HYBRID BALANCE ARTIFICIAL POTENTIAL FIELD NAVIGATION SYSTEM FOR AN AUTONOMOUS SURFACE VESSEL IN RIVERINE ENVIRONMENT

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HYBRID BALANCE ARTIFICIAL POTENTIAL FIELD NAVIGATION SYSTEM FOR AN AUTONOMOUS SURFACE VESSEL IN RIVERINE ENVIRONMENT

by

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DEDICATION

To my parents and family,

My brother and sister,

For their endless love, support, and encouragement.

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LIST OF SYMBOLS

CR	collision risk
$C_{ND}(\lambda)$	coefficients on Z direction
$C_{XD}(\lambda)$	coefficients on X direction
$C_{YD}(\lambda)$	coefficients on Y direction
d	side hull separation (from hull centerline to ASV centerline)
d_m	distance threshold
d_r	environmental force disturbance on yaw
d_u	environmental force disturbance on surge
d_v	environmental force disturbance on sway
$d(X_R, X_G)$	the distance from robot to the goal
$d(X_R, X_o)$	distance from obstacle to robot
$D_{L'}$	left distances from riverbank to ASV
$D_{R'}$	right distances from riverbank to ASV
D_L	image height of $D_{L'}$
D_R	image height of $D_{R'}$
E_d	Euclidean distance between the two points
E_{ld}	the Euclidean distance between two lines
F	magnitudes of the collective thrust
F_{att}	attractive force operated on the ASV
F_l	port force
F_r	starboard force
F_{repi}	repulsive force of the ith obstacles
F_u	control inputs provided by propeller

ΔF	differential thrust
K	forces and moments rotation in the *x*-direction (roll, heel)
K_a	attractive potential field constant
$\mathrm{K}_{\mathrm{att}}$	scalar parameter
K_C	scale coefficient
K_p	proportional gain
K_r	repulsive potential field constant
K_v	scalar parameter
$mean$	the average value of the matrix
M	forces and moments rotation in the *y*-direction (pitch, trim)
N	forces and moments rotation in the *z*-direction (yaw)
n_{obs}	the number of obstacles
$\mathbf{n}_{\mathrm{RO}}$	unit vector pointing from the robot to the obstacle
p	angular velocities rotation in the *x*-direction (roll, heel)
$\mathbf{p}(\mathrm{t})$	positions of robot
$\mathbf{p}_{\mathrm{tar}}(\mathrm{t})$	positions of target
q	angular velocities rotation in the *y*-direction (pitch, trim)
r	angular velocities rotation in the *z*-direction (yaw)
s	element of water color sampling patch matrix
T_d	differential gain of heading controller
T_r	control inputs provided by rudder
u	linear velocities in the *x*-direction (surge)
U	speed of ASV
U_T	peed value of absolute wind
u_R	component of U_R
v	linear velocities in the *y*-direction (sway)

v_0	velocity of own ship
v_c	velocity of the water current expressed {B}
v_R	component of U_R
v_T	velocity of target ship
$\mathbf{v}_{\mathrm{tar}}(\mathrm{t})$	velocities of robot
$\mathbf{v}(\mathrm{t})$	velocities of target
w	linear velocities in the z-direction (heave)
x	position in the x-direction (surge)
X	forces and moments in the x-direction (surge)
x_0	position of own ship
x_{obs}	position of the obstacles in the x-direction
x_T	position of target ship
y	position in the y-direction (sway)
y_0	position of own ship
y_{obs}	position of the obstacles in the y-direction
y_c	longitudinal coordinates of centreline
y_T	position of target ship
Y	forces and moments in the y-direction (sway)
z	position in the z-direction (heave)
Z	forces and moments in the z-direction (heave)
α_p	scalar parameter
α_v	scalar parameter
β	drift angle
χ	wave encounter angle
δ	angle input for heading control

ϕ	Euler angles rotation in the *x*-direction (roll, heel)
φ_0	course of own ship
φ_T	course of target ship
γ	polar coordinate
η	the scalar parameter
λ	wavelength
θ	Euler angles rotation in the *y*-direction (pitch, trim)
θ_{ref}	reference heading angle
ρ	the distance from robot to obstacle
ρ_o	influence range of obstacle
τ	tolerance factor
ψ	Euler angles rotation in the *z*-direction (yaw)
ζ_D	mean wave amplitude

LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
AIS	Automatic Identification System
ANN	Artificial Neural Network
APF	Artificial Potential Field
ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
CAMs	Cameras
COLREGs	The International Regulations for Preventing Collisions at Sea
DC	Direct Current
DAPF	Dynamic Artificial Potential Field
DCPA	Distance of Close Point of Approaching
DGPS	Differential GPS
DOF	Degree of Freedom
EA	Evolutionary Algorithm
GA	Genetic Algorithm
GPS	Global Position System
IMO	International Marine Organisation
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LOS	Line-of-sight
NGC	Navigation, Guidance and Control
ODA	Obstacles Detection and Avoidance
PD	Proportional-Derivative
PID	Proportional-Integral-Derivative
SAR	Synthetic Aperture Radar
UAV	Unmanned Aerial Vehicles
UGV	Unmanned Ground Vehicles
USV	Unmanned Surface Vehicle
VCD	Variance of Compass Degree
VTS	Vessel Traffic Service

SISTEM NAVIGASI MEDAN KEUPAYAAN BUATAN SEIMBANG HIBRID UNTUK KENDERAAN PERMUKAAN BERAUTONOMI DI DALAM PERSEKITARAN SUNGAI

ABSTRAK

Keperluan kepada Kenderaan Permukaan Berautonomi (ASVs) bagi aplikasi-aplikasi seperti pengukuran Bathymetri Sungai dan pengawasan persekitaran semakin meningkat sejak akhir-akhir ini. Walaubagaimanapun, secara relatifnya, kesukaran masih wujud bagi navigasi berautonomi platform ASVs yang terkesan dengan faktor-faktor tidak diketahui dan laluan air tidak berstruktur, dan kewujudan halangan-halangan objek statik dan dinamik. Platform ASV memerlukan takat keupayaan autonomi dan kepintaran tertentu untuk megambil keputusan dan melakukan analisa risiko bagi navigasi berautonomi yang selamat. Terdapat dua isu yang berkait dengan navigasi berautonomi sungai bagi ASV; pemodelan persekitaran sungai dan perancangan jejakan secara autonomi dan pengelakan objek. Maka, matlamat penyelidikan ini adalah untuk membangunkan algoritma pengenalpastian persekitaran sungai, dan algoritma penjejakan sungai dan pengelakan objek. Bagi algoritma pengenalpastian persekitaran sungai, bahagian tebing sungai dipilih sebagai isyarat visual untuk penjejakan sungai. Terdapat kesukaran-kesukaran untuk menentukan tebing sungai kerana faktor-faktor seperti perubahan warna dengan keadaan pencahayaan, balikan air dan gambaran rumit bagi paparan tumbuhan-tumbuhan sepanjang tebing sungai. Bagi mengatasi masalah ini, algoritma pembezaan warna terhad penjelmaan Hough dicadangkan. Bagi menilai prestasi kaedah yang dicadangkan, ralat purata dan varians telah dikira. Jarak Euclidean bagi garisan-garisan yang dikesan daripada titik benar telah digunakan untuk

membandingkan prestasi kaedah yang dicadangkan. Purata ralat lencongan bagi kaedah yang dicadangkan, kaedah segmentasi warna dan kaedah penjelmaan Hough adalah 3.145 piksel, 16.736 piksel dan 27.507 piksel. Ralat lencongan varians bagi ketiga-tiga kaedah adalah 0.099, 5.467 dan 19.749. Bagi masalah jejakan sungai, satu skim kawalan seimbang dicadangkan dengan sasaran menyelesaikan jejakan sungai dan pengelakan halangan secara serentak. Kaedah hibrid seimbang-APF yang dicadangkan adalah kaedah yang tidak menggunakan maklumat GPS bagi navigasi sungai dan ini bermaksud ia sesuai untuk kes tanpa maklumat pemetaan sungai. Halangan-halangan statik dan dinamik di dalam sungai telah digunakan untuk mengesahkan kaedah seimbang-APF yang dicadangkan. Keputusan-keputusan menunjukkan kaedah seimbang-APF telah berjaya untuk menyelesaikan jejakan sungai dan pengelakan halangan-halangan secara serentak. Sebagai tambahan, Ketetapan berkenaan Peraturan Antarabangsa untuk Pengekangan Pelanggaran di Laut (COLREGs) telah digabungkan ke dalam sistem navigasi ASV yang telah membolehkan ASV mematuhi peraturan-peraturan piawai trafik marin. Daripada adaptasi keperluan COLREGs, platform ASV boleh melakukan navigasi secara selamat bagi sebarang pertembungan di sungai seperti pengelakan halangan statik dan dinamik, pertembungan berhadapan dan pergerakan memintas. Secara ringkasnya, sebuah sistem navigasi persekitaran sungai berasaskan penglihatan berautonomi untuk ASV telah berjaya dibangunkan.

HYBRID BALANCE ARTIFICIAL POTENTIAL FIELD NAVIGATION SYSTEM FOR AN AUTONOMOUS SURFACE VESSEL IN RIVERINE ENVIRONMENT

ABSTRACT

The demands of Autonomous Surface Vessels (ASVs) for applications such as river bathymetry survey and environmental monitoring are increasing rapidly. However, it is still relatively challenging for the ASVs platform to navigate autonomously due to factors such as unknown and unstructured waterway, and the presence of static and dynamic obstacles. The ASV platform needs some level of autonomy and intelligence in order to make reasonable decisions and risk analysis for safe autonomous navigation. There are two issues related to ASV autonomous riverine navigation; river environment modelling and autonomous path planning and obstacles avoidance. Thus, the objectives of the research are: to develop a riverbanks identification algorithm for ASV navigation; and to develop a marine traffic rules compliant navigation and obstacles avoidance algorithm for ASV in the unstructured riverine environment. The riverbanks are selected as the visual cues for the river tracking. The issues of recognising the riverbanks include factors such as color variation with the light condition, water reflection and the complex scene of plants on the riverbanks. In order to overcome these issues, a Color Segmentation Constrained Hough Transform Algorithm is proposed. The results show that the proposed method identified all the riverbanks successfully. To evaluate the performance of the proposed method, the average and variance error deviation are calculated. The Euclidean distances of detected lines from ground truth are used to compare the accuracy of the proposed method. The average error deviation of the proposed method, color segmentation method, Hough Transform method are 3.145 pixel, 16.736 pixel and 27.507 pixel, respectively. The variance error deviation of the three methods are 0.099, 5.467 and 19.749, respectively. For the river tracking problem, a balance control scheme is proposed in order to achieve simultaneous river tracking and obstacles avoidance. The proposed Hybrid Balance-Artificial Potential Field (APF) method is a method that does not utilize the GPS information for the river navigation which means that it is suitable for the case without known river map. Static and dynamic obstacles in the river are used to verify the proposed balance-APF method. The simulation results show that the Hybrid Balance-APF method successfully achieved simultaneous river tracking and obstacles avoidance. In addition, convention on the International Regulations for Preventing Collisions at Sea (COLREGs) is integrated into the ASV navigation system, which makes the ASV able to abide by the standard marine traffic rules. From the adaptation with COLREGs requirements, the ASV platform can navigate safely from typical riverine encounter such as static and dynamic obstacles avoidance, head-on and overtaking encounter. In summary, feasible autonomous riverine environment navigation system for ASV has been successfully developed.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Water transportation is an ancient mode of transportation. More than 90% of the global trade are achieved by water transportation (Dobbins & Abkowitz, 2002). Owing to the advantages of large volume of transport, low energy consumption, low cost, less space occupied, water transportation has irreplaceable advantages in the comprehensive transportation system of the world. With the development and increasing demands of inland river shipping, the number of floating crafts/ships increases rapidly. The risks of marine traffic accidents such as collision of ships and collision of ships with bridges are also increasing, which seriously threaten the safety of navigation of ships and the ecological environment of rivers. Thus it becomes more challenging to deploy an Autonomous Surface Vehicle (ASV) on the river – without colliding or crashing into the other ships/boats.

As an unmanned platform, Autonomous Surface Vehicle (ASV) which is also called Unmanned Surface Vehicle (USV), is able to undertake long-term, large-scale and low-cost marine scientific research and engineering missions in the water area (Bertaska et al., 2015; Murphy et al., 2011). Therefore, unmanned craft has an extremely wide application prospect in civil and military fields, such as hydrological information collection, underwater topography survey, environmental monitoring and surveillance, and various military applications (Bertaska et al., 2013; Casalino, et al., 2009; Kitts et al., 2012; Sarda & Dhanak, 2014).

Compared with the well known Unmanned Aerial Vehicles (UAVs), Autonomous Surface Vehicle (ASV) is still being stranged for people although it has appeared for more than 70 years (Manley, 2008). It is a member of four unmanned vehicles families, other unmanned vehicles include Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs) and Autonomous Underwater Vehicles (AUVs). Same as other unmanned vehicles, ASVs are widely used in complex environments for harsh and dangerous missions (Bertram, 2008; M Breivik, 2010; Roberts & Sutton, 2012). The complex water environment normally refers to the water area with wave, current, or obstacles. ASV technology has great potential for further development in many aspects, such as the design of the hull, propeller system, and control system. As an unmanned platform, ASV has the following characteristics:

i. ASV has certain autonomous mobility, it is able to carry out dangerous tasks, but the crew is not in danger of life. It shows certain intelligent features, and can automatically execute specific tasks according to the requirements of users with strong autonomy and adaptive ability such as target tracking and obstacles avoidance (Liu & Bucknall, 2015).
ii. Activities of ASV are not easily affected by the environment, such as climate, and can be arranged to perform tasks in specific areas for a long time without considering the adaptability of personnel (Kitts et al., 2012). Therefore it has a wide range of activities, low operating cost, is able to work in shallow water areas such as in ports and other areas.
iii. ASV can collaborate with other unmanned platforms, such as UAV, UGV, and AUV, to form heterogeneous communication and surveillance networks (Huntsberger & Woodward, 2011). The network will have unique situational awareness, which is helpful to the realization of the network-centric platform. It is able to communicate

with an underwater and above water devices at the same time, or work as a relay station. ASV could also be used to track the target such as moving ship, which will significantly improve the ability of ships to perform various monitoring tasks.

The present chapter is organized as follows: Section 1.1 describes the research background. The problem statements are described in Section 1.2. Section 1.3 presents the research objectives, while Section 1.4 describes the research scope in order to fulfill the research objectives. Finally, Section 1.5 presents the thesis outline.

1.2 Problem Statements

The ASV in this research is required to cruise in river area. Thus, the problems for ASV riverine navigation are studied. The river environment is a confined water area, where the ASV's motion is limited by the riverbanks. ASV navigated in river is similar with the mobile robot moving in corridor. However, generally the river environment is more complex because the river is natural and unstructured. More specifically, a fully autonomy of the ASV is required when the river map is unknown or GPS is denied. To perform ASV navigation in unknown and unstructured riverine environment, there are two problems needed to be solved. The first problem is that the riverbanks are needed to be detected from the natural complex river scene (El-Gaaly et al., 2013; Subramanian et al., 2006). The second problem is ASV simultaneous river tracking and obstacles avoidance of ASV navigation, in where the existing riverine path planning methods mostly are based on the GPS, thus they are not suitable for unknown and unstructured riverine environment (Yang et al., 2011).

1.2.1 The riverbanks detection for natural and unstructured riverine environment

The GPS-based methods are very popular for the ASV navigation (Caccia, et al., 2008). However, these methods are not working for two cases of ASV riverine navigation. One case is that there is no prior river map for the ASV navigation, such as the riverbanks of the river are unknown (Snyder, et al., 2004; Sonnenburg & Woolsey, 2013). The other case is that the Global Position System (GPS) signals are blocked due to the thick and high canopy, especially in tropical riverine. For these two cases the image processing technique is a solution of riverbanks detection which is needed to be achieved for the ASV navigation.

The riverbanks detection is a challenging task since the river water area is poorly mapped, constrained and unstructured natural environment, in which the topography and the scene of the riverbanks are changing. As shown in Figure 1.1, there are two issues for the riverbanks detection by image processing, one is the color of the river water area is close to the color of the plants on the riverbanks; the other is the water surface reflection is strong (Furfaro et al., 2009). Hence, there is a need to develop a image processing algorithm to identify the riverbanks from the river scene.

(a) (b)

Figure 1.1 Riverbank scenes with tropical plants

1.2.2 Marine traffic rules compliant navigation of the ASV in unknown riverine environment

Path planning and obstacle avoidance are basic issues for autonomous vehicles navigation (Caccia et al., 2008). Artificial Potential Field (APF) which was first proposed by Khatib (1986) for mobile robot obstacles avoidance, is widely used in local path planning and obstacle avoidance because of its simplicity and effectiveness. The basic idea of the APF is that the robot in the environment is subjected to the attractive potential field from the target point and the repulsive potential field from the obstacle. The robot's motion information is determined by the combined potential field composed of the attractive potential field and the repulsive potential field in the environment. The basic APF method is able to achieve static obstacles avoidance but not dynamic obstacles avoidance since only the distances between the robot to target and obstacle are taken into account.

To make the APF method be able to avoid dynamic obstacles avoidance, Ge and Cui (2002) modified the APF method by adding the velocity information of the robot into the attractive and repulsive force potential field. They proposed a potential field method for mobile robot motion planning in a dynamic environment where both the target and obstacles are moving. The potential functions take into account not only the relative positions of the robot with respect to the target and obstacles, but also the relative velocities of the robot with respect to the target and obstacles. Accordingly, the virtual force is defined as the negative gradient of the potential with respect to both position and velocity. The motion of the mobile robot is then determined by the total virtual force through the Newton's Law or steering control depending on the driving type of the robot. Computer simulations and hardware experiments demonstrated the effectiveness of the mobile robot motion planning schemes based on the proposed potential field method.

Furthermore, Naeem et al. (2016) proposed a marine traffic rules compliant APF method to make the ASV have the ability to abide the The International Regulations for Preventing Collisions at Sea (COLREGs). All these methods are suitable for the open water area such as open sea and large lake. However, the river is a confined water area. Therefore, a novel ASV navigation method in riverine environment is needed to be developed.

1.3 Research objectives

The aim of this research is to develop a navigation algorithm for the ASV to be navigated in riverine environment in different conditions, such as scenarios with static and dynamic obstacles. Therefore, the sub-objectives are as below:

i. To develop a riverbanks identification algorithm to improve the color segmentation method in natural river scene.

ii. To develop a marine traffic rules compliant navigation and obstacles avoidance algorithm to improve the Artificial Potential Field method for ASV in the unstructured riverine environment.

1.4 Research scopes

In order to achieve the objectives stated above, the scope of this research is confined to the simulation of developing a riverine navigation system for the ASV. In addition to the riverbanks identification algorithm, the main contribution of the research is to develop a marine traffic rules compliant navigation algorithm for the riverine ASV.

The simulated riverine environment is acquired from the Sungai Kerian River which is located in Nibong Tebal, Penang, Malaysia, near Universiti Sains Malaysia Engineering Campus. For the riverbanks identification, a video with 4200 frames are captured for image processing. For the marine traffic rules compliant navigation, a part of Google map of the Sungai Kerian River with the length of 1km, with the maximum width of 166m and the minimum width of 56m is used as the river environment.

In the riverbanks identification phase, the ASV is navigated with a vision system and to recognize the unknown riverine environment, the navigation is determined by the visual cues that are provided by two lateral cameras which is to detect the riverbanks. This ASV is required to track along the river by keeping in the center of the river, and be able to avoid obstacles in the meantime. To perform this task, the first work to be performed is to measure the distance from ASV to the left and right side riverbanks. However, it is difficult for rangefinders since there are many plants on the riverbanks. Thus a riverbank lines recognization method is proposed with image processing approach. The riverbank lines are extracted from complex nature scenes with various plants, water surface reflection and changing riverbanks.

After the riverbanks detection, the ASV is expected to use the riverbank lines cues to keep in the center of the river. However, the riverbank lines detected by monocular vision is still not a distance information to navigate the ASV. Therefore, a balance control scheme is proposed to achieve the navigation, which is to imitate navigation manoeuvre of the human being. The left and right side riverbank lines instead of distances are compared to keep the ASV in the center of the river. The heading of the ASV is determined by the comparison of riverbank lines. This method is not an accurate guidance approach but it is simple and practical to perform ASV river navigation.

Another issue in ASV riverine navigation is obstacles avoidance. Thus the Artificial Potential Field (APF) is combined with the proposed balance control scheme when the ASV encounters objects on the river. The objects that the ASV encounters include static and dynamic obstacles, which may be a moving boat. Some of the surface vehicles (with or without crew) follow the marine traffic rules when they traverse the water area. So the ASV is required to obey the marine traffic rules when encountering other vehicles to decrease the collision risk. In this research, the marine traffic rules are integrated into APF method to perform obstacles avoidance. In addition, the maximum speed of the ASV limited by the time-cost of image processing is discussed.

1.5 Thesis outline

This thesis has 5 chapters, including the introduction, literature review, methodology, results and discussion, and conclusions of the research. The orgnization of this thesis is as below.

Chapter 1 briefly addresses the introduction of the research work. Section 1.1 introduces the research background. The application and characteristics of ASV are described. The problem statements are presented in Section 1.2. In Section 1.3, the research objectives are listed, while the research scopes are presented in Section 1.4. At last, the thesis outline is presented in Section 1.5.

Chapter 2 discusses the literature review. The literature review summarizes the related previous research work by other researchers. Section 2.1 presents a brief introduction of ASV. The historical Overview of ASV is reviewed in Section 2.2. The Modelling, Navigation, Guidance and control (NGC) system of ASV are addressed in Section 2.3. The riverbanks identification is reviewed in Section 2.4. The global and local path planning methods are discussed in Section 2.5. Section 2.6 reviews the ASV riverine navigation researches. Finally, a summary of Chapter 2 is presented in Section 2.7.

Chapter 3 explains the methodology of the research. Section 3.1 presents the overall research steps. In Section 3.2, the riverbank detection by image processing is described, which includes image segmentation and Hough Transform line detection. Section 3.3 presents the Hybrid Balance Artificial Potential Field method for river tracking and obstacles avoidance. In addition, the marine traffic rules are integrated into the ASV navigation algorithm as well. At last, a summary is presented in Section 3.4.

Chapter 4 presents the results and discussions of the research. Section 4.2 indicates the results of riverbanks detection with the proposed Color Segmentation Constrained Hough Transform method. Section 4.3 presents the results of the riverine navigation of ASV, which is realized by the proposed Hybrid Balance Artificial Potential Field. Finally, a summary is presented in Section 4.4.

At last, Chapter 5 addresses the conclusion and highlights the contributions of this study. The recommendations for future works are presented as well.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the literature review on ASV technologies, which contains a historical overview of ASVs, Guidance, Navigation and Control system (GNC). Besides, the global and local path planning methods are discussed, and the Artificial Potential Field (APF) method for obstacle avoidance is extensively reviewed. Finally, the collision risk assessment approaches and marine traffic rules are discussed.

2.2 Historical overview of ASV

ASV technology dates back to World War II and was originally designed as torpedo shape to clear mines and other obstacles on the sea. ASVs are widely used for civil, science research and military applications (Veers & Bertram, 2006). For Civil applications, ASVs are employed for ocean observation, marine resource exploration and exploitation, marine environment monitoring and so on (Veers and Bertram, 2006; Bertram, 2008; Manley, 2008; Motwani, 2012). After 911, the security of ports has become a key concern. The US Navy has added more attention to the coastal war and anti-terrorism, thus promoting the rapid development of the ASV. It has been an important component of the future US naval force. At present, a variety of ASVs have been used in the military field (Campbell et al., 2012). Recent developments of ASVs are listed in Table 2.1.

Table 2.1 ASV prototypes (Liu et al., 2016; Peng et al., 2017; Zhao et al., 2011)

Country	**Name of ASV**	**year**	**Length (m)**	**Endurance**	**Max speed(/kn)**
USA	Sea Owl	1993	3	10h/12kn	45
	AN/WLD-1	2001	7	20-24h	10
	Spartan Scout	2002	7/11	8h/28kn	50
	Ghost Guard	2003	8	24h	40
	Piranha	2003	8	24h	40
	Blue Knight	2005	40.4	24h	50
Israel	Protector	2003	9	400nm/30 kn	40
	SeaStar	2005	11	10h	40
	Stingray	2005	8	8h	40
	Silver Marlin	2007	10.67	24	45
France	FDS-3	1999	8.3	20h	12
Japan	OT-91	2005	4.4	20h	40
China	Jinghai-I	2013	6.28	10h/10kn	18

where kn denotes the speed with knot, 1kn=1 n mile/h= 0.5144444 m/s= 1.852 km/h.

2.2.1 ASV developed by the USA

As the only superpower in the world at present, the USA's ASV development is in the leading level in the world and dominates the direction of ASV development. The typical high-speed ASVs developed by the USA are the "Spartan Scout" and "SSC San Diego", as shown in Figure 2.1 and Figure 2.2. The main objectives of Spartan Scout are to protect troops from asymmetric threats; to enhance battlefield space early warning capabilities; to verify the sensor and weapon effectiveness of ASV. The platform is capable of unmanned control, in which the task module can be replaced by modularization according to the requirements (Motwani, 2012). There are also several companies in the USA that are developing various types of ASVs. They have achieved good research results. For example, the high speed ASV SSC San Diego which is developed by the Space and Naval Warfare Systems Center of USA (Larson, Bruch, Halterman, Rogers, & Webster, 2007).

Massachusettes Institute of Technology's study of ASV began in 1993 with the first ASV known as “ARTEMIS” (Vaneck *et al.*, 1996; Vaneck, 1997). The ASV is a scale-down model of a fishing vessel, which is used to test ASV's navigation and control system. The craft was used to collect simple ocean data from Boston's Charles River. The research team at MIT in 2000 studied autonomous coastal exploration systems and designed a new type of "AutoCat" catamaran. "AutoCat" can be conveniently deployed and surveyed by remote control or autonomous navigation (Manley et al., 2000).

ASV is working on the air-sea interface, which can act as a relay station between underwater acoustics and aerial radio communications, thus it can be seen that ASV is a key component of future network-centric warfare (Liu et al., 2016). In recent years, the ASV applications of moving along baseline navigation have been verified (Peng et al., 2017). In the future, ASV may become the network node of naval application. In this research background, “Kayak” has been developed by MIT, which can be used as the reference point for mobile navigation of AUV (Motwani, 2012).

Figure 2.1 Spartan ASV (Motwani, 2012)

Figure 2.2 SSC San Diego ASV (Larson et al., 2007)

2.2.2 ASV developed by other countries

Although Israel is a small country in the Middle East, it has very high research and development capabilities in military science and technology, especially in the field of unmanned system research, such as Unmanned Aerial Vehicle (UAV). Israel is not only a member of the "Spartan" ASV research program but also independently developed "Protector" and other advanced ASVs.

In 2003, Israel's Rafal Company and Aeronautics Defense Systems developed a multipurpose ASV "Protector", which is a typical example of Israeli ASVs. "Protector" is a rigid shell inflatable planning craft. It has a total length of 9m, a displacement of 4 ton, a maximum speed of 40 kn and a maximum payload of 1000 kg. It can be operated either by autonomous navigation or by remote control (Breivik et al., 2008).

Israel's Elbit Systems Ltd developed the “Silver Marlin” in 2006 and began sea trials in early 2007 (Bertram, 2008). The craft, known as the second generation ASV, can be operated remotely but mainly autonomously. The ASV is with a length of

10.67m, weight 4 ton, payload 2500kg, speed up to 45knn, endurance 500n mile, duration 24 hours.

In 2005, Israel's Elbit Systems Ltd developed the "Stingray" ASV (Bertram, 2008). This ASV is based on a civilian water-jet propulsion boat, which can travel at a speed of 40 kn, with a payload of 150 kg and a self-sustaining capacity of more than 8 hours. It can achieve coastal target identification, reconnaissance, surveillance, electronic warfare and electronic reconnaissance and other functions. It is easy to stealth due to the small hull.

Israel Aeronautics Defense Systems has also designed the ASV "Starfish", which is 11m in length, 6 ton in weight, 2500kg in payload, 45kn in cruising speed and 300 n mile (Yang et al., 2011). It is equipped with two diesel engines and uses water-jet propulsion. The ASV uses an open architecture, equipped with optoelectronic systems, target search systems, communications and intelligence systems, and a small caliber naval gun that can be controlled by land-based, sea-based or space-based platforms.

Since 2000, France's Sirehna company has been working on the development of ASV. In 2007, they successfully developed an unmanned high-speed planning boat “Rodeur” (Bertram, 2008). It is capable of carrying out multiple missions, such as mine hunting, anti-submarine warfare, protection and surveillance of marine pollution investigation and chemical detection, etc. The French Navy also designed multi-type of ASVs such as "Seakeeper" (Yang et al., 2011). In addition, the French company ACSA has developed ASVs such as BasilI\ II Mini VAMP and so on (Bertram, 2008).

Yamaha of Japan has carried out research on ASV, the main models of which are Unmanned Marine Vehicle High-Speed (UMV-H) and Unmanned Marine Vehicle Ocean type (UMV-O), as shown in (Bertram, 2008). UMV-H ASV is a V-shaped planing boat, equipped with 90KW engine and jet propulsion, with a max speed of 40kn. It can be controlled by manned or unmanned mode. With the length of 4.44m, it is easy to be carried by ships. It has enough space to equip with other necessary devices and tools, such as underwater cameras, sonar equipment and so on. The UMV-O ASV is mainly used for the biogeochemistry of marine environment monitoring task with a long time, a wide range of activities.

The United Kingdom has made rich research achievements in the field of ASV, among which the University of Plymouth has successfully developed the "Springer" catamaran ASV (Naeem et al., 2008). In 2002, UK Qineti Q Limited has designed the "MIMIR" ASV(Zhao et al., 2011). In 2006, the ASV company developed a semi-submersible autonomous measuring boat (Motwani, 2012).

The Italian CNR-ISSIA robotics group has made many achievements in the research of ASV. Among them, Caccia et al. (2007) developed the "Charlie" catamaran ASV, which is with 2.4m length, 1.7m wide and 300kg weight. It is propelled by propellers and equipped with a rudder-based control system. The two fixed steering gears are mounted behind the propeller and driven by a brushless DC motor. The navigation is performed by GPS and the gyroscope. The power source of "Charlie" ASV is a lead-acid battery of 12V and 40Ah. Besides, it is equipped with four groups of flexible solar panels. The single-board computer on board is operated by GNU / Linux. The real-time computer control system is developed by C++ language.

In 2008, Xinguang company of China developed the "Tianxiang 1" USV, which can be controlled by the remote autonomous way (Yan et al., 2010). With a length of 6.5m and carbon fiber hull, this ASV is equipped with GPS, radar, image transmission and processing system, and an intelligent navigation system. During the Qingdao Olympic Sailing Contest in 2008, the ASV is working as a meteorological emergency equipment to provide weather support services for the Olympic Sailing events.

The latest ASV in China is developed by Research Institute of USV Engineering, Shanghai University (Peng et al., 2017). As the first self-developed surface unmanned intelligent measurement platform in China, “Jinghai-I” ASV carried out its first voyage in March 2013 during the second maritime cruise in the South China Sea, which took on the surveying task of the islands and reefs in the South China Sea and achieved good results. The “Jinghai-I” ASV has built-in sonar, high precision optical fiber compass, laser rangefinder system and image monitoring system, collision avoidance radar and high-precision GPS and Beidou satellite navigation guiding and positioning system which is developed by China. The data collected by the devices can be stored in the built-in mass storage system. So far, Jinghai series ASVs have been developed from“Jinghai-I” to “Jinghai-IV” to perform different missions in different conditions.

2.3 Modelling and navigation, guidance and control (NGC) system of ASV

The majority of ASVs are equipped with main propulsion and rudder, which means only two control variables are used to control the heading and position (x,y) of ASV, 3 degrees of freedom movement. These ASVs are called underactuated surface vessel system and are typical second-order nonholonomic constraint dynamic systems

(Do & Pan, 2009). Theoretically, the problems of underactuated systems control are the controllable degrees of freedom (system outputs) are greater than the actuators of system (control inputs). The Brockett theorem points out that (Brockett, 1983), there is no any smooth (even continuous) time invariant state feedback control law causes the underactuated system asymptotically stable. In addition, if the control methods for redundant system were applied to these underactuated systems, the performance would be extremely poor and unacceptable (Caharija et al., 2014).

For these underactuated ASVs, related research works are divided into three parts, stabilization control, which are trajectory tracking and path tracking. Lyapunov direct method (Mbede et al., 2000), backstepping method (Sonnenburg & Woolsey, 2013), sliding mode control (Gazi, 2005), and feedback linearization method (Ge and Cui, 2002) are applied to underactuated ASV system. Modelling of underactuated ASV is the fundamental of control.

2.3.1 Modelling of ASV and environment

2.3.1(a) Modelling of common ASV

In this section the model of underactuated ASV equipped with rudder-propeller system will be discussed. When describing ASVs' motion, two reference frames are considered: an inertial, earth-fixed frame {E} and body-fixed frame {B}. 6 degrees of freedom (DOF) for marine vessels are shown in Figure 2.3, which is defined as, surge, sway, heave, roll, pitch, and yaw. The corresponding motion variables are listed in Table 2.2 (Fossen, 2011).

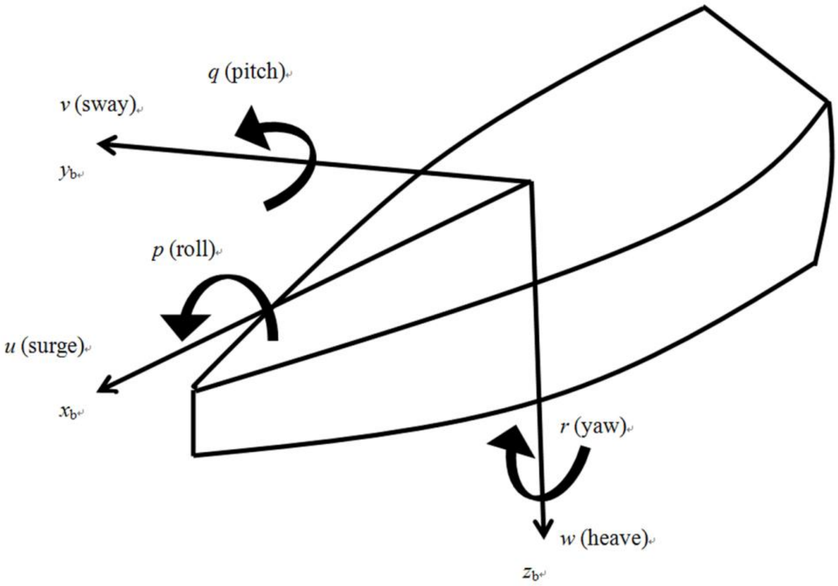

Figure 2.3 Motion variables for a marine vessel

Table 2.2 The notation of 6 degrees of freedom (Fossen, 2011)

DOF		**forces and moments**	**linear and angular velocities**	**positions and Euler angles**
1	motions in the *x*-direction (surge)	X	u	x
2	motions in the *y*-direction (sway)	Y	v	y
3	motions in the *z*-direction (heave)	Z	w	z
4	rotation in the *x*-direction (roll, heel)	K	p	ϕ
5	rotation in the *y*-direction (pitch, trim)	M	q	θ
6	rotation in the *z*-direction (yaw)	N	r	ψ

Since the ASV travels on the water surface which means that the motion is basically on horizontal plane, the model of ASV is simplified to 3 variables, surge, sway, and yaw. In the ASV navigation mode, position and orientation of the ASV are the basic motion parameters. As shown in Figure 2.3, position is determined by surge and sway and orientation is determined by yaw. In Table 2.2, surge, sway and yaw $[x, y, \psi]^T$ of the vessel are expressed in earth-fixed frame {E}, while surge and sway velocities (with respect to the water) and yaw rate $[u, v, r]$.

As shown in Figure 2.4, assuming that the ASV motion is restricted to the horizontal plane, and pitch, roll and heave are neglected. Thus, $\eta = [x, y, \psi]^T$, $\nu = [u, v, r]^T$. The control inputs of ASV are longitudinal force F_u and yaw moment T_r. {E} is earth-fixed frame and {B} is body-fixed frame.

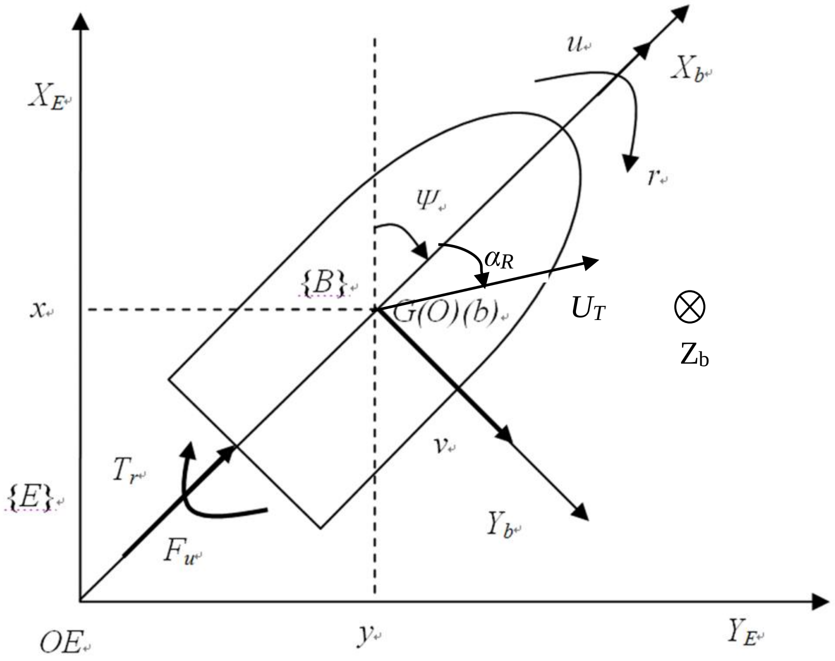

Figure 2.4 Illustration of Planar motion model of ASV

With the assumption that (Fossen, 2011),

(1) The hull is symmetrical on X_bZ_b planar.

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

Then 3 degrees of freedom model is indicated as follows (Fossen, 2011),

$$\begin{cases} \dot{\eta} = J(\eta)\nu \\ M\dot{\nu} + C(\nu)\nu + D(\nu)\nu = \tau + \tau_E \end{cases} \tag{2.1}$$

Where η and ν are generalized velocities and positions used to describe motions in 3 DOF, matrices *M* is the rigid-body inertia matrix, *C* is a matrix of rigid-body Coriolis and centripetal forces. *D* is a damping coefficients matrix. *J* is a transformation matrix which can be computed by using MSS toolbox (Perez & Fossen, 2010). $J(\eta)$, M, $C(\nu)$, $D(\nu) = D + D_n(\nu)$ are expressed in Equation (2.2),

$$J(\eta) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \mathrm{M} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{u}} & -Y_{\dot{r}} \\ 0 & Y_{\dot{r}} & I_{zz} - N_{\dot{r}} \end{bmatrix}$$

$$\mathrm{C}(\nu) = \begin{bmatrix} 0 & 0 & -\mathrm{m}\nu + \mathrm{Y}_{\dot{\nu}}\nu + \mathrm{Y}_{\dot{r}}\mathrm{r} \\ 0 & 0 & mu - X_{\dot{u}}u \\ \mathrm{m}\nu - \mathrm{Y}_{\dot{\nu}}\nu - \mathrm{Y}_{\dot{r}}\mathrm{r} & -mu + \mathrm{X}_{\dot{u}}u & 0 \end{bmatrix} \tag{2.2}$$

$$\mathrm{D} = \begin{bmatrix} X_u & 0 & 0 \\ 0 & Y_\nu & Y_r \\ 0 & N_\nu & N_r \end{bmatrix}, \quad \mathrm{D_n}(\nu) = -\begin{bmatrix} \mathrm{X}_{|u|u} & 0 & 0 \\ 0 & \mathrm{Y}_{|\nu|\nu}|\nu| + \mathrm{Y}_{|r|\nu}|\mathrm{r}| & \mathrm{Y}_{|\nu|r}|\nu| \\ 0 & \mathrm{N}_{|\nu|\nu}|\nu| + \mathrm{N}_{|r|\nu}|\mathrm{r}| & \mathrm{N}_{|\nu|r}|\nu| + \mathrm{N}_{|r|r}|\mathrm{r}| \end{bmatrix}$$

where m is the mass of the ASV, $X_u, Y_\nu, \ldots, N_r$ are the linear damping coefficients and $X_{\dot{u}}, Y_{\dot{u}}, \ldots, N_{\dot{r}}$ represent hydrodynamic added mass. $\mathrm{X}_{|u|u}, \mathrm{Y}_{|\nu|\nu}, \ldots, \mathrm{N}_{|r|r}$ are the manoeuvring coefficients. I_{zz} is the moment of inertia about the Z_b axes.

The thrust moment is represented as

$$\tau = \begin{bmatrix} F_u \\ 0 \\ T_r \end{bmatrix} \tag{2.3}$$

where T_r and F_u are the torque and force which are provided by rudder and propeller equipped on ASV, respectively.

Environmental disturbances are expressed as

$$\tau_E = \begin{bmatrix} d_u \\ d_v \\ d_r \end{bmatrix} \tag{2.4}$$

where d_u, d_v, d_r is the environmental force disturbance on surge, sway and yaw. The simplified ASV model on horizontal planar is

$$\begin{cases} \dot{x} = ucos\psi - vsin\psi \\ \dot{y} = usin\psi + vcos\psi \\ \dot{\psi} = r \\ \dot{u} = \frac{m_{22}}{m_{11}} vr - \frac{d_{11}}{m_{11}} u + \frac{Fu}{m_{11}} \\ \dot{v} = -\frac{m_{11}}{m_{22}} ur - \frac{d_{22}}{m_{22}} v \\ \dot{r} = \frac{m_{11} - m_{22}}{m_{33}} uv - \frac{d_{33}}{m_{33}} r + \frac{T_r}{m_{33}} \end{cases} \tag{2.5}$$

where $d_{11} = X_u$, $d_{22} = Y_v$, $d_{33} = N_r$, m_{11} , m_{22} and m_{33} are the components of symmetry which can be computed by M (Perez & Fossen, 2010).

As shown in Figure 2.5, ASV model for the research is a catamaran with differential propellers, which means that both of the steering angle and the speed are controlled by two differential thrusters.

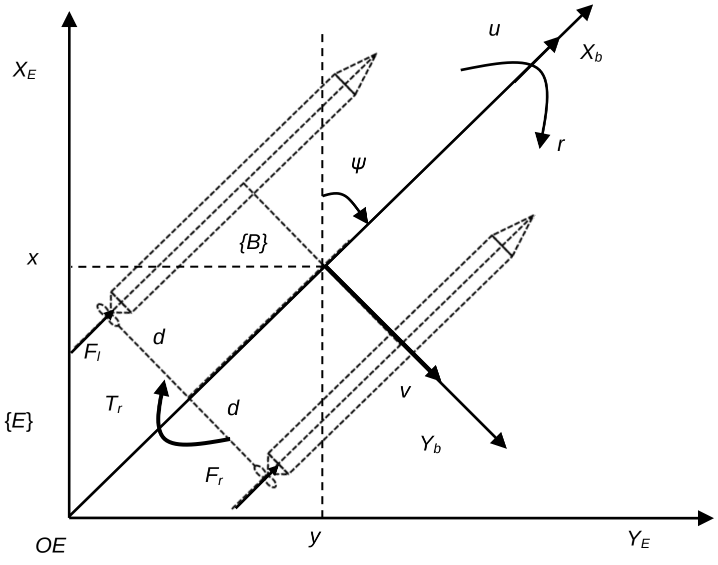

Figure 2.5 Planar model of the ASV with differential thrust

In Equation (2.1), τ is a vector that contains the sum of all other forces and moments acting on the ASV (Klinger et al., 2014).

$$\tau = \begin{bmatrix} (F_l + F_r) \\ 0 \\ (F_l - F_r) * d \end{bmatrix} \tag{2.6}$$

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).

From Figure 2.5 it can be seen 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 forces F_l and F_r could be decomposed into,

$$F_l = F + \Delta F / 2 \tag{2.7}$$

$$F_r = F - \Delta F / 2 \tag{2.8}$$

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

2.3.1(b) Environmental disturbances of wind, wave and current

The model discussed above is to calculate the manoeuvrability of ASV in calm water area. However, the ASV is affected by the disturbances such as wind, wave and current when it is moving in the practical environment.

Due to the randomness of wind, wave and current, it is difficult to set up the disturbance force models of wind, wave and current since a large amount of data needed to be collected and processed (Azzeri et al., 2015; Sarda et al., 2016; Song et al., 2017). To simplify the disturbance model, the wave is assumed to be generated by a consistent wind, thus the direction of the wind and wave are same. The wind and wave conducted force are added to the right hand side of Equation (2.1) based on the principle of superposition, (Fossen, 2011).