POSITION TRACKING OF UNDERWATER VEHICLE USING EXTENDED KALMAN FILTER

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DEDICATION

This project report is dedicated to my parents, who always provided me with the love and support to always strive on and move forward in life. It is also dedicated to my brother, who have always help and support me from behind the scenes. I would not have been able to do this without any of them by my side.

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ABSTRACT

Position tracking is essential for mobile robots for autonomous functionalities and navigation especially for robots that are deployed in underwater conditions. Hence, this thesis proposes the usage of the Extended Kalman Filter (EKF) for position tracking of an underwater vehicle. Underwater vehicles cannot use conventional GPS for position tracking due to radio signals being damped by the body of water surrounding it. Underwater GPS(UGPS) is used for predicting the position of underwater vehicles, but it suffers from latency issues. Therefore, estimation algorithms like Kalman Filter (KF) and EKF are applied to provide a consistent position value from the UGPS. The main advantage of the EKF estimation algorithm is it can estimate the state of a non-linear system without an observable model. It is a nonlinear extension of KF, and it is a popular method used in estimating robot position due to its simplicity and consistency. The main objective of this research is to implement EKF in underwater conditions using UGPS relative position and Inertial Measurement Unit (IMU) orientation. The secondary objective of this research is improving EKF positioning estimation by implementing of outlier filters. Overall, the proposed system allows accurate position tracking of underwater vehicles. Before EKF is applied, the dead reckoning model of the ROV was developed as the vehicle odometry. In addition, an experiment is conducted by evaluating the odometry of the robot where the transmitter of the UGPS is attached to the Remotely Operated Vehicle (ROV) and need to travel a pre-measured distance and compare the odometry output of the ROV with the measured distance. To test the effectiveness of the proposed method, the EKF was implemented offline with recorded data consisting of Underwater GPS (UGPS) and Inertial Measurement Unit (IMU). The filtered EKF output is evaluated by using MSE and RMSE to ensure the distinct features of the output signals are retained. The MSE and RMSE of median mean filter are less than 0.1 meter which signifies the filtered output of EKF retains the distinct features of the raw output of EKF. The proposed method can overcome the UGPS latency issues and accurately estimate the underwater vehicle's pose.

ABSTRAK

Penjejakan kedudukan adalah penting untuk robot mudah alih untuk fungsi dan navigasi autonomi terutamanya untuk robot dalam air. Oleh itu, tesis ini mencadangkan penggunaan Penapis Kalman Lanjutan (EKF) untuk pengesanan kedudukan kenderaan dalam air. Kenderaan dalam air tidak boleh menggunakan GPS konvensional untuk penjejakan kedudukan kerana pengecilan isyarat radio dalam badan air di sekelilingnya. “Underwater GPS” (UGPS) digunakan untuk meramalkan kedudukan kenderaan dalam air, tetapi ia mengalami masalah kependaman, oleh itu algoritma anggaran seperti KF dan EKF digunakan untuk memberikan nilai kedudukan yang konsisten daripada UGPS. Kelebihan utama algoritma anggaran EKF ialah ia boleh menganggarkan keadaan sistem bukan linear tanpa model anggaran. Ia dianggap sebagai lanjutan tak linear KF, dan ia merupakan kaedah popular yang digunakan dalam menganggar kedudukan robot kerana kesenangan dan konsistensinya. Objektif penyelidikan adalah untuk melaksanakan EKF dalam keadaan bawah air dengan menggunakan kedudukan relatif UGPS dan orientasi IMU dan penilaian data dari EKF dengan gabungan penapis terpencil. Objektif sekunder penyelidikan ini adalah menambah baik anggaran kedudukan EKF dengan melaksanakan penapis terpencil. Secara keseluruhannya, sistem yang dicadangkan membolehkan pengesanan kedudukan kenderaan bawah air. Sebelum EKF digunakan, model “dead reckoning” ROV telah ditulis dan dijadikan sebagai odometri “Remotely Operated Vehicle” (ROV). Di samping itu, eksperimen dijalankan dengan menilai odometri robot di mana pemancar UGPS dipasang pada ROV dan perlu menjalan jarak pra-ukur dan membandingkan output odometri ROV dengan yang diukur. Selain itu, bagi menguji keberkesanan kaedah yang dicadangkan, EKF telah dilaksanakan secara “offline” dengan data yang direkodkan terdiri daripada UGPS dan Unit Pengukuran Inersia (IMU). Output EKF yang ditapis dinilai dengan menggunakan MSE dan RMSE untuk memastikan ciri-ciri berbeza isyarat output dikekalkan. MSE dan RMSE bagi penapis purata median adalah kurang daripada 0.1 meter yang menandakan keluaran ditapis EKF mengekalkan ciri-ciri berbeza keluaran asal EKF. Kaedah yang dicadangkan boleh mengatasi isu kependaman UGPS dan menganggarkan pose kenderaan dalam air dengan tepat.

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LIST OF ABBREVIATIONS

UUV	-	Unmanned Underwater Vehicle
AUV	-	Autonomous Underwater Vehicle
ROV	-	Remotely Operated Vehicle
KF	-	Kalman Filter
EKF	-	Extended Kalman Filter
EM	-	Electromagnetic
GPS	-	Global Positioning System
UGPS	-	Underwater GPS
IMU	-	Inertial Measurement Unit
INS	-	Inertial Navigation System
USBL	-	Ultrashort Baseline
SBL	-	Short Baseline
LBL	-	Long Baseline
VRU	-	Vertical Reference Unit
SNR	-	Signal to Noise Ratio
MKF	-	Multi-Kalman Filter
LVS	-	Laser-based Vision
AWMF	-	Adaptive Window Median Filter

LIST OF SYMBOLS

x	-	position coordinates in x axis
y	-	position coordinates in y-axis
z	-	position coordinates in z-axis
$\dot{x}$	-	velocity experienced x axis / derivative of position x
$\dot{y}$	-	velocity experienced y axis / derivative of position y
$\dot{z}$	-	velocity experienced z axis / derivative of position z

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

The majority of the surface of the earth is covered by water in the form of oceans, rivers, and lakes, many of which have not yet been fully explored. Some of the environments are rich with natural resources such as fossil fuels. However, these environments are dangerous, and the depth is too deep for a normal human being to explore. Therefore, the invention of underwater vehicles for marine exploration. Through this exploration underwater robotic vehicles can also help protect habitats from environmental contamination and make the best use of the existing natural resources for human growth [1].

Underwater vehicles are usually mobile robots utilized by the marine industry and the military for underwater survey operations. Originally developed for marine science and rescue missions, they became popular in the 1980s as oil and gas exploration reached depths beyond human reach [2,3]. It is a complex machine with a range of mechanical, electrical and software subsystems [4]. Underwater vehicles can be divided into 2 categories which are unmanned underwater vehicles (UUVs) also known as autonomous underwater vehicles (AUVs) and manned underwater vehicles or also known as remotely operated vehicles (ROVs). There is a significant difference between AUV and ROV which is AUV are untethered while ROV requires tethering for communication and power [5]. The pose of the underwater vehicle is crucial for tracking the position and orientation of the vehicle especially for Autonomous Underwater Vehicles (AUV). Localization and navigation of an AUV is essential to ensure its autonomous functionalities [6]. Thus, the stability of localization and navigation of the vehicle depends on the accuracy and stability of the robot pose.

Figure 1.1: Remotely Operated Vehicle (ROV) [7].

Figure 1.2: Autonomous Underwater Vehicle (AUV) [8].

When a mobile robot is deployed in a designated location it is essential to track the robot relative to the environment regardless on the condition of the environment [9]. Mobile robots are equipped with high frequency sensors and the ability to triangulate its location based on the environment. Unfortunately, underwater vehicles could not use the same type of sensors due to the rapid attenuation of radio signals. Therefore, the utilization of different sensors that work better in underwater environment such as sonar and acoustics sensors. In underwater vehicle applications acoustic sensors are most suitable for tracking purposes. However, these sensors with acoustic communication principle have limited bandwidth and operates in low frequency [10].

Hence, the usage of pose estimators such as Kalman Filter (KF) or Extended Kalman Filter (EKF) to provide a stable pose estimate of a vehicle. EKF is the nonlinear extension of KF and commonly utilize on non-linear systems. EKF is infamous for fusing sensors with different frequencies to provide a state estimate of a vehicle. However, output of EKF is noisy compared to KF due to KF is an optimal estimator. To improve the EKF performance, outlier filters were added to remove the noise and smoothen the EKF output. The filtered EKF undergoes MSE and RMSE to check the retainment of distinct features of the raw EKF output. The procedures are discussed further in the upcoming chapters.

1.2 Problem statements

Underwater vehicles cannot use conventional GPS to obtain position information due to the radio frequency signals by the GPS are being damped by the body of water surrounding it [11]. For underwater network and communications acoustic signals, unlike land networks and communications, which mostly consists of Electromagnetic (EM) waves. Acoustic signals have a lower-frequency characteristic, enabling them to resist underwater transmission damping. However, acoustic channels are limited in bandwidth, have a long propagation latency, and have a high bit error rate [12].

Position drift is a common occurrence for underwater robots due to the lack of a stable localization while submerged and the effect of ocean currents. The effect of ambient ocean currents is a major difficulty in underwater robotics. Ocean currents can cause significant position drift due to the lack of GPS while submerged [6].

Therefore, the use acoustic positioning system in tracking underwater vehicle. Acoustic positioning system commonly utilize in tracking underwater vehicles. However, acoustic positioning system uses sound waves to propagate information and sound waves are much slower than radio waves which results in low update frequency [13,14].

1.3 Research Objectives

The objectives of this research are:

a) To implement Extended Kalman Filter (EKF) estimation algorithm in underwater conditions using Underwater GPS (UGPS) and Inertial Measurement Unit (IMU).
b) To evaluate EKF pose performance with combination of outlier filters.

The methods of accomplishing these objectives will be elaborated on in the research methodology chapter.

1.4 Research Scope

In this section the scopes and limitations of this research. The research scopes are:

a) The underwater vehicle used in this research is a ROV developed by A2lab. The ROV is a non-holonomic vehicle and the kinematics of the ROV is differential drive. The maximum depth of the ROV is 2 meters.
b) The EKF is implemented in offline conditions using ROV motion recordings. The recording is done underwater conditions.
c) The experiment in underwater conditions is done in Hydrotherapy room in UTM.
d) The EKF analysis is done externally with a developer kit called Nvidia Jetson TX2 with ROS framework installed.
e) The ROS framework version utilize in this research is noetic and melodic. ROS noetic is in the ROV while the TX2 uses melodic.
f) For this research, the depth is a fixed variable which is 1.6 meters.
g) Another fixed variable is the window size of the median and mean filters.
h) MATLAB software is used to plot and analyze the extracted data.
i) The publishing frequency of the UGPS is 1 Hz.

1.5 Organization of the Thesis

This thesis consists of 5 chapters and the following chapters are organize as follows:

Chapter 1 is the introduction of the thesis mainly discussing the problem statements and objectives of the research. This chapter highlights the objective and scope of the research.

Chapter 2 is literature review done throughout this research. This chapter discusses about other methods used to track the position of underwater vehicle and introduce acoustic positioning system. Motivation for extended research is also included in this chapter.

Chapter 3 explains the methodology of the research. This chapter discuss about the equipment used and the phases involve in achieving the research objectives.

Chapter 4 visualize and discuss the results obtained from this research. The fusion of UGPS and IMU results and shown and discussed and the filtered EKF is observed and evaluated in this chapter.

Chapter 5 summarizes and concludes the overall research as well as highlighting achievements of objectives and the future works.

REFERENCES

[1] Sahoo, A., Dwivedy, S.K. and Robi, P.S., 2019. Advancements in the field of autonomous underwater vehicle. Ocean Engineering, 181, pp.145-160.

[2] Petillot, Y.R., Antonelli, G., Casalino, G. and Ferreira, F., 2019. Underwater robots: From remotely operated vehicles to intervention-autonomous underwater vehicles. IEEE Robotics & Automation Magazine, 26(2), pp.94-101.

[3] H. Johannsson, M. Kaess, B. Englot, F. Hover, and J. Leonard, “Imaging sonar-aided navigation for autonomous underwater harbor surveillance,” in Proc. of IEEE/RSJ IROS, 2010, pp. 4396–4403.

[4] Bellingham, J.G., 2009. Platforms: Autonomous underwater vehicles.

[5] Christ, R.D. and Wernli Sr, R.L., 2013. The ROV manual: a user guide for remotely operated vehicles. Butterworth-Heinemann.

[6] Lee, K.M.B., Yoo, C., Hollings, B., Anstee, S., Huang, S. and Fitch, R., 2019, May. Online estimation of ocean current from sparse GPS data for underwater vehicles. In 2019 International Conference on Robotics and Automation (ICRA) (pp. 3443-3449). IEEE.

[7] ECA Group. (n.d.). H800 / ROV / Remotely Operated Vehicle. [online] Available at: https://www.ecagroup.com/en/solutions/h800-rov-remotely-operated-vehicle.

[8] www.kongsberg.com. (2022). Hydroid Introduces the New Generation REMUS 100 AUV. [online] Available at: https://www.kongsberg.com/maritime/about-us/news-and-media/news-archive/2016/hydroid-introduces-the-new-generation-remus-100-auv/.

[9] Huang, S. and Dissanayake, G., 1999. Robot localization: An introduction. Wiley Encyclopedia of Electrical and Electronics Engineering, pp.1-10.

[10] Watson, S., Duecker, D.A. and Groves, K., 2020. Localisation of unmanned underwater vehicles (UUVs) in complex and confined environments: A review. Sensors, 20(21), p.6203.

[11] Erol, M., Vieira, L.F.M. and Gerla, M., 2007, August. AUV-aided localization for underwater sensor networks. In International Conference on Wireless Algorithms, Systems and Applications (WASA 2007) (pp. 44-54). IEEE.

[12] Paull, L., Saeedi, S., Seto, M. and Li, H., 2013. AUV navigation and localization: A review. IEEE Journal of oceanic engineering, 39(1), pp.131-149.

[13] Taraldsen, G., Reinen, T.A. and Berg, T., 2011, June. The underwater GPS problem. In OCEANS 2011 IEEE-Spain (pp. 1-8).

[14] Molland, A.F. ed., 2011. The maritime engineering reference book: a guide to ship design, construction, and operation. Elsevier.

[15] MIT News | Massachusetts Institute of Technology. (n.d.). Wireless communication breaks through water-air barrier. [online] Available at: https://news.mit.edu/2018/wireless-communication-through-water-air-0822.

[16] Ye, P., Zhai, C., Du, G. and Zhan, X., 2009, August. Experiment evaluation of rapid error compensation for magnetic compass in underwater vehicle. In 2009 International Conference on Mechatronics and Automation (pp. 4880-4884). IEEE.

[17] AS, B. (2020). Nortek Underwater Instruments. [online] Water motion. Available at: https://www.nortekgroup.com/knowledge-center/wiki/new-to-subsea-navigation.

[18] Hegrenaes, O. and Berglund, E., 2009, May. Doppler water-track aided inertial navigation for autonomous underwater vehicle. In OCEANS 2009-EUROPE (pp. 1-10). IEEE.

[19] Navy Recognition. (n.d.). Delivery of 500th AN/WSN-7 Inertial Navigation System to US Navy by Northrop Grumman. [online] Available at: https://www.navyrecognition.com/index.php/naval-news/naval-news archive/2021/october/10847-delivery-of-500th-an-wsn-7-inertial-navigation-system-to-us-navy-by-northrop-grumman.html [Accessed 27 Jul. 2022].

[20] Vickery, K., 1998, August. Acoustic positioning systems. A practical overview of current systems. In Proceedings of the 1998 Workshop on Autonomous Underwater Vehicles (Cat. No. 98CH36290) (pp. 5-17). IEEE.

[21] Smith, S.M. and Kronen, D., 1997, October. Experimental results of an inexpensive short baseline acoustic positioning system for AUV navigation. In Oceans' 97. MTS/IEEE Conference Proceedings (Vol. 1, pp. 714-720).

[22] Vickery, K. (1998). *ACOUSTIC POSITIONING SYSTEMS 'A PRACTICAL OVERVIEW OF CURRENT SYSTEMS' Session Index ACOUSTIC POSITIONING SYSTEMS 'A PRACTICAL OVERVIEW OF CURRENT SYSTEMS'*. [online] Available at: https://dynamic-positioning.com/proceedings/dp1998/SVickery.PDF [Accessed 27 Jul. 2022].

[23] Karras, G.C. and Kyriakopoulos, K.J., 2007, June. Localization of an underwater vehicle using an IMU and a laser-based vision system. In 2007 Mediterranean Conference on Control & Automation (pp. 1-6). IEEE.

[24] Huang, W. and Kovacevic, R., 2011. A laser-based vision system for weld quality inspection. Sensors, 11(1), pp.506-521.

[25] Candy, J.V., SIGNAL PROCESSING IN ACOUSTICS: SCIENCE OR SCIENCE FICTION?

[26] Hartmann, W.M. and Candy, J.V., 2014. Acoustic signal processing. In Springer Handbook of Acoustics (pp. 519-563). Springer, New York, NY.

[27] Almeida, J., Matias, B., Ferreira, A., Almeida, C., Martins, A. and Silva, E., 2020. Underwater localization system combining iusbl with dynamic sbl in¡ vamos! trials. Sensors, 20(17), p.4710.

[28] Wang, J., Li, J., Yan, S., Shi, W., Yang, X., Guo, Y. and Gulliver, T.A., 2020. A novel underwater acoustic signal denoising algorithm for Gaussian/non-Gaussian impulsive noise. IEEE Transactions on Vehicular Technology, 70(1), pp.429-445.

[29] Barfoot, T.D., 2017. State estimation for robotics. Cambridge University Press

[30] Welch, G. and Bishop, G., 1995. An introduction to the Kalman filter.

[31] Kim, Y., Bang, H., 2018, 'Introduction to Kalman Filter and Its Applications', in F. Govaers (ed.), Introduction and Implementations of the Kalman Filter, IntechOpen, London. 10.5772/intechopen.80600.

[32] Simon, D., 2006. Optimal state estimation: Kalman, H infinity, and nonlinear approaches. John Wiley & Sons.

[33] Montella, C., 2011. The Kalman filter and related algorithms: A literature review. Research Gate.

[34] Gustafsson, F., Gunnarsson, F., Bergman, N., Forssell, U., Jansson, J., Karlsson, R. and Nordlund, P.J., 2002. Particle filters for positioning, navigation, and tracking. IEEE Transactions on signal processing, 50(2), pp.425-437.

[35] Kim, J.Y., Paeng, D.G., Kim, Y.H., Choi, H.S. and Kim, K., 2012. Implementing short baseline acoustic positioning system for small-sized remotely operated vehicle. Advanced Science Letters, 15(1), pp.197-201.

[36] Demim, F., Benmansour, S., Abdelkrim, N., Rouigueb, A., Hamerlain, M. and Bazoula, A., 2021. Simultaneous localisation and mapping for autonomous underwater vehicle using a combined smooth variable structure filter and extended kalman filter. Journal of Experimental & Theoretical Artificial Intelligence, pp.1-30.

[37] Kepper, J.H., Claus, B.C. and Kinsey, J.C., 2018. A navigation solution using a MEMS IMU, model-based dead-reckoning, and one-way-travel-time acoustic range measurements for autonomous underwater vehicles. IEEE Journal of Oceanic Engineering, 44(3), pp.664-682.

[38] Konatowski, S. and Pieniężny, A.T., 2007. A comparison of estimation accuracy by the use of KF. EKF, and UKF filters.

[39] Ben-Ari, M. and Mondada, F., 2018. Robotic motion and odometry. In Elements of Robotics (pp. 63-93). Springer, Cham.