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Design for a Guidance and Control System for a Wave-Adaptive Modular Vessel

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Abstract: George Mason University is developing a Wave-Adaptive Modular Vessel (WAM-V) for the 2022 RobotX competition. The Guidance & Control System (G&CS) is a critical system on the WAM-V. It must autonomously steer the vessel safely from a competition course start line to the course finish line. The G&CS has access to RADAR, LiDAR, and camera data that identifies the angular distance to the course red and green buoys. A digital-twin G&CS was developed in MATLAB Simulink to simulate vessel dynamics and controller design and to evaluate the design parameters for a Proportional Derivative (PD) controller for Heading and Velocity control. The G&CS provides modeling functionality for an end user to determine optimal PD constants KP and KD for ship movement from any location within the RobotX course. A test run of the G&CS initialized to the center of the start-line with a 90-degree heading and 0.5 m/sec velocity, KP = 120 and KD = 100 results in reaching 5% steady state error in 55 seconds, and 10% steady state error in 26 seconds, with a rise time of 24 seconds.

Keywords: Guidance and Control System, Decision Support Tool, Autonomous Navigation

1. Design for a Guidance and Control System for a Wave-Adaptive Modular Vessel

George Mason University plans to send an Autonomous Marine System (AMS) to the 2022 RobotX competition, an opportunity for colleges and universities to demonstrate autonomous development skills. The AMS must successfully navigate the qualifying course using a Guidance and Control System (G&CS) which can identify the position of the physical platform, a Wave-Adaptive Modular Vessel (WAM-V), within the course. The G&CS must guide the WAM-V successfully across the finish line. A digital replica of the G&CS has been developed as a decision support tool for the design of the physical system.

1.1 Context Analysis: Enterprise

The RobotX competition is a multi-university student competition with the goals of familiarizing students with autonomous technology in a marine environment and advancing autonomous technology. Competing teams will participate in several challenges as part of the RobotX competition, consisting of qualifying, semifinal, and final rounds (RobotX, 2021). Semifinal rounds test various permutations of AMS navigation, communication, and sensing technology, such as identifying hyperspectral signatures and performing navigation actions based upon the type of signature. Final rounds are more complex combinations of semifinal tasks. Passing the qualifying round itself is a challenging task as approximately 30% of craft failed to pass the qualifying round at previous RobotX competitions per a personal interview with Dave Edwards, a former RobotX competition judge.

A Wave-Adaptive Modular Vessel (WAM-V) is the physical platform for the RobotX competition. It consists of a 16' long pontoon boat with a sensor suite and guidance computer mounted at its center of mass (Figure 1). The guidance and control system (G&CS) sends heading and thrust commands to the WAM-V's motors. These motors have asymmetrical thrust which enables steering. The G&CS must operate without a navigation data base and without GPS coordinates for buoys. Instead, the G&CS has access to RADAR, LiDAR, and camera data that identifies the angular distance to the course red and green buoys.

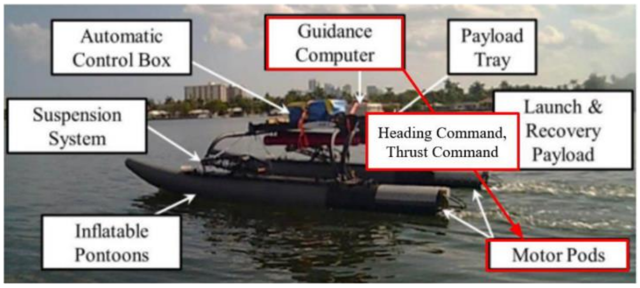

Figure 1. The guidance computer uses a sensor suite and a guidance and control system to send heading and thrust commands to the motor pods.

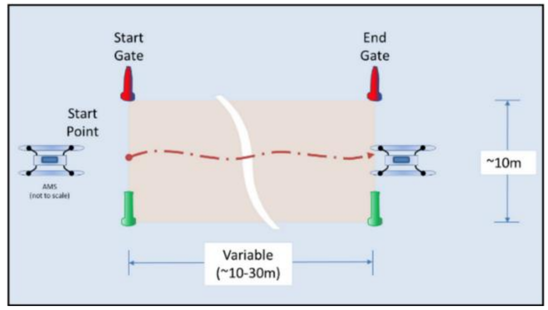

Figure 2. RobotX course buoy positions.

1.2 Process

The first challenge is the qualifying round. The vessel must navigate a 10-to-30-meter course delineated by two sets of red (port) and green (starboard) buoys. There is no set time limit for this qualifying round. The WAM-V will be manually navigated by the onshore team of engineers to a point in front of one set of buoys, the "entry gate" (Figure 1). At this point, the autonomous Guidance and Control System (G&CS) becomes active to steer and control the speed of the WAM-V. The WAM-V must proceed through the first set of buoys, the entry gate and exit the second set of buoys, the "finish gate."

1.3 Problem and Needs Statement

The Guidance and Control System (G&CS) shall provide asymmetric thrust commands to the WAM-V motors, as illustrated in Figure 2, to steer the vessel for the qualifying round of the Robot-X competition. The G&CS must use RADAR, LiDAR, and camera data to identify the relative position of the vessel to the course, as GPS cannot identify buoy positions.

1.4 Concept of Operations

The WAM-V will be manually navigated by the onshore team of engineers to a point in front of one set of buoys, the "entry gate." At this point, the autonomous Guidance and Control System (G&CS) become active to steer and control the speed of the WAM-V. The WAM-V must proceed through the first set of buoys, the entry gate and exit the second set of buoys, the "finish gate." The WAM-V must constantly transmit data to shore throughout its operation, some of which (position, velocity, etc.) is from the G&CS. The G&CS uses information from the senor suite's scan of the environment to distinguish the two gates (start and finish) and orient itself with respect to the course-based reference frame. Once it has distinguished the gates, it uses a propulsion command to change the velocity of the WAM-V, moving forward towards the start gate. If necessary, it steers by continually determining position relative to the buoys and utilizing propulsion adjustments accordingly. Once the WAM-V has successfully passed the finish line, the AMS has completed its task. It stops WAM-V propulsion, cuts the required transmission to the judges, cedes control to the onshore team, and powers down.

2. Requirements

The mission requirements for the system are derived from the Concept of Operations and based on RobotX regulations. They provide criteria to define successful operation of the G&CS and are as follows:

- MR.1 - The G&CS shall navigate through the RobotX 2022 Qualifying Course from a position behind the starting line and pass the finish line within 30 minutes.
- MR.2 - The G&CS shall provide guidance commands to steer no closer than 2 meters from any buoy.
  - Note: This is defined based on response time and turn radius.
- MR.3 - The G&CS shall receive as inputs from the sensor system ship-based angles looking forward through the prow of ship to Start Line Red Buoy, Finish Line Red Buoy, Finish Line Green Buoy, and Star Line Green Buoy once per second within an accuracy of +/- 2 degrees.

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- MR.4 - The G&CS shall transmit all data (i.e. sensor data, modes, commands) to a telemetry receiver on the shore.

The mission requirements have been further decomposed into functional requirements which highlight specific aspects of the system design. A summary of the functional requirements is as follows:

- G&CS shall utilize sensor suite (RADAR, LiDAR, cameras, etc.) to orient the ship with respect to the course.
- G&CS shall use the sensor suite input to calculate the ship's position within the course.
- G&CS shall calculate necessary heading adjustments to change ship course.
- G&CS shall implement heading adjustments as necessary.
- G&CS shall continue operation until ship has finished the course.

3. Design

The Guidance and Control System utilizes two reference frames (one for the course, one for the ship) to determine ship position relative to the buoys which delineate the course and act as waypoints for positional reference. It uses angles formed by the WAM-V with buoys to identify its position and navigate within the course (Figure 3).

3.1 Reference Frame

The digital twin uses two separate reference frames for its position, as does any moving platform – ship, aircraft, land vehicle, etc. (Massey, 2006). First, there is the frame directly attached to the vehicle, usually oriented in reference to the earth. The vehicle gets its position through GPS tracking and can update its position based on its changes in position and velocity. Here, the vehicle reference frame is the ship-based reference frame – essentially from the point of an observer on the WAM-V in relation to the earth. The second reference frame is developed in reference to the physical context in which the moving platform operates. This reference frame is based on the qualifying round course delineated by a set of four buoys, as seen in Figure 3. The model relates functions directly related to position and velocity to the platform, and functions related to determining navigational changes to the physical context.

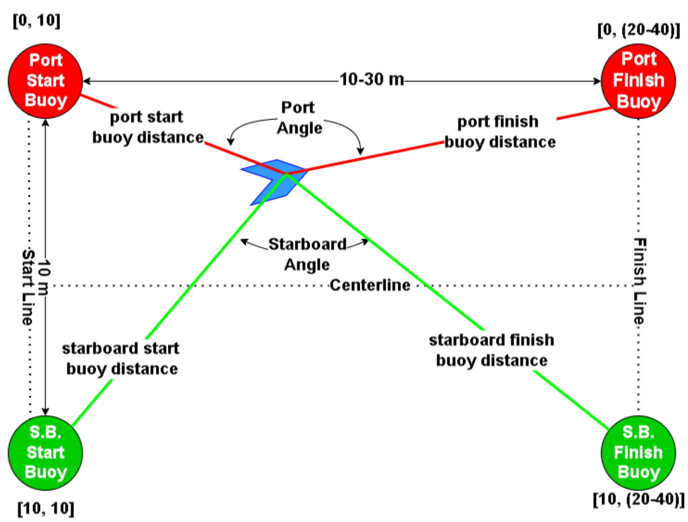

Figure 1. Course reference frame and WAM-V positioning.

3.2 Navigation Modeling

The model begins by identifying the positions of buoys according to RobotX rules. In current simulation development, buoy positions are oriented according to the course-based reference frame starting 10 m behind and 10 m to the left of the port side start buoy (Figure 3). The system uses a proportional – derivative heading controller and a velocity controller to control the ship's movement. The simulation includes a model of vehicle dynamics and sensor suite.

4. Implementation

The known buoy positions inform distance calculations using Equation 1, which determines the distance between the position of the boat and a buoy. For Equation 1, the port start buoy has been chosen to represent the buoy portion of this equation; however, this equation applies to any buoy. Here, d_{psb} is the total distance to the port start side buoy, x_{psb} and y_{psb} are the x and y coordinates of the port start buoy, respectively, and x_b and y_b are the x and y coordinates of the boat. Other buoys are represented as *pfb* (port finish buoy), *ssb* (starboard start buoy), and *sfb* (starboard finish buoy).

$$d_{psb} = \sqrt{\left(x_{psb} - x_b\right)^2 + ((y_{psb} - y_b)^2)} \quad (1)$$

The system then calculates angles between the WAM-V and the port and starboard buoys to determine its location in relation to those buoys. The port angle is calculated using Equation 2, and the starboard angle is calculated by substituting the starboard buoys in place of the port buoys in Equation 2.

$$\angle Port = \arccos(\frac{(x_{pfb} - x_b)}{d_{pfb}}) + \arccos(\frac{(x_b - x_{psb})}{d_{psb}}) \quad (2)$$

The G&CS then assesses the relative size of the port and starboard angles using the centerline angle of error ($\angle CAE$) (Equation 3). In this implementation, if the port and starboard angles are equal, the boat is on the centerline. If port is larger, the boat is to the left of centerline. If starboard is larger, the boat is to the right of centerline.

$$\angle CAE = \angle Port - \angle Starboard \quad (3)$$

A proportional constant and derivative constant (KP and KD, respectively) control the proportion by which $\angle CAE$ affects the heading command (Equation 4) (Benedict & Kirchoff, 2007). This is the implementation of a proportional-derivative controller as previously discussed. Here, KP and KD function as essentially a spring-dampening system, bringing the system to a steady state through continually decreasing oscillations around the centerline. The value of these constants varies for each implementation of the system, and sample values are in the Results section.

$$HC = KP * \angle CAE + KD * \frac{d}{dt}\angle CAE \quad (4)$$

This heading command provides the optimal new heading for the boat to return to the centerline and navigate through the course. The next step is to calculate system velocity using this heading (Pandey & Hasegawa, 2015). The system currently assumes the velocity is held constant. Separate X and Y velocities are calculated according to equations 5 and 6. Here, *Heading* is the heading provided by the heading command limit function referenced in the previous paragraph, $V_x(t)$ and $V_y(t)$ are the x- and y-directional components of velocity, and $V(t)$ is the velocity of the boat from the velocity controller (here a constant velocity determined by the end user of the system).

$$V_x(t) = \sin(Heading) * V(t) \quad (5)$$

$$V_y(t) = \cos(Heading) * V(t) \quad (6)$$

Then, system position (for x and y coordinates relative to the course) must be calculated using Equations 7 and 8, where x_b and y_b indicate the course-based position of the WAM-V on the previous iteration of the cycle.

$$P_x(t) = x_b + t * V(t) \quad (7)$$

$$P_y(t) = y_b + t * V(t) \quad (8)$$

On the very first iteration, the WAM-V has known coordinates for modeling purposes. After the x and y coordinates of the boat are updated, the cycle continues using the new coordinates until the WAM-V has passed the finish line, which is determined when the y position of the WAM-V is equal to the y position of the finish line. These equations have been incorporated into a Simulink model as seen in Figure 4.

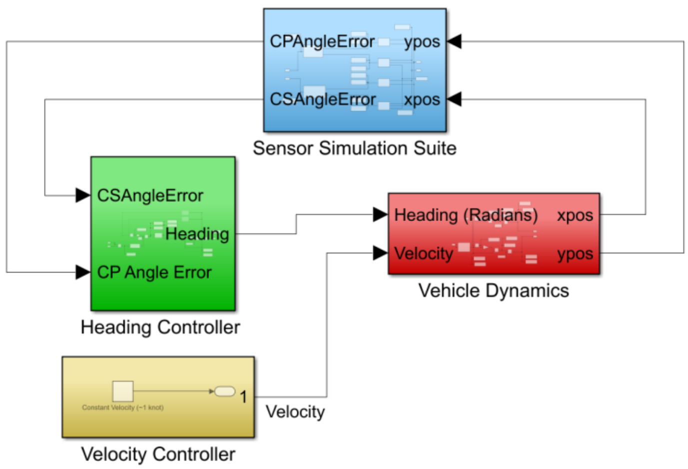

Figure 4. Simulink model of system equations.

5. Verification Testing

The four primary subsystems (Sensor Simulation Suite, Heading Control, Velocity Control, and Vehicle Dynamics) have been tested on a subsystem level – 280 total tests, 90 for Sensor Simulation Suite, 40 for Heading Control, 10 for Velocity Control, 140 for Vehicle Dynamics. Verification testing identified several errors, which were resolved, and all subsequent verification tests passed. A sample verification test is in Figure 5, demonstrating successful verification of the distance to buoy calculation in the Sensor Simulation Suite.

Test Number	Starting U values (x, y)		Expected Results	Actual Result - Simulink	Pass/Fail
SSS.1				**DPS**	
SSS.1.1	5	10	5	5	P
SSS.1.2	5	15	7.071067812	7.07	P

Figure 5. Successful tests for distance to the port start buoy from the WAM-V.

6. Validation Testing

Validation testing resulted in the KP and KD values present in Table 1. These were obtained in a system test using a 90-degree heading offset from the centerline, a starting position of [5, 10] (on the course centerline and start line), and constant velocity of 0.5 m/s. Figure 6 shows the graphed results of WAM-V movement for KP = 120, KD = 100.

Table 1. Controller Performance Results

KP Value	70	120	200	70	120
KD Value	100	100	100	150	150
10% Steady State Time (s)	44	26	40	45	63
5% Steady State Time (s)	49	55	43	52	54
Rise Time (s)	64	24	25	82	34
% Overshoot	0.006	0.099	0.196	0.0008	0.08
# Turns	2	5	5	3	5
Along-Track Distance (m)	30.87	31.12	31.12	30.87	31.13

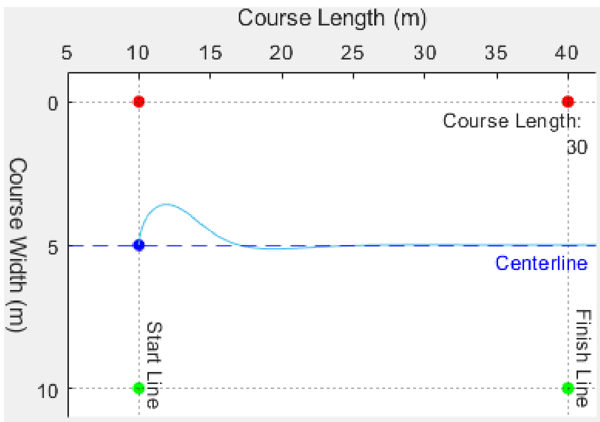

Figure 6. WAM-V movement graphed over RobotX course for KP = 120, KD =100.

The results in Table 1 are a sample of 70 test runs of the system, selected to best illustrate the system results. The test runs consisted of a KP incremented by 10, from 70 to 200 and a KD incremented by 50, from 0 to 200. The first column is the lowest value of KP where the system showed oscillations and rose to a steady state within the course limits. It does not have ideal rise or steady state times. The second column is the ideal run for the system with a KD value of 100. It has the best combination of rise times and steady state times in comparison to the rest of the KD 100 results. The third column illustrates a point where the oscillations from the KP parameter become large enough that it dramatically increases the time to steady state. Testing beyond this point provided increasingly worse results. The fourth and fifth columns demonstrate that KD = 150 is a less optimal KD resulting in higher rise and steady state times for both options selected. Along track distance did not vary significantly for any results, covering a range of about 0.5 meters. This result is reasonable given that the course covers maximum 30 meters assuming a perfectly straight line with no oscillations.

These results are optimal for a single starting position, velocity, and heading. The full G&CS consists of a tool for an end user to utilize the system knowing only their desired input variables, providing instant results for those variables.

7. Conclusion

The current model has basic functionality to simulate a Guidance and Control System for a WAM-V. It can identify optimal KD and KP parameters for a PD controller to direct movement of a WAM-V on a physical course from a hypothetical starting location. The equations are incorporated into a MATLAB Simulink model which can be easily manipulated by an end user to reflect alternate starting locations and headings. This supports end user goals of developing a WAM-V G&CS to operate on a physical system with minimal physical testing and prototyping. Potential future improvements for the G&CS include adding an integral function to the PD controller to improve steady state error and modeling a velocity controller to better reflect the changing physical environment in which the WAM-V will operate.

8. References

Benedict, K., & Kirchoff, M. (2007). Explaining Ships Dynamic and Handling Using MATLAB & SIMULINK as Simulation Tool in Teaching Maritime Students.