Autonomous Navigation of Catamaran Surface Vessel

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Abstract - Motivation for the investigation of position and waypoint controllers is in demand for Wave Adaptive Modular Vessel (WAM-V) capable of fulfilling various useful applications. Hence, this paper deals with the development of a GPS based position control system for WAM-V able to navigate between waypoints. A waypoint guidance algorithm is discussed with the double loop feedback controller. The outer loop is fuzzy reasoned and generate the desired heading. The inner loop is a PID controller with thrust allocation command. This control design greatly simplifies the control design process and easily applied to underactuated catamaran vessel WAM-V. The fuzzy reasoning fairly represents the behavior and decision making almost like human operator. Based on the manoeuvring experiments, the lookup table is developed for thrust allocation. The WAM-V is equipped without rudder, thus it is driven by a combination of different thrusts to control both speed and heading. The proposed control scheme performed well in the experiments and using that experimental data simulation is improved. The obtained results affirmed that the fuzzy waypoint guidance control algorithm is powerful to realize the autonomous navigation path planning.

Keywords - Waypoint Navigation, Manoeuvring, Intelligent Guidance, Autonomous Surface Vessel (ASV), Thrust Allocation.

1. Introduction

Automatic navigation of the ship is one of the most complicated problems. Usually, highly expert and robust algorithms are required to make a suitable decision considering various environmental conditions. In this context the accurate determination of the current position is very important and this problem has been solved by global positioning system (GPS), Intertial Navigation System (INS), Radio Detection and Ranging (RADAR), Magnetic Compass etc. INS and GPS are complimentary navigation systems and can be integrated to produce a more reliable and accurate positioning system. Most of the real world applications of the robots are based on accurate positioning and only scale of requirement changes from global navigation to local navigation and personal navigation. Since waypoint tracking is widely used in wheeled mobile robots, surface ships, remotely operated vessels (ROV) and autonomous underwater vessel (AUV). One of the tasks in ocean robotics is a path following of an autonomous vessel. Path following is a very challenging problem in terms of navigation, controller design and guidance algorithm, one should have a robust controller, which takes into account of external disturbances as well as generate accurate heading angle. Path tracking uses positional information, typically obtained from GPS, IMU and vehicle odometry, to control the vessel speed and steering to follow a specified path. There are number of autonomous vessels developed with various sensors used for navigation. The brief hardware development for control and navigation development are discussed for autonomous surface vessel [1]. Hasegawa et al. [2], [3] and [4] developed Automatic Navigation System called "SAFES" for harbor manoeuvring for path planning, normal operations and collision avoidance. This navigation path planning algorithm using fuzzy logic is developed for collision avoidance which can be used for waypoint tracking. The fuzzy control rules are constructed based on the human operator's experience. In the literature, there are several guidance algorithms such as pure pursuit (PP), line of sight (LOS), and constant bearing (CB) is widely discussed in the research of Fossen [5] for waypoint navigation and control applications. International Regulations for preventing Collisions at Sea (COLREGs) rules and regulations based algorithms are used in many researches for collision avoidance and path planning. One of the related work is done by Lee for the development of autonomous navigation algorithm called COLREGS- based collision avoidance in the presence of moving obstacles [6]. Beard and Maclain [7] used the algorithm based on Dubins paths. It was found that the Dubin's path is an optimal (shortest) path between two waypoints. These are constructed from two circular arcs and a line. They introduced an algorithm which selects the shortest Dubin path between two waypoints, but does not deal with waypoint reachability and with the direction of the next waypoints

Waypoint (WP) guidance is very useful for terrestrial navigation, air navigation and ocean navigation. Although there are various control techniques are available in the literature but most of them are based on modern control theory. These methods require precise mathematical models of the dynamic behaviour of the system. Fuzzy is an effective alternative approach for system which is difficult to model.

In 2008 marine science research Inc. launched a revolutionary new generation surface vessel called WAM-V [8]. It has been designed to adapt to the shape of the water surface. WAM-V is equipped with springs, shock absorbers, and ball joints, giving enough agility to the vessel and damping stresses to the structure and payload. There is a tremendous application possible using this kind of new generation vessel.

Pandey and Hasegawa [9,10] studied the maneuvering performance of WAM-V in calm and deep water and also simulated the fuzzy guided waypoint algorithm after developing the MMG type of mathematical model of catamaran WAM-V vessel. This waypoint guidance algorithm is also simulated for WAM-V by Pandey and Hasegawa [11]. Ahmed and Hasegawa [12] presented the simulation and experimental results of the same fuzzy waypoint guidance algorithm for Esso Osaka Ship and showed the promising experimental and simulation results.

This paper shows how the problem of autonomous navigation of a catamaran Surface vessel WAM-V was formulated and solved. A lookup table based controller is used to allocate the desired thrust able to navigate between the desired waypoints. Firstly, it is shown how the fuzzy based waypoint algorithm was applied to navigate through waypoints using the measurements from IMU (Inertial Measurement Unit), GPS and a digital compass. A mathematical model of the WAM-V is improved using the experimental results. Finally the paper shows how the proposed algorithm for the waypoint navigation was implemented and tested using an embedded computer and the sensors (IMU, GPS and digital compass) aboard the ship.

2. Problem Formulation

The guidance problem is to navigate to and cross on a specified heading defined by the series of waypoints. In various marine applications it is of primary importance to steer the ship along a desired path. The desired path consists of a turning and straight line segments which is defined by the waypoints. A vessel cannot change its yaw rate instantaneously. There are three phases exist for a turning manoeuvre

- Zero Yaw Rate
- Accelerating/ De-accelerating yaw rate
- Constant yaw rate

The purpose of this paper is to present a solution to the waypoint tracking problem for a class of underactuated catamaran vessels. This could be owned to a design choice. From a practical perspective deigning a controller for underactuated system is easier. Underactuated provides backup control techniques for a fully actuated system. If a fully actuated system is damaged or failed, then a controller for fully actuated system is available to recover from the problem.

In this paper, we address the problem of disturbance compensation controller for an underactuated WAM-V. It has been found in the field experiments of waypoint navigation that there should be a good controller to counteract the effects of environmental disturbances.

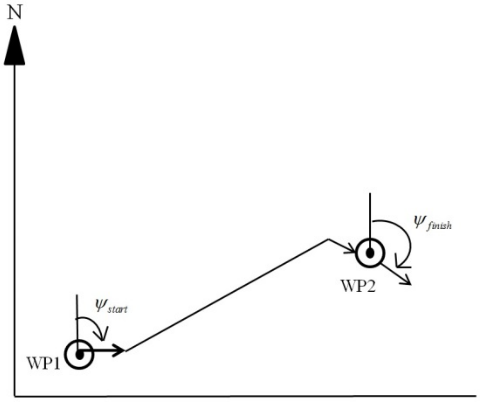


Fig. 1. The ship departs WP1 on a heading ψ_{start} and is to cross WP2 heading ψ_{finish}. The dots represent the positions of the WP.

Figure 1. shows the guidance problem where the vessel need to navigate to and cross on a specified heading, a series of waypoints. In this research the fuzzy based waypoint algorithm is used which is very simple, computationally inexpensive and flexible to sudden changes in the desired path. The behaviour and decision making of ship navigators are done using fuzzy theory. Fuzzy theory is suitable for complicated and hierarchical human behaviours. These kinds of expert system can apply to the more realistic environmental conditions.

This paper shows improved simulation results after field experiments including reference heading correction methods to give smoother vehicle path in turn at a waypoint, tuned PID controller parameters, removal of sensor noise and compensation with environmental disturbances. The improvement address the mentioned flaws of the basic simulation results and yet to keep it simpler than in the case for the most used waypoint navigation and guidance algorithms. Automatic navigation subsystem is supervised by knowledge- based system where execution of each command is done by fuzzy control or reasoning. The system can solve almost all situations in field tests.

3. Fuzzy Reasoned Waypoint Controller

In this research, fuzzy controller is used to decide the course for navigation path planning. Based on the ship operator's manipulating experience, the control rules for desired course are developed. As mentioned earlier, the navigational path consists of several set points named waypoints (WPs). These waypoints are usually selected at the turning points. Then, the path is planned normally directing to the next point (WP) to be passed. However, near the turning point, the fuzzy system will decide to choose the appropriate course defined by the next two WP as Eq. (1).

$$\psi_1 = \psi_1 + (\psi_2 - \psi_1) * CDH \tag{1}$$

Where ψ_1 is order of course and ψ_1 is course of the shortest path to the next WP, ψ_2 is course of the shortest path to the second next WP. CDH is reference degree to the second WP (0≤CDH≤1). In this algorithm, to judge the nearness of the waypoint, TCPA (time to closest point of approach) and DCPA (distance of the closest point of approach) are used for fuzzy reasoning. Fig. 2 (a) and (b) shows the graphical layout of waypoints and path.

At first the waypoints (WP) are initialized as $W_i = (X_i, Y_i)$, $W_{i+1} = (X_{i+1}, Y_{i+1})$ and current vehicle position (P) and vessel heading ψ is obtained from the sensor.

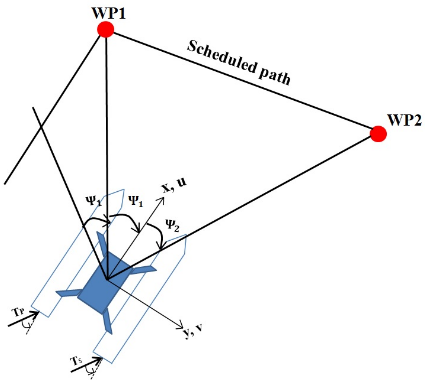
The distance between the ship and nearest waypoint (D) is calculated Eq. (2).

$$D = \sqrt{(X_0 - X_t)^2 + (Y_0 - Y_t)^2} \tag{2}$$

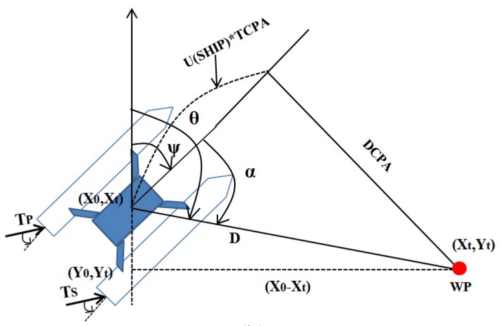
Encountering angle of waypoint from the vertical axis (θ) and bearing angle of the waypoint (α)from the ship are calculated with the help of Eq. (3) and (4). Here, if the value of ψ ,θ or α becomes negative, then 2π is added to make to them positive.

$$\theta = a\tan 2\frac{(Y_t - Y_0)}{(X_t - X_0)} \tag{3}$$

$$\alpha = \theta - \psi \tag{4}$$



(a)



(b)

Fig. 2. (a) Course command near a course changing point (b) Bearing relationship between ship and waypoint

Finally time to closest point of approach (TCPA) and distance of the closest point of approach (DCPA) are calculated with the help of Eq.(5) and (6).

$$DCPA = D|D\sin\alpha| \tag{5}$$

$$TCPA = \frac{D\cos\alpha}{U_{ship}} \tag{6}$$

Another important point to be considered is the scale effect. There should be some difference on the nearness between a large ship and a small one. Therefore, the following equations are used for non-dimensionalised TCPA and DCPA. The nearness is then reasoned from DCPA' and TCPA' instead of DCPA and TCPA using the Eq. (7) and (8)is calculated.

$$DCPA' = \frac{DCPA}{L} \tag{7}$$

$$TCPA' = \frac{TCPA}{L} \tag{8}$$

When the TCPA' becomes negative the waypoint is switched and next set of waypoints are targeted. The nearness of the waypoint is judged using Fuzzy logic by calculation TCPA', DCPA' and CDH. The waypoints are stored in a database and are used to generate the desired trajectory to follow.

The guidance algorithm is expected to perform specific types of manoeuvre, depending on the magnitude of the distance of the waypoint. Some of the important part of the algorithm is described as follows

- The algorithm doesn't ensure the reachability of waypoints rather reaching to the target is the main concern.
- This algorithm targets two waypoints at a time and choose an optimal path between two.
- When the distance to the waypoint is larger it target to steer towards the waypoint.
- When the distance to the waypoint is smaller it starts targeting to the next set of waypoints.
- Nearly zero distance to waypoint make only small course corrections.

Control system layout designed contains two loops as shown in the fig. 3.. For outer loop fuzzy controller is used to feed the desired heading to the inner loop. In the inner loop a PID feedback controller is used to correct the desired course generated by the fuzzy reasoned algorithm. The control system provides the necessary feedback signal to track the desired heading comes from the fuzzy algorithm. After PID generate the appropriate command the thrust is allocated to the portside and starboard side thrusters along with the command from lookup table. This system processes information to infer the state of the WAM-V plant and to generate an appropriate command for the actuators so as to reduce the reference heading and actual heading. The WAM-V is controlled by differential thrust for surge and yaw motion control.

In this control system waypoints are input. The PID control system provides the necessary feedback signal to track the desired heading comes from the guidance algorithm (τ_{com}). The lookup table based thrust allocation is used to send the necessary signal to the thrusters (τ_{order}). The lookup table is made with the help of previous knowledge of the dynamics of the system. This differential command added with the thrust allocation command generated using looking table is combined and allocated to both the thrusters as given by Eq. (9) and (10).

$$T_{port} = \tau_{com} + \tau_{order} \quad (9)$$

$$T_{starboard} = \tau_{com} - \tau_{order} \quad (10)$$

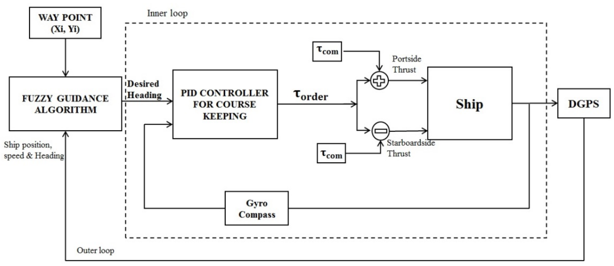


Fig. 3. Control system layout

4. Field Experiments

To perform such experiments firstly the system should be prepared in terms of hardware and software module. Development of the system for waypoint guidance is discussed in this part. Fig.4 shows the main components of the navigation system. The control station consists of a stand alone personal computer, which is used to control the autonomous or manual mode of the ship. A radio modem that acts as a communication link. The propulsion module consists of trolling Minn Kota motors with customize motor drivers. The sensor module consists of Furuno SC-30 GPS satellite compass. This sensor provides very accurate navigation information. Apart from this a low cost IMU and iPhone are also used to measure the same parameters. Field experiments were conducted at the Osaka University pond facility. Initially, one waypoint was used to verify that the controller produced smooth paths. For controller, additional tuning was necessary in terms of PID parameters.

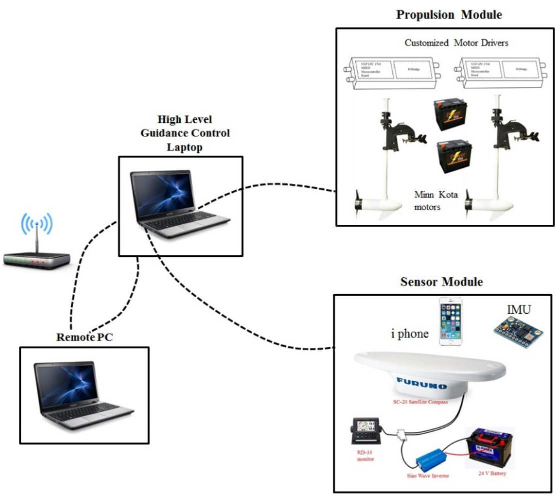


Fig. 4. Hardware Architecture of experiments

5. Improvement in Simulation

In the previous research the MMG- type modular maneuvering model has been found to be suitable as a mathematical model [13]. After doing field experiment, it is experienced that wind has a huge impact on the results. So it is decided to include wind effect in the mathematical model. Fujiwara wind model [14] is adopted considering the steady wind effect. The PID coefficients are also tuned during experiments. In the first trial of the experiment, it was found that there was an overshoot in the path followed by the vessel to reach the waypoint. The output of the PID controller for the desired course was found too sensitive and prompt. Therefore, for further experiment the coefficient of the PID controller is tuned to cope up with the overshoot in order to ensure smooth operation. The lookup table was also checked in the first experiment. Depends on the pond area the limit of the speed and turning was set in order to avoid boundary collision. After field experiments, simulation in Matlab/Simulink is improved to get better results. Fig. 5. Shows the Simulink model for waypoint navigation and guidance. Another improvement is done by using running average smoothing of GPS data. In this algorithm output value of each data sample is a weighted average of the input values of data samples that fall within a given window created in the sample. The window slides across the entire data set one sample at a time. In this experiment the window of 3 data is considered. The wider averaging window result is more aggressive smoothing, but it can increase the likelihood of filtering part of the signal along with the noise.

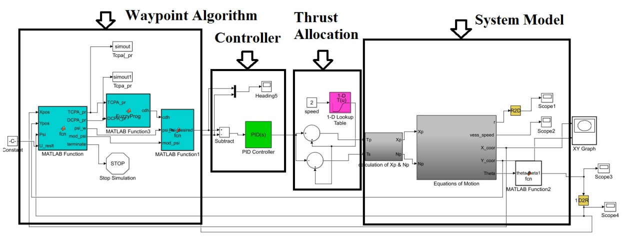


Fig. 5 Simulink Model for waypoint guidance and control of WAM-V

6. Results

A fuzzy waypoint guidance controller was developed and tested at the Osaka University pond facility. The first test was conducted with one waypoint. Fig. 6 shows the google view of the experimental data at the Osaka University pond. In this preliminary test only one waypoint was chosen in order to check the algorithm. Fig. 7 (a) shows the x-y plot of experimental and simulation results with the given waypoint. Experiment and simulation trajectories show good agreement. The graph of the experiment result is not very smooth as there is some noise in the data of GPS even after applying the smoothing filter. Fig. 7 (b) Heading error graph of simulation and experiments. These two graphs also show good agreement with each other.

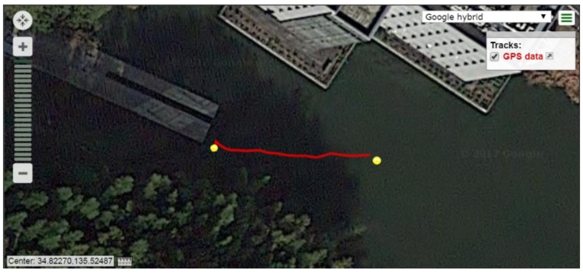
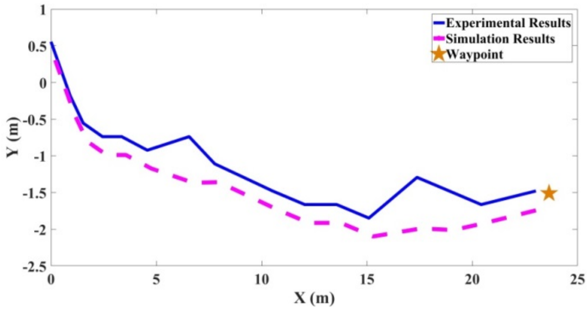
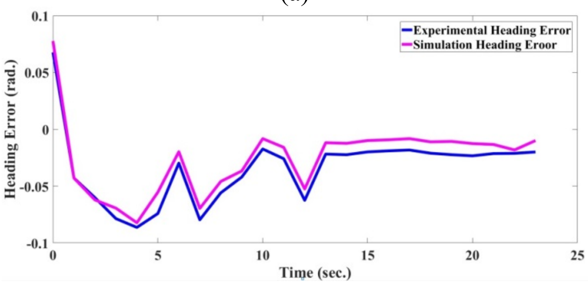


Fig. 6. google map view of the first experiment



(a)



(b)

Fig.7. (a) x-y plot of experiment and simulation of the 1st experiment (b) Experiment and simulation graph of heading error

Google map view of 2nd experiment is shown in fig. 8. In this experiment 3 waypoints were chosen in a zigzag pattern. Fig. 9 (a) shows the trajectory of simulation and experiment of 2nd experiment. The x-y graph of simulation is making a good agreement with experiments after improvement in the simulation process rigorously. Fig. 9 (b) shows the heading error graph of simulation and experiment of the second experiment. The vessel almost follow the waypoint with the minimum heading error.

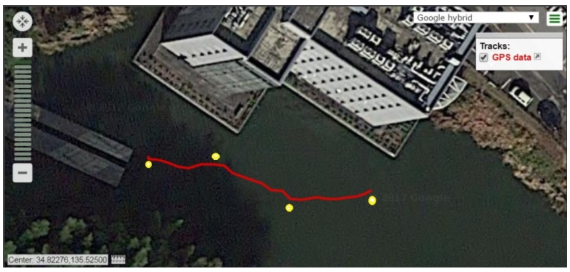
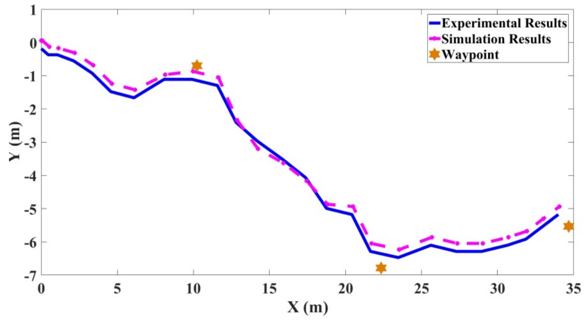
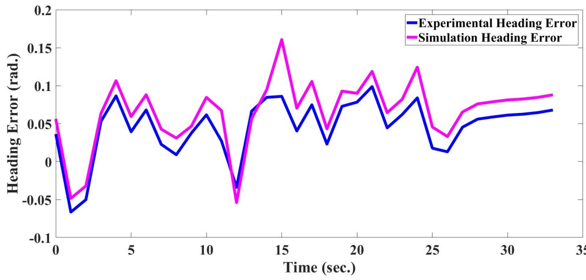


Fig. 8. Google map view of 2nd experiment



(a)



(b)

Fig. 9. (a) x-y plot of experiment and simulation of 2nd waypoint (b) Experiment and simulation graph of heading error

7. Conclusions

This paper describes the simulation and experimental result of a robust waypoint algorithm which is reasoned by fuzzy implemented on WAM-V. The experiments with waypoint algorithm is conducted and based on the results simulation is improved. The waypoint algorithm is found comparatively simple, robust and can be implemented in any kind of system. Firstly the hardware and software module is developed to conduct a navigational experiment. Once the SC-30 satellite compass, IMU, Minn Kota propellers, etc. is tested separately. Later on full hardware and software modules are tested together. In this paper many modifications and improvement are discussed which couldn't observed during simulation done before. Fujiwara wind model is also applied in the existing mathematical model to simulate the results. The simulation results of waypoint navigation show that the fuzzy reasoned waypoint algorithm followed by feedback controller gives satisfactory performance. There are many applications possible using this algorithm of path tracking. This paper also proves the advantage of underactuated scheme. The control law has a concise form and easy to implement in the practice due to a smaller computational burden with only few online parameters being tuned.

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