Thus a Proportional controller is designed as speed controller:

$$U = K_p \times (D_L + D_R) \tag{6}$$

where U is the speed of ASV, and K_p is proportional gain to control the forward force F.

4.0 SIMULATION RESULTS AND DISCUSSIONS

4.1 Heading and Speed Control Simulation Results

The specification of this catamaran ASV is presented in [10], in which the length=1.5m, width=1m, height=0.5m, weight=50 kg (with batteries). Then the model could be obtained according to the formula in Section 2.

The balance control scheme presented in Section 3 is applied to this ASV. In order to test the performance of proposed control method, four cases are simulated in Matlab, and the results are shown in Figure 4, Figure 5, Figure 6 and Figure 7. A reference speed is set as 2m/s in all these cases. The heading is controlled by a PD controller while speed is controlled by a P controller as presented above.

Figure 4 shows the case that ASV is controlled to maintain a course with yaw angle ψ = 10° and speed = 2m/s. From Figure 4(a) we can see that the ASV is moving on a straight line and the steady state of yaw angle ψ = 11.131° which is indicated in Figure 4(b). Thus steady state error of heading is (11.131-10)/10×100%= 11.31%. Since the ASV is driven by differential thrust, the steady state speed U =1.999m/s and input angle caused by differential thrust δ =1.132°. This result is similar with the case that ASV equipped with common propeller-rudder system.

Figure 5 shows a case that ASV is required to travelling in the centre of river. The two vertical axes in Figure 5(a) represent the left and right detected riverbank lines as a simulated visual environment, which means that the width of river is constant. The ASV is required to travel along with the river by keeping in the centre of the river. The position of middle line of two riverbank lines is calculated as the value of y= -10 and indicated in Figure 5(a). The ASV is start from the initial position of (0, 0). The steady state position of ASV is tracking along with the line of y=-8.426. Thus the steady state error is (10-8.426)/10×100%=15.74%. This is because that the PD controller cannot eliminate steady state error. In Figure 5(b), the steady state of speed U =1.999m/s, which indicates that the speed control is quite accurate.

Figure 6 shows a case that the river is becoming wider when ASV is moving. The riverbank in this case is defined by two symmetrical straight lines, as shown in Figure 6(a). Similarly, the middle line and ASV initial position is indicated. The steady state position of ASV is tracking along with the line of y=-8.587, and the error is 14.13%. Since the speed of ASV varies with the width of river by a P controller, the speed is increasing proportionally, which is indicated in Figure 6(b).

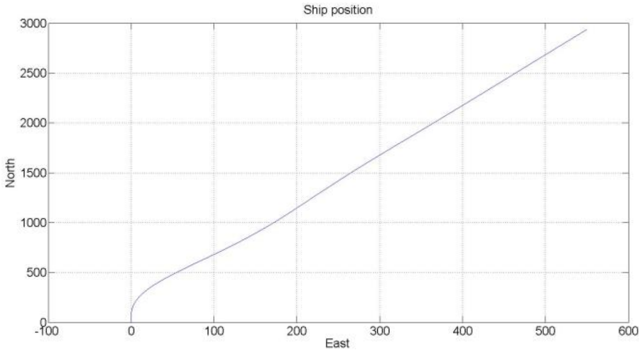


Figure 4(a) ASV motion with yaw angle ψ= 10°, speed U=2 m/s

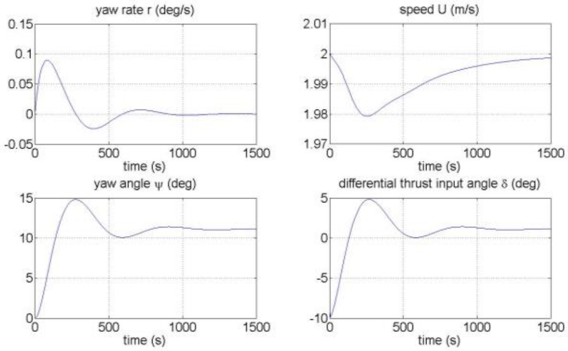


Figure 4(b) Motion parameters

Figure 5(a) Motion control with constant river width

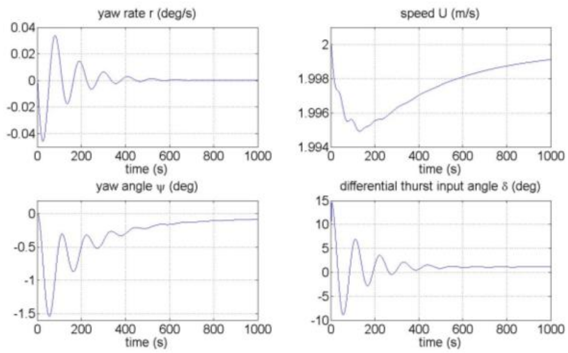


Figure 5(b) Motion parameters

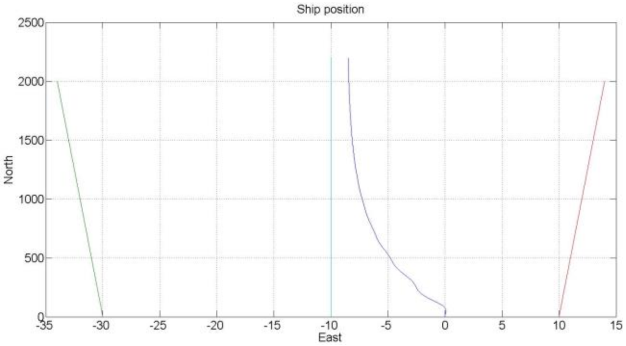


Figure 6(a) Riverbank becomes wider

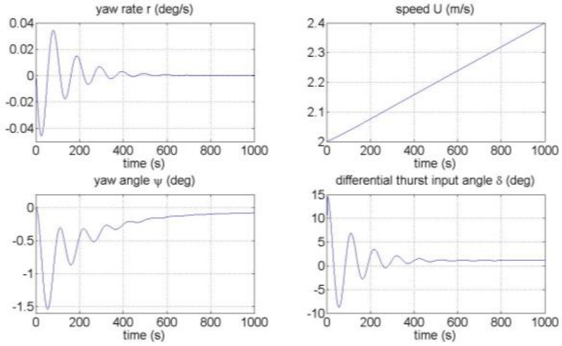


Figure 6(b) Motion parameters

Figure 7 shows a case that the river is becoming narrower when ASV is moving. This requires that the ASV moving slower with respect to the width of river. Similar with the case in Figure 7, the steady state position of ASV is tracking along with the line of $y=-8.333$, and the error is 16.67%. The speed is decreasing proportionally, which is indicated in Figure 7(b).

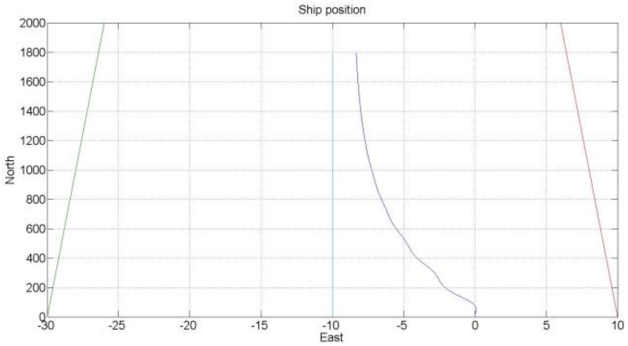


Figure 7(a) Riverbank becomes narrower

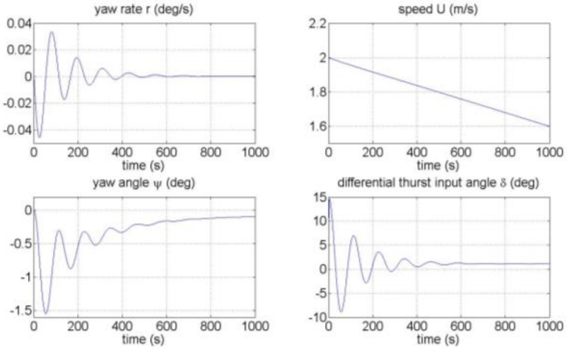


Figure 7(b) Motion parameters

4.2 Simulation Results from Real River Data

To verify the performance of proposed balance control scheme, the real river map is applied to get the simulation result. Figure 8 illustrates part of a river from google map, with name of Sungai Kerian that is located in Nibong Tebal, Penang, Malaysia, near Universiti Sains Malaysia Engineering Campus. The length of this part of river is 1064 m, with maximum width of 166 m and minimum width of 56 m. In this part of river, it is assumed that,

(1) No shallow water
(2) No rapids disturbance
(3) No obstacles

which means that the ASV is able to traverse in the whole water surface without obstacles, and ASV is assumed moving in the calm water, and the current and wave disturbances are not involved.

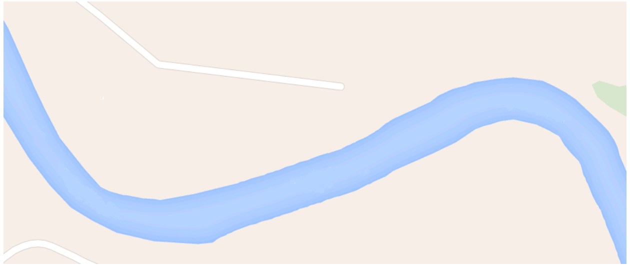


Figure 8 Sungai Kerian river map from google map

The river map is processed firstly to obtain the riverbank lines and extract the Cartesian coordinates for ASV navigation. In Figure 9(a), the green lines are the left and right riverbank lines extracted from Figure 8. The ASV is expected to track along the river and keep in the center of river. Thus, the centerline of river is calculated and shown as blue dash line in Figure 9(a). The red line is the simulated ASV trajectory with balance control scheme that presented in section 3. The result shows that the ASV is basically moving along with the river with acceptable position error.

The initial position of ASV is set to (0, 0), and offset to centerline is 15m. Figure 9(a) shows two bends in this part of river, and the result shows that the proposed balance scheme and PD controller are sufficient for ASV to negotiate the bends. Since PD controller is not capable of eliminating steady state position error, the simulated trajectory does not coincide with river centerline.

To evaluate the position error performance, the average distance from centerline to ASV trajectory is calculated,

$$meanerror = \frac{\sum_{1}^{N} |y_c - y|}{N} \tag{7}$$

where y_C is longitudinal coordinates of centerline and y is the longitudinal coordinates of ASV trajectory, N is number of simulation samples. The simulation shows that the average position error is 7.8547 m, and the average width of river is 78.0234 m, thus the average position error is 10.07%.

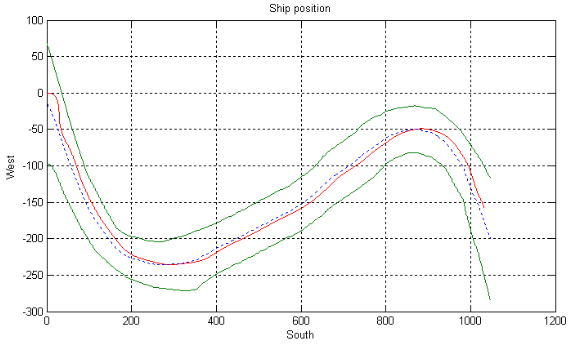


Figure 9(a) Simulation results from real river data

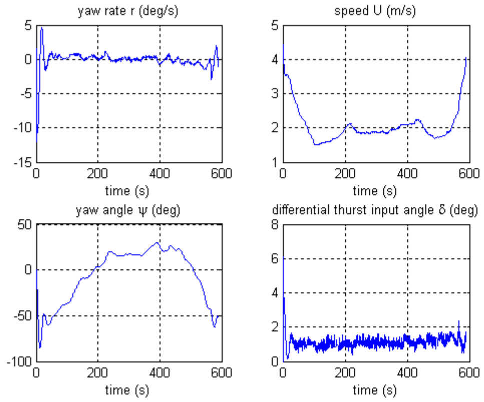


Figure 9(b) Motion parameters.

Figure 9(b) is the motion parameters corresponding to Figure 9(a). The ASV speed is set to vary with width of river, therefore the maximum speed is 4.4322 m/s and minimum speed is 1.4942 m/s, with respect to maximum and minimum width of river of 166 m and 56 m respectively.

4.3 Discussion

Figure 4 to Figure 7 show the heading and speed control simulation results in different cases. All the water environment such as riverbank lines are generated in MATLAB to test the navigation performance of proposed balance control scheme. More specifically, the ASV is able to keep in the center of river when river width is changing, such as becoming wider and narrower.

Figure 9 shows a simulation result from real river data, and the riverbank lines in this result are extracted from google map. The result verifies that ASV is able to be navigated in the real river. The heading controller guides the ASV travelling through the bends of river and being close to the centreline of river. The speed is changing with the width of river to ensure that ASV is moving in a safety state.

These simulation results are performed with assumption that ASV is moving in obstacles free water area, thus the proposed method alone is not sufficient to be applied to real river navigation. For real application, an OA (obstacle avoidance) algorithm has to be combined with the proposed balance control scheme. Steady state position error cannot be eliminated in this simulation since PD controller is used for quick response. It is supposed to be better if integral element is added to compose PID controller.

5.0 CONCLUSION AND FUTURE WORK

This paper presents modeling and motion control of a differential thrust ASV that developed by URRG (Underwater Robotic Research Group, Universiti Sains Malaysia) for autonomous bathymetry survey and environmental monitoring at riverine areas. The modelling of ASV and differential thrust steering dynamic is discussed, and a balance control scheme is proposed for the motion control with visual navigation. The ASV in this paper is expected to be navigated in the river by keeping in the centre of river and speed is able to vary with the width of river. The simulation results show that the ASV could perform these requirements with the proposed control method. When river width is becoming wider and narrower, the ASV is able to keep the heading and control the speed. Also, the ASV is proved to be able to negotiate the bends of river without collision with the riverbank, and the heading and speed is controlled well.

Future work will consist in obstacle avoidance algorithm and experiment in real riverine environment. The riverine trial will be done to obtain the parameters of environment disturbances. The vision system will be calibrated to calculate the distances from riverbank by image cues. After that, the controller parameters will be tuned and combined with obstacle avoidance method to perform the complete real riverine navigation and environmental monitoring of ASV.

Acknowledgement

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