2018 3rd International Conference on Control, Robotics and Cybernetics (CRC)

Motion Control Algorithm for Path Following and Trajectory Tracking for Unmanned Surface Vehicle: A Review Paper

Putri Nur Farhanah bt Mohd Shamsuddin
Faculty of Engineering Technology
Universiti Malaysia Pahang, 26300
Gambang, Malaysia
e-mail: putrishamsuddin94@gmail.com

Muhamad Arifpin bin Mansor
Faculty of Engineering Technology
Universiti Malaysia Pahang, 26300
Gambang, Malaysia
e-mail: ariffin@ump.edu.my

***Abstract*—A capability of tracking and follows the target object on the water surface is an essential measurement in the control system for a Unmanned Surface Vehicle (USV). Path following algorithm usually used to describe the target, compute in the controller and minimize as well as to zero the distance between USV; and the angle between the vessel speed and the tangent to the path. USV needs to follow a time-parameterized reference curve are defined as a trajectory tracking. This paper gives an attention in reviewing a few common path following as well as path tracking techniques used in the design of USV where there is no predefined position will be declared in the control system. In particular, this paper is focused on a motion control approaches developed using USV by reviewing forty journals for last ten years. Based on the reviews, a line-of-sight (LOS) technique is a frequently implemented in the USV control system than another method such as constant-bearing guidance, Kalman filtering, PID guidance, Lyapunov-based guidance, pure-pursuit (PP) guidance, motion goal prediction, back stepping method and Jacobian task priority. As the conclusion, various types of mathematical computation are introduced in the USV control system is customizes with the requirement based on the situation needed will make this autonomous vehicle more advanced.**

Keywords-Unmanned Surface Vehicle (USV); motion control; path following; trajectory tracking

I. Introduction

Unmanned Surface Vehicle (USV) is attracting more and more attention from researchers all over the world because this autonomous vehicle has an enormous amount of potential to the environment includes military reconnaissance, homeland security, shallow water surveys, environmental monitoring, and having communication in coordinating the operation with autonomous underwater vehicles (AUV) [1][2][3]. As other autonomous vessel, USV is typically purposed in the marine environment for use in so-called dirty, dull, and hazardous mission. USV technology harbors great potential for several qualities, including possibilities for new vehicle designs and new concepts of mission [4].

Furthermore, given that USVs are typically small, fast and highly maneuverable vehicles with a sizeable power-to-weight ratio, new motion control concepts must be developed to take advantage of such properties. In particular, trajectory tracking and path following of surface vessel have been a long-standing control problem that has attracted attention from the control community for many years [5]. Thus, a capability of tracking and follows the target object on the water surface is an essential measurement in the control system for USV.

The hierarchical structure for the motion control system has been illustrated by Valavanis *et al.* [6]. The purposes of the motion control system are; the autonomous vehicle needs to undergo at least three control levels in the system and fulfil the motion control objective. Based on the hierarchy, at the top level is the system will be controlled by the human operator or the guidance system known as strategic control level. This level also can be called as the kinematic control level; which takes a lot of responsibility to predict the vehicle velocity commands to achieve the motion control objective in the mission of the workspace. Therefore, this kinematic control is similar to the workspace control and the guidance law will be referred to the kinematic controller. This level is purely from the forces and the movement where it can be considered as the geometric aspect of motion.

The research done by Ebken *et al.* [7] stated that only several of the paper are discuss the USV motion control system; where the motion control technology is adapted from the Unmanned Ground Vehicle (UGV) to rapidly achieve basic motion control functionality for USV including the modes of the waypoint navigation and remote control [8]. Cacia *et al.* [9] were developed the small USV to accomplish the mission of high-precision survey operation in the shallow water, employing the traditional autopilot design method in the steering controller. Besides, the researchers also apply the conventional motion control techniques in the small USV where this autonomous vehicle equipped with Global Positioning System (GPS) and compass to work in straight-line following tasks, auto-heading and auto-speed toward the target.

Path following algorithm in the USV usually used to define, compute and reduce to zero the distance between the autonomous vehicle and the path as well as the angle between the vessel speed and the tangent to the path. The leader follows its reference path at the desired speed, while the follower executes a path following algorithm, controlling its rate according to a measured generalized along-path distance between the two vessels [10].

Besides, USV needs to follow a time-parameterized reference curve are defined as a trajectory tracking, i.e. to be at specific points at specific instants of time. This statement is the case of vehicles characterized by a preferred direction of motion and in the presence of external disturbance, such as waves, sea current and wind, typically leads to high

978-1-5386-7738-4/18/$31.00 ©2018 IEEE
DOI 10.1109/CRC.2018.00023

actuator activity and jerky movements [10]. Thus, in practical applications, temporal constraints are usually relaxed, maintaining only the forward vehicle speed reference, and the so-called path following problem is faced, i.e. the vehicle has to follow a planar path without temporal constraints [10].

This paper gives a review of few common path following as well as trajectory tracking techniques used in the design of USV where there is no predefined position will be declared in the control system. In particular, this paper is focused on a motion control approaches developed using USV by reviewing fifteen journals for last ten years.

II. LITERATURE REVIEW OF THE PATH FOLLOWING AND TRAJECTORY TRACKING TECHNIQUES

Based on the previous research, there are several techniques such as; line-of-sight, constant-bearing guidance, Kalman filtering, PID guidance, Lyapunov-based guidance, pure-pursuit (PP) guidance, line following guidance control, motion goal prediction, backstepping method and Jacobian task priority.

A. Line of Sight Guidance

In the path following application, Line of sight guidance is one of the methods; which is widely used in the marine vehicle for generating the heading reference [11]. This technique gets attention from the researchers due to the flexibility of this method approach to the target by manipulates the speed. LOS guidance is a three- point guidance which are included missile (vessel, boat, etc.), launch platform and the target. The missile eventually needs to collide the target if the missile remains on the line joining the launch platform and the target [12].

Basically, this algorithm will be implemented in two ways; Beam Rider (BR), Command-to-Line-of-Sight (CLOS) [13]. This technique can be said to be interesting because this technique is capable of giving the guidance command by using the uplink and; by the missile deviation generated by the LOS. Then, USV will be guided to follow the trajectory path toward the target in the straight-line [14] instead of curvature trajectories path. This is due to the high speed of the motion controller design [15], [16]. However, several researchers take the initiative for combining this technique with other models for converging USV to the desired target [16-19].

B. Pure Pursuit Guidance

Pure pursuit (PP) guidance is the most popular geometric controller implemented in an autonomous ground vehicle (AGV) compared to USV. This autonomous vessel is built to understand the mission i.e. chase a moving target throughout the duration. Lekkas *et al.* states that this high-speed motion technique is implemented in the USV for tracking the target in the short time. In this process, PP guidance velocity vector is directly pointed to the instantaneous target position [14]. Besides, this guidance is able to maneuver a big autonomous vehicle at high speed by using the GPS as the guider towards the target [20]. Other than that, PP guidance is implemented in the controller to create a virtual goal path at the look-ahead distance [21]. PP algorithm is effective geometric method to guide the autonomous vehicle towards the target by compute the setpoint and the pose of the vehicle. The advantages of this method to the autonomous vehicle are; zero of the derivative terms tuning ease of the look- ahead distance and computational simplicity [22]. However, this technique is rarely founded in many autonomous vehicles due to the decency have been occurred. Consequently, the PID controller is faced a challenge to optimize the parameter and the overshoot in the tracking behavior [20].

C. Constant Bearing Guidance

Constant bearing (CB) guidance is one of the missile community counterparts; other than PP guidance and LOS guidance [11]. CB guidance is the method; which is the interceptor must align the relative interceptor-target velocity along the interceptor-target line of sight. Basically, CB is the two-point guidance scheme; which is often referred to as parallel navigation. This method usually used at the sea to maneuvers the marine vessel out of the obstacle [23]. Specifically, this method is selected by the researcher to controls the specific motion of the USV that generated to have a same range with the mother vessel. Besides, CB guidance is implemented in the controller where the USV needs to match the motion with the mother vessel [24]; which also known as the target rendezvous [25]. Indeed, the motion range between the USV and the mother vessel is based on the virtual target designed in the circumstance. Hence, the collision avoidance is free between USV with other vessel and this autonomous vehicle able to drive safely towards the final goal position [24]. Constant bearing guidance has a similar target tracking behavior with the PP guidance as mentioned by Breveik and Fossen in year 2008 [15].

D. Lyapunov-based Guidance

A Lyapunov method is the one of the essential guidance algorithm usually used in the USV control system. This algorithm computes with other technique for controls the surge and yaw of the USV such as Virtual Target Approach [25]. Indeed, the slave vessel has an ability to maintain the desired range from the mother vessel by adjusting the surge velocity to control the desired distance as well as the linear or curvilinear path between two vehicles. The Lyapunov method is implemented in the path following vessel having a communication with the mother vessel. Hence, USV vessel can give less error connection with the mother vessel. Although, USVs are faced the constraint from having the same steering dynamics with the mother vessel as reported by Bibuli *et al.* [25]. The basic theorem of Lyapunov establishing stability of an equilibrium point for USV. However, the converse theorem from the Lyapunov will exists when the equilibrium point is in the stable mode. Consequently, this problem may affect the computable technique for generating the function [26].

Besides, Lyapunov-based control approach have an ability to stabilize the non-linear system and; this method is frequently implemented in the marine control literature. There are to crucial types are introduced by this method which are; propose the control law and the results of the stability have been proved. The researcher succeeds to prove the ability of Lyapunov method in solving non-linear setting control problem. Although, the controller is difficult to show the physical insight into the system due to the nature of the approach [26].

E. Jacobian Task Priority

The development of Jacobian task priority; is an advanced control algorithm to make the autonomous vehicle able to complete the mission and become useful. This method is under development to accomplish the mission with more robustness and effective. Commonly, Jacobian task priority is a new technique and this method was applied in the USV by Bibuli *et al.* [27]. The researchers are implements this technique for separating the prioritized task done; which are path following mission and the vehicle velocity regulation. Hence, the controller will be computed the primary task as the priority; which is the trajectory that USV needs to follow. However, the target vessel will have the different motion than the USV. Consequently, this constraint will influence the braking distance between USV and the target goal prediction motion [27].

F. Predictive Trajectory Planning

A predictive trajectory planning is the one of other model used to follow the target boat and prevents the USV collide with the other boat; where the boats have not follow the rules of Coast Guard Collision Regulation (COLREGs) [28]. This model is determining and minimize the trajectory tracking behind the target boat and collision-free control commands for this autonomous vehicle approach to the target vessel. The structure and implementation of this model are similar to vehicle controller [29].

Based on the research done by Petr Svec *et al.*, the researchers are implements the lattice-based trajectory planning to allow the USV to reliably reach the motion goal. This technique is approached for preserving motion safety and guides the USV by using the trajectory following controller to achieve high tracking efficiency [30]. Then, USV tracks the path in the lower speed due to the different thrust usually occurred during USV follows the planned trajectories. However, USV faced a constraint to lose the target boat due to the lower-level feedback controller where the approach distance to the target is commonly lower than the limitation set by the user reported by Campbell *et al.* in year 2012.

G. Kalman Filtering

Kalman filtering is the one of famous method usually used in the autonomous vehicle. This technique has become familiar in term of following the target, indoor positioning robot, dead reckoning and fusion trilateration [31]. This is because Kalman filtering is capable of communicating with the Global Positioning System (GPS) and compass measurement [32]. Hence, USV receives the estimation of the speed and the position of the vehicle; by using the the GPS and the compass. However, the noise and time variable-offset between the GPS in the autonomous vehicle gives an error during undergoing the mission as reported by [25]. Other than that, Kalman Filtering also used to compensate the discontinuities of the GPS as this have been applied by Caccia *et al.* [33].

H. Backstepping Method

A backstepping method has approached for autonomous vessel due to the ability of this technique in the setpoint, path following approach and the trajectory tracking towards the target. The research activity is increased the attention with this method in developing the underactuated control law [34]. The experiment is done by implemented the method to navigate small boat towards the following target. In particular, GPS is used in the experiment to provide the position feedback to the controller. However, the rudder angle is developed to give movement in forwarding motion resulting will faced a problem and give some error to the USV motion undergoing the path. Many researchers have undergone the experiment by modifying this method to have a good result for accomplish the task [35-38].

I. Motion Goal Prediction

Motion goal prediction is the algorithm that computes in real time where this model is directly processed by the trajectory planner. The main sequences for ultimate the output are; desired pose of the autonomous, velocity and the time arrival [39]. In particular, the computed trajectories are executed with low-level controller for maintaining the waypoints and arrive to the motion goal at the desired time. Hence, this motion goal prediction method is reasonable to apply in the USV for harvesting in the cluttered environment [40].

III. Discussion

In summary, several techniques and method are implements in the controller where the control selections are influenced by the dynamic model such as; underactuated high speed, rudder or thruster controlled and the mission for the USV.

Line of sight is frequently mention in many journals included the experiment due to the ability of the technique to track the path following and guides the USV follows the trajectories. Moreover, many of the marine vehicles are developed to follow the mother vessel to accomplish the mission. However, USV is faced a problem to compute the control input such as surge force and the yaw movement where the aforementioned problem needs an advanced technique to manipulate the motion, distance between two vessels (mother vessel and USV), real-time data collection (static and moving obstacle) to design the new trajectory path toward the target.

Implementing the sensor such as GPS is the initiative to get a raw data from the sensor configuration and the perception method when conducting the experiment. For instance, gathering real-time data is most important to realize the current position of the autonomous vehicle.

Hence, to defend USV from losing the target, the line of sight guidance, constant bearing guidance and pure pursuit guidance are the best suggestion to implements in the system.

However, motion goal prediction, Lyapunov method and predictive model trajectory planning are the recommended techniques for use in the cluttered environment as well as the high traffic on the water surface.

IV. Conclusion

In conclusion, this paper has reviews the vital path following and tracking model from the last ten years resources for the marine vehicle. Based on the previous research, Line of sight and PP guidance are used in the mission for reaching the target in the short period[12], [14] [20]. However, the researcher will have combined both of the method for reach a target in straight line and in the non-linear path respectively. Constant bearing guidance also will be implemented in the system for make the communication with the mother vessel i.e. the motion of the two vehicles [21].

However, only several papers used the backstepping method and Lyapunov method because these algorithms need to combined with other technique for making the USV zero of the error when maneuver towards the target. Furthermore, Jacobian task priority and predictive trajectory planning are implemented in the controller to maneuver USV in the low-level feedback controller; which are suitable to work in the cluttered environment. Lastly, motion goal prediction usually will estimate the motion of the target for estimate the motion that the slave vessel needs to follow [31]. Other than that, Kalman filtering is usually will be implement in the indoor positioning vehicle and the vehicle will be guide by using the GPS and the compass measurement [27].

Hence, this paper has been proved the line of sight guidance is the favorite method implements in the USV due to the advantages included gives a guidance commands by using the uplink and missile deviation generated by the Line of sight [13]. The author also augments the benefit and lack of each method. All of the algorithms implement in the controller are influenced by the mission that needs to accomplish.

Acknowledgment

This research for was financially supported by the Universiti Malaysia Pahang Internal Grant, RDU180346.

References

[1] Larrazabal, J. M., & Peñas, M. S. (2016). Intelligent rudder control of the unmanned surface vessel. Applications with Expert Systems, 55, 106–117. https://doi.org/10.1016/j.eswa.2016.01.057

[2] Liu, T., Dong, Z., Du, H., Song, L., & Mao, Y. (2017). PATH FOLLOWING CONTROL OF THE UNDERACTUATED USV BASED ON THE IMPROVED LINE-OF-SIGHT GUIDANCE, 24(1), 3–11.

[3] Sohn, S. I., Oh, J. H., Lee, Y. S., Park, D. H., & Oh, I. K. (2015). Design of a Fuel-Cell-Powered Catamaran-Type Unmanned Surface Vehicle. IEEE Journal of Oceanic Engineering, 40(2), 388–396. https://doi.org/10.1109/JOE.2014.2315889

[4] Fossen, T. I. (2005). A NONLINEAR UNIFIED STATE-SPACE MODEL FOR SHIP MANEUVERING AND CONTROL IN A SEAWAY.

[5] Oh, S. R., & Sun, J. (2010). Path following of underactuated marine surface vessels using line-of-sight based model predictive control. Ocean Engineering, 37(2–3), 289–295. https://doi.org/10.1016/j.oceaneng.2009.10.004

[6] Valavanis, K. P., Gracanin, D., Matijasevic, M., Kol- luru, R., and Demetriou, G. A. Control architectures for autonomous underwater vehicles. IEEE Control Systems Magazine, 1997. 17(6):48—64.

[7] Ebken, J., Bruch,M., and Lum, J. Applying unmanned ground vehicle technologies to unmanned surface vehicles. In Proceedings of SPIE 5804: Unmanned Ground Vehicle Technology VII, Orlando, Florida, USA. 2005 .

[8] Majohr, J. and Buch, T. Modelling, simulation and control of an autonomous surface marine vehicle for surveying applications Measuring Dolphin MESSIN. In G. N. Roberts and R. Sutton, editors, Advances in Unmanned Marine Vehicles, pages 329—351. The Institution of Electrical Engineers, 2006.

[9] Caccia,M., Bibuli, M.,Bono, R.,and Bruzzone,G. Basic navigation, guidance and control of an unmanned surface vehicle. Autonomous Robots, 2008a. 25(4):349—365.

[10] Amer, N. H., Zamzuri, H., Hudha, K., & Kadir, Z. A. (2017). Modelling and Control Strategies in Path Tracking Control for Autonomous Ground Vehicles: A Review of State of the Art and Challenges. Journal of Intelligent & Robotic Systems, 86(2), 225–254. https://doi.org/10.1007/s10846-016-0442-0

[11] Lekkas, Anastasios & Fossen, Thor. (2013). Line-of-Sight Guidance for Path Following of Marine Vehicles. .

[12] D. G. (2018, February 15). The Line of Sight Guidance Law. Reading presented at Introduction of LOS Guidance.Guidance, Control, and Decision Systems Laboratory Department of Aerospace Engineering Indian Institute of Science Bangalore, India.

[13] M. B. (2018, February 15). The Brains of Motion Control Systems. Lecture presented at Guidance Systems in Norwegian University of Science and Technology.

[14] Svec, P., Shah, B. C., Bertaska, I. R., Alvarez, J., Sinisterra, A. J., Von Ellenrieder, K., … Gupta, S. K. (2013). Dynamics-aware target following for an autonomous surface vehicle operating under COLREGs in civilian traffic. IEEE International Conference on Intelligent Robots and Systems, 3871–3878. https://doi.org/10.1109/IROS.2013.6696910

[15] Breivik, M., & Fossen, T. I. (2008). Guidance laws for planar motion control. Proceedings of the IEEE Conference on Decision and Control, 570–577. https://doi.org/10.1109/CDC.2008.4739465

[16] Liu, T., Dong, Z., Du, H., Song, L., & Mao, Y. (2017). PATH FOLLOWING CONTROL OF THE UNDERACTUATED USV BASED ON THE IMPROVED LINE-OF-SIGHT GUIDANCE, 24(1), 3–11.

[17] Peng, Z., Wang, D., Chen, Z., Hu, X., & Lan, W. (2013). Adaptive dynamic surface control for formations of autonomous surface vehicles with uncertain dynamics. IEEE

[18] A. Rodríguez-Castaño, G. Heredia, and A. Ollero, "Analysis of a GPS-based fuzzy supervised path tracking system for large unmanned vehicles," in Proceedings of the 4th IFAC International Symposium on Intelligent Components and Instruments for Control Applications (SICICA'00), 2000, pp. 141-146

[19] K. Petrinec, Z. Kovačić, and A. Marozin, "Simulator of multi-AGV robotic industrial environments," in Industrial Technology, 2003 IEEE International Conference on, 2003, pp. 979-983

[20] M. Abbas, "Non-linear model predictive control for autonomous vehicles," University of Ontario Institute of Technology, Ontario, Canada, 2011.

[21] O. Amidi and C. E. Thorpe, "Integrated mobile robot control," in Fibers' 91, Boston, MA, 1991, pp. 504-523.

[22] Breivik, M., Fossen, T.I.: Guidance laws for autonomous underwater vehicles, chap. 4, pp. 51–76. INTECH Education and Publishing (2009)

[23] M. B. (2018, February 15). The Brains of Motion Control Systems. Lecture presented at Guidance Systems in Norwegian University of Science and Technology.

[24] Breivik, M. (2010). Topics in Guided Motion Control of Marine Vehicles. PhD thesis. Norwegian University of Science and Technology, Trondheim, Norway

[25] Bibuli, M., Caccia, M., Lapierre, L., & Bruzzone, G. (2012). Guidance of unmanned surface vehicles: Experiments in vehicle following. *IEEE Robotics and Automation Magazine*, *19*(3), 92–102. https://doi.org/10.1109/MRA.2011.2181784

[26] Q. H. (2016). WIND FEEDFORWARD CONTROL OF A USV (Master's thesis, Florida Atlantic University, 2016) (pp. 1-143). Boca Raton: Florida Atlantic University. http://fau.digital.flvc.org/islandora/object/fau%3A33482/datastream/OBJ/view/Wind_Feedforward_Control_of_a_USV.pdf

[27] Bibuli, E. Z. M., & Caccia, G. B. M. (2013). Jacobian Task Priority-based Approach for Path Following of Unmanned Surface Vehicles. IFAC Proceedings Volumes (Vol. 46). IFAC. https://doi.org/10.3182/20130918-4-JP-3022.00042

[28] Svec, P., Shah, B. C., Bertaska, I. R., Alvarez, J., Sinisterra, A. J., Von Ellenrieder, K., Gupta, S. K. (2013). Dynamics aware target following for an autonomous surface vehicle operating under COLREGs in civilian traffic. IEEE International Conference on Intelligent Robots and Systems, 3871–3878. https://doi.org/10.1109/IROS.2013.6696910

[29] S. Campbell, W. Naeem, and G. Irwin, “A review on improving the autonomy of unmanned surface vehicles through intelligent collision avoidance manoeuvres,” Annual Reviews in Control, 2012

[30] Svec P, Thakur A, Shah BC, Gupta SK. USV Trajectory Planning for Time Varying Motion Goals in an Environment With Obstacles. ASME. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Volume 4: 36th Mechanisms and Robotics Conference, Parts A and B ():1297-1306. doi:10.1115/DETC2012-71239.

[31] Röbesaat, J., Zhang, P., Abdelaal, M., & Theel, O. (2017). An improved BLE indoor localization with Kalman-based fusion: An experimental study. Sensors (Switzerland), 17(5), 1–26. https://doi.org/10.3390/s17050951

[32] De Mel, D. H. S., Stol, K. A., Mills, J. A. D., & Eastwood, B. R. (2017). Vision-based object path following on a quadcopter for GPS-denied environments. 2017 International Conference on Unmanned Aircraft Systems, ICUAS 2017, 456–461. https://doi.org/10.1109/ICUAS.2017.7991500

[33] Caccia, M., Bruzzone, G., & Bono, R. (2006). Modelling and identification of the Charlie2005 ASC. In Proc. of IEEE 14th mediterranean conference on control and automation.

[34] Ashrafiuon, H., Muske, K. R., & McNinch, L. C. (2010). Review of nonlinear tracking and setpoint control approaches for autonomous underactuated marine vehicles. American Control Conference (ACC), 2010, 5203–5211. https://doi.org/10.1109/ACC.2010.5530450

[35] J.-J. Slotine and W. Li, Applied Nonlinear Control, Prentice-Hall, 1991.

[36] M. I. K. a. P. V. K. Berlin. Krstic, "Nonlinear and Adaptive Control Design," in John Wiley & Sons,Inc. New York, NY., 1995.

[37] T. I. Fossen and J. P. S. , "Nonlinear passive weather optimal positioning control (WOPC) system for ships and rigs: experimental results," Automatica, pp. Volume 37, Issue 5, Pages 701-715, ISSN 0005-1098, May 2001.

[38] Fossen, I. Thor and T. A. Johansen, "A survey of control allocation methods for ships and underwater vehicles," in Control and Automation, 14th Mediterranean Conference on. IEEE, 2006.

[39] S.K. Gupta, Developing Autonomy for Unmanned Surface Vehicles, Technical Report, Simulation Based System Design Laboratory, University of Maryland, College Park, MD 20742, October 2013

[40] Seder, M., & Petrović, I. (2007). Dynamic window based approach tomobile robot motion control in the presence of moving obstacles.