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Design of a Vegetation Entrainment Detection System for Autonomous Surface Vehicles

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Abstract: Autonomous Surface Vehicle (ASV) have seen an increase in usage for military and commercial operations. These ASVs operate in shallow waters and are susceptible to Vegetation Entrainment (VE). VE is the entanglement of any type of vegetation along the ASV, such as the entanglement of seaweed on the ASV's propellers. VE occurs in one out of thirty operations and is correctly detected one out of three times. When undetected, VE poses a threat to the mission through fuel exhaustion and/or engine damage. A digital twin system was developed to provide more timely and accurate detection of VE. This is done by comparing the ideal values of vehicle dynamics, computed through a MATLAB model of the ASV, against data from sensors on the physical twin (ASV). Once an abnormality in vehicle dynamics is detected, the system sends a signal to alert the human operator of possible VE.

Keywords: Digital Twin, Autonomous Surface Vehicle, MATLAB, Arduino, Vegetation Entrainment.

1. Introduction

The Autonomous Surface Vehicle industry is a current ever-growing field with broad applications in autonomous missions that require extended time or carry risk to human lives. According to Trembanis and McPherran (2021), an autonomous surface vehicle is, "an unmanned vessel that operates on the sea surface without real-time input or control from human operators". ASVs' capabilities are used for both commercial and military applications. ASVs are mainly used in commercial missions such as environmental and climate monitoring, seafloor mapping, surveillance and inspections of infrastructure. According to MarketsandMarkets's report in 2021, the ASV market is estimated to be USD 0.7 billion in 2023 with 19 main manufacturers worldwide (L3Harris Technologies, Fugto, Textron, etc.) and is projected to reach USD 1.2 billion by 2027.

Commercial missions often take place in shallow waters where depth can be an issue for passenger-carrying larger boats. When a boat is operating in shallow waters, thick vegetation comes to dominate the depths. When vegetation is involved, there will of course be vegetation entrainment. Currently, through talking to ASV field experts at DARPA (Defense Advanced Research Projects Agency) and other ASV companies, we have made an informed estimate, despite the information being for the most part classified, that 1 out of every 30 missions are affected by vegetation entrainment. Of those affected missions, 1 out of every 3 occurrences are accurately detected. This is done by manually estimating vegetation entrainment through estimations of data relations and regularly checking on the boat. Thus, a decision support tool is desperately needed by the industry to simplify and automate vegetation entrainment detection.

2. Stakeholder Analysis

The ASV remote controller, the command center which the remote controller reports to and the maintenance team are the primary stakeholders. Through a rigorous process of 20 stakeholder interviews, no conflicts were discovered between these primary stakeholders. The ASV remote controller, the command center, and the maintenance team all have a common interest in their jobs being simpler by vegetation entrainment detection being optimized and automated. The remote controller has the need to simplify the process of detecting VE to prioritize important duties such as controlling the boat, monitoring important wildlife signs and maintaining shallow water surveillance. The command center has the need to save money and time to satisfy by avoiding unnecessary system down-time due to vegetation entrainment going undetected for too long. The maintenance team must work with both the remote controller and the command center to diagnose possible VE and untangle the ASV's propeller when VE is confirmed. These stakeholders all agree that a decision needs to be made as to whether to stop the boat due to vegetation entrainment quickly before any undue problems occur.

3. Performance Gap (AS-IS), Problem and Need Statement

From the interview with Dr. Greg Avicola who works for the No Manning Required Ship Program (NOMARS) at DARPA on October 28th, 2022, VE goes undetected for a prolonged period of time. ASV controllers fail to notice the abnormality in the ASVs dynamic, such as vehicle velocity, due to the extremely clustered display of data, in which the operator cannot easily see when VE has occurred. An estimation of VE occurrence shows that every 1/30 missions are met with VE, yet only 1/3 occurrences are accurately detected. When VE is not detected or is detected after 30 minutes of the occurrence, cascading problems occur to the ASV including engine overheat, fuel exhaustion, damage to engine and damage to propellers. Once the engine is damaged, the entire mission must be aborted. The average cost of lost productivity and vehicle repair is estimated to be millions of dollars, according to an average calculation from 20 different stakeholder interviews on cost analysis, depends on the type of vehicle and mission.

There is a need to build a Vegetation Entrainment Detection System (VEDS) for a faster and more accurate way of detecting VE.

4. Concept of Operations (TO-BE)

The Vegetation Entrainment Detection System (VEDS) uses multiple sensors to collect ASV's dynamics, such as its acceleration, velocity, angles, position, RPM, etc., while operating in shallow waters with no vegetation (normal operations in ideal conditions). This data is compared to a digital twin model, that computes the actual velocity, and position according to the thrust inputted. Differences in the values between actual and ideal conditions mean that there is a possible VE incident. The operator is then given a salient cue to alert them of possible VE. Figure 1 shows the schematic representation of the concept of operations. The operator physically presses the thrust button on the remote, which turns into a digital thrust command that starts the motor or the engine. Then the engine starts the propellers by giving them RPM, and the propellers begin moving the boat. Since vegetation entrainment happens in the propellers' section, they might spin slowly or stop moving, affecting the boat's output dynamics, such as its velocity, acceleration, position, angles, RPM, etc. The VEDS monitors these abnormalities and alerts the user. The VEDS is aimed to get an accurate VE detection rate of 91%

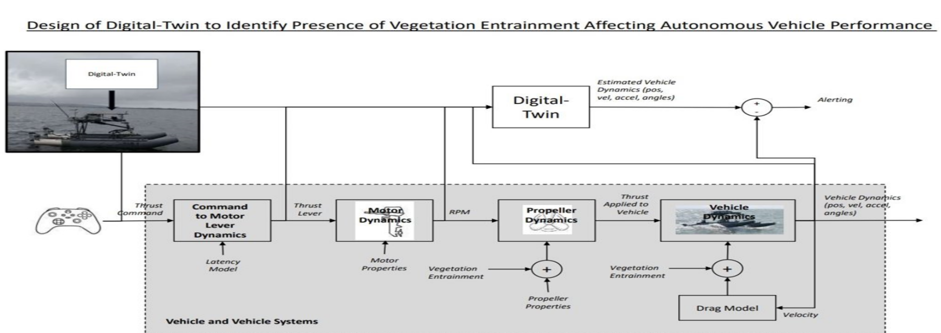

Figure 1. Schematic Representation of the Concept of Operations

5. VEDS Design and Implementation of skateboard on ramp substituting ASV

The VEDS has two main subsystems as depicted in figure 2: 1) the hardware component, or the sensor suite (figure 3) which is mounted on the vehicle to collect and send data using the Communication Subsystem, and 2) the software component, or the digital twin model, which receives and compares live data with the ideal condition data (Table 1) to alert the ASV controller when error is detected.

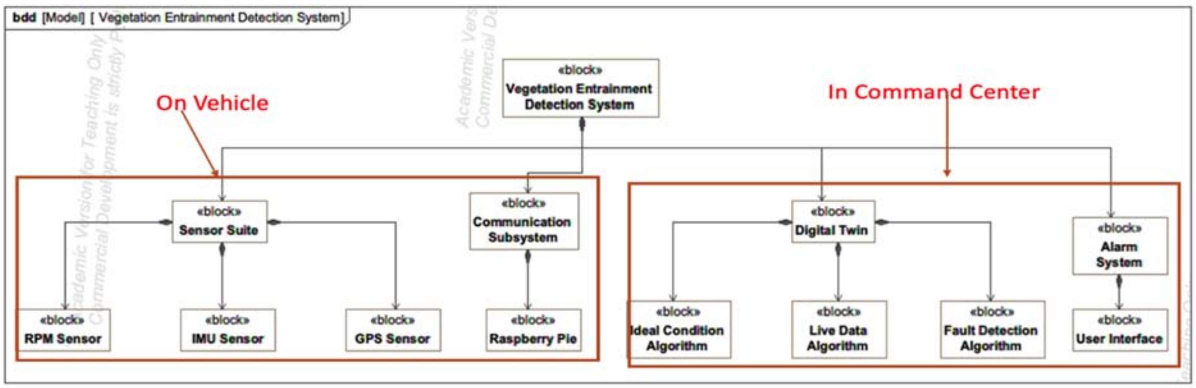

Figure 2. Decomposition of the Vegetation Entrainment Detection System

5.1 Design of the Digital Twin Table – Ideal Condition Value

Due to time and cost restraints, access to an actual boat was limited. Undeterred, a skateboard was used to simulate a boat on dry land. A skateboard and a boat both need thrust to produce velocity effects. But a boat needs a motor in the case of an ASV to provide that thrust. Usually, this thrust is set at certain levels where it produces acceleration for a certain time before coming to a constant velocity. This constant velocity is called steady state velocity. To model thrust effects on steady state velocity, lab testing was conducted on a ramp with 6 different angles to test the ideal steady state velocity using the sensor suite and Tracker software. The ramp angle input is a proxy for the Thrust Setting. The output is the average velocity in ideal conditions. The calibration of the VEDS for steady-state velocity is shown in Table 1 which will be embedded into the digital twin model.

Table 1. Digital Twin Table - Input and Ideal Condition Output

Input	Output (Ideal Condition)		
Ramp Angle (aka Thrust Setting) (degrees)	Average Steady-State Velocity (m/s)	STD range	Tracker Steady-State Velocity(m/s)
5°	0.35	+/-2.6	0.32
10°	0.61	+/-1.6	0.64
12.5°	0.78	+/-1.0	0.73
15°	0.88	+/-0.3	0.84
20°	0.91	+/-1.8	0.94
25°	1.2	+/-2.0	1.0

To further verify the ideal steady-state velocity, its standard deviation range, and the accuracy of the IMU MPU6050 sensor, the data gathered from the sensor was compared to the data gathered by analysis of video recordings as shown in figure 4. When testing the IMU sensor, noise was corrected for by taking a confidence interval from error range of the Tracker Software compared to actual sensor readings. Note that the ramps in figure 4 are only visual demonstration of the test. The skateboard was tested on a much longer ramp in order to achieve steady state velocity.

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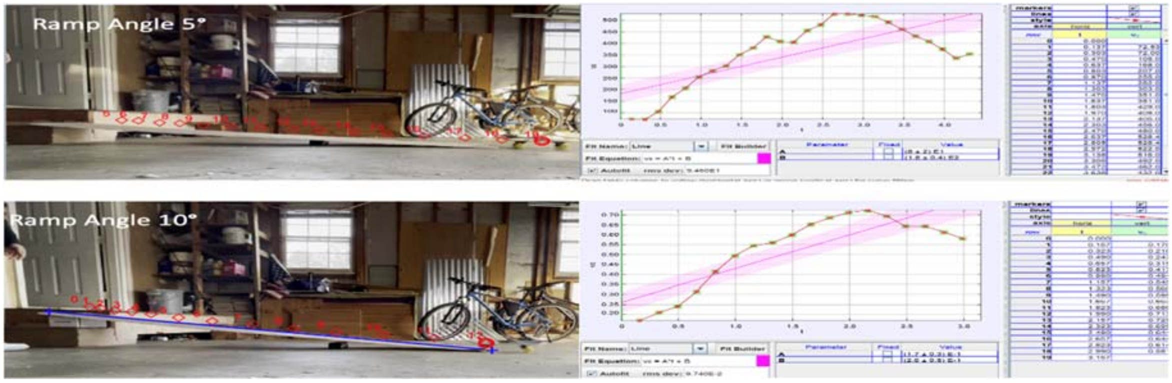

Figure 3. Tracker Software video analysis of skateboard velocity on ramp angle of 5 degrees and 10 degrees.

5.2 Digital Twin model that processes and compares ideal condition data and live data.

5.2.1 Skateboard version

As shown in figure 5, a skateboard version of the Simulink/Matlab model was built to capture IMU sensor data and compare it to the data recorded from Table 1 (denoted as "ExpectedSST" in the model). The model has two main functions: Binary Output for Steady State and Binary Output for Detection. Binary Output for Steady State is evaluated to a "1" if the skateboard's velocity reached steady state. Binary Output for Detection is evaluated to "1" if the live steady state velocity from the skateboard is less or greater than the ideal condition value by 1 m/s given the same ramp angle. The detection function takes in the actual velocity, current ramp angle and expected velocity from Table 1 as input. Based on the binary output, MATLAB generates a GUI that states whether the difference is significant or not. That is, if the binary detection function evaluated to 1, an alert to the operator would be displayed. Since the output is binary, false positive rates are bound to be high at first. With extensive testing of different materials entraining the skateboard, a unique vegetation entrainment signature effect can be found.

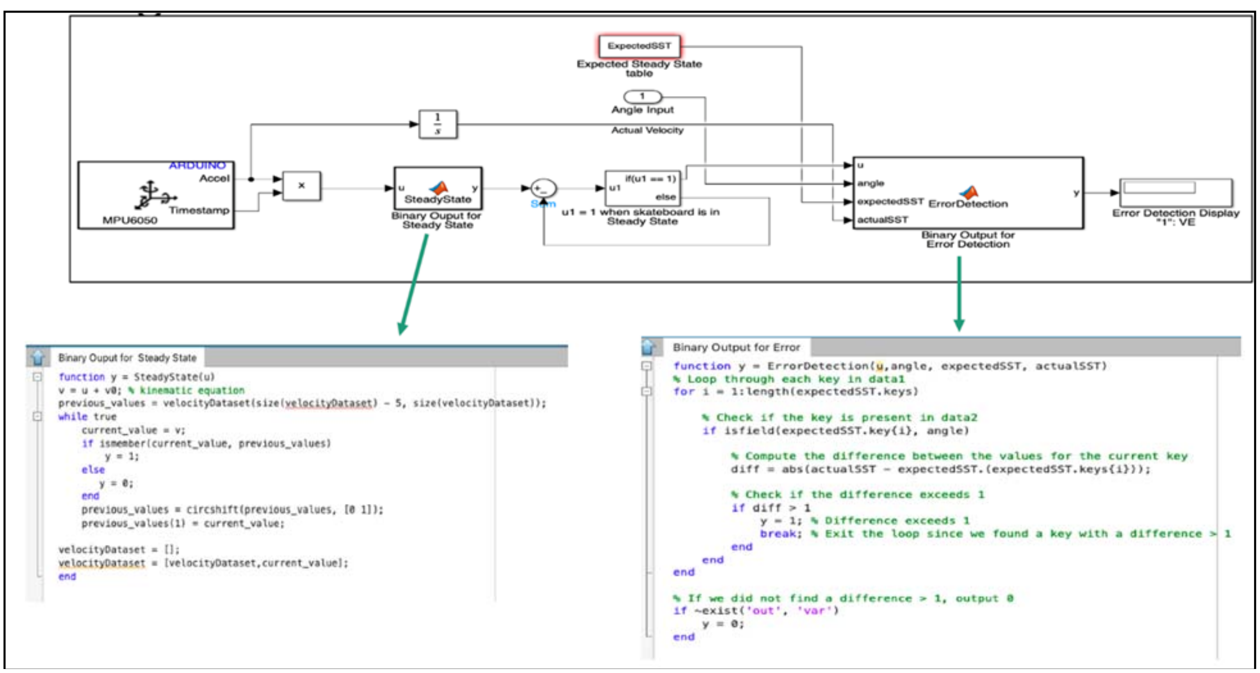

Figure 4. Skateboard MATLAB/ Simulink model

5.2.2 ASV version

Shown in Figure 5 is a model for an ASV digital twin taking into account disturbance such as waves and eddies in the ideal thrust input. Overall, the skateboard model is generalizable to this model given the few tweaks visible here.

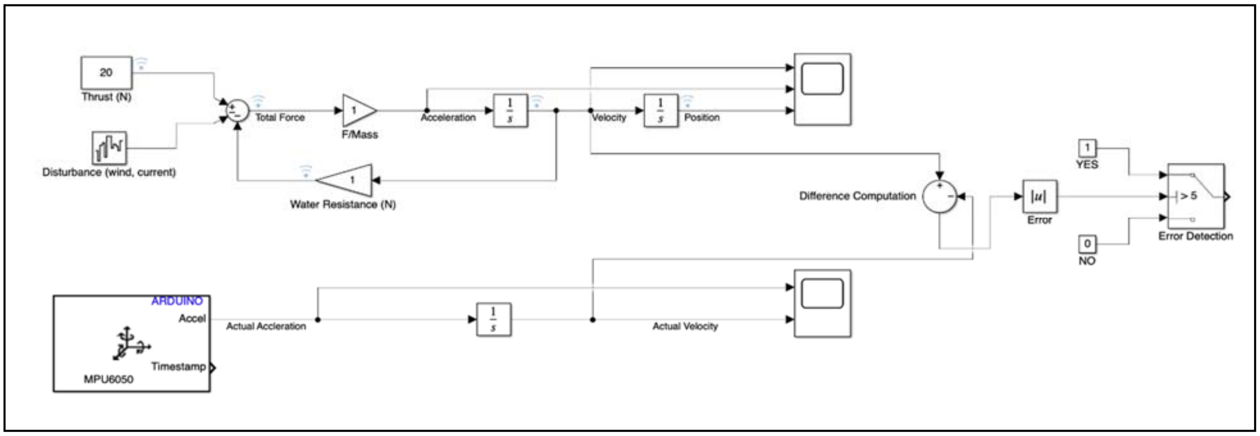

Figure 3. VEDS Simulink model for ASV

5.3 Implementation of the Sensor Suite for data collection

Depicted in figure 6 is the Arduino board, with its labeled sensors, that is implemented onto the skateboard in order to report back the dynamics. Starting with a GPS sensor, this is what is used to determine the location, longitude, and latitude. The IMU MPU6050 is used to get the acceleration, and velocity of the skateboard. The Wi-Fi chip is used to wirelessly transmit the data from the Arduino board to the onshore operator. The power source is connected to the boat's battery to power the sensors. The tachometer, which will be implemented during future iteration of this design, is placed to determine the RPMs of the vehicle. This is all coupled with the Arduino code to gather skateboard or vehicle dynamics.

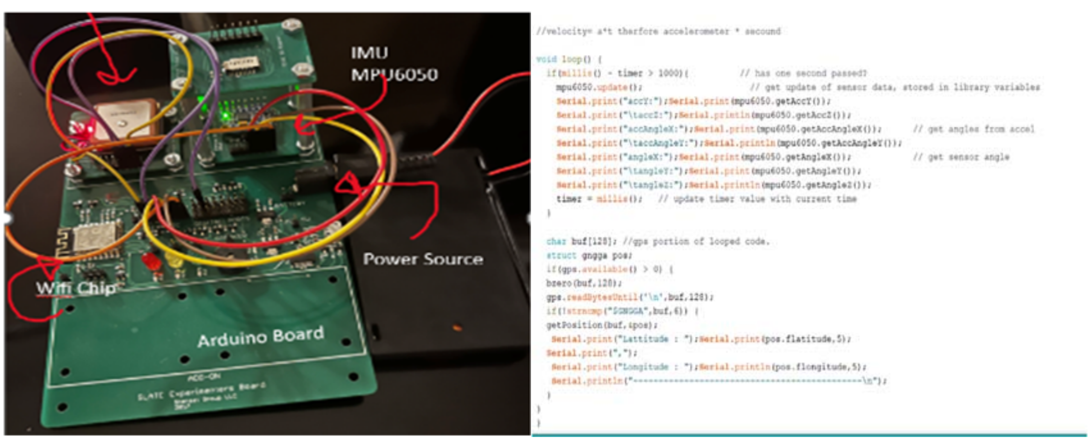

Figure 6. Sensor Suite Configuration (left) and Arduino Code (right)

6. Results

Validation testing demonstrated that the VEDS system alerted correctly when the dynamics of the skateboard changed at a certain location on the ramp due to a change in the ramp's friction (independent variable 1) and a change on the skateboard wheel's rotational dynamic (independent variable 2) which was done by attaching a piece of chewing gum on the rear wheels.

Each ramp angle was tested to validate the VEDS requirements where on each run, a different independent variable was introduced to the experiment. Out of the total twelves run that were executed, only 1 run failed to detect the change in the dynamic which satisfies the VEDS's 91% accuracy detection rate requirement.

Figure 5 shows the demonstration of the result from the model of the skateboard on a higher friction ramp at an angle of 15 degrees. The blue curve is the expected velocity – the velocity computed based on the acceleration from video recordings analysis. The red curve is the actual velocity of the skateboard collected by the IMU sensor suite. Once the skateboard reaches steady state velocity (at time 2.8s), the difference between actual and expected velocity is detected. This occurs when the sensor data flows out of the accepted tolerance range (shaded area).

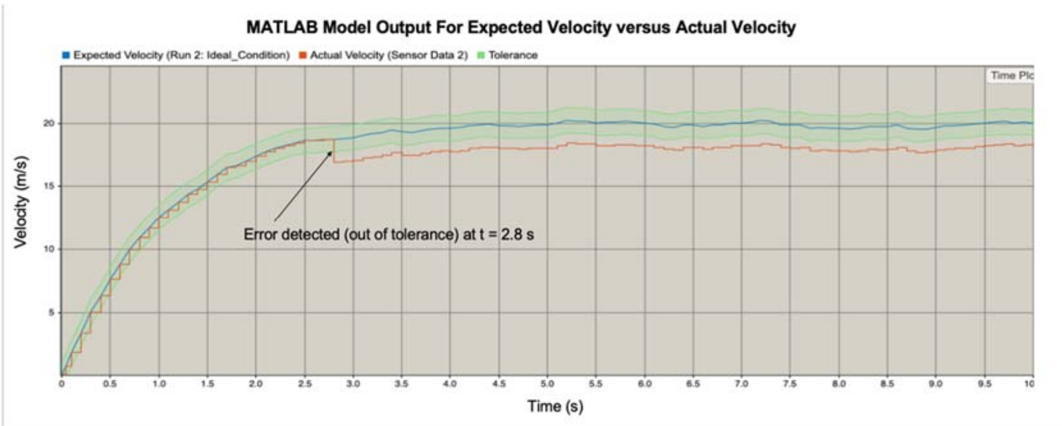

Figure 7. Result of Skateboard Test

7. Conclusions

The concept of the VEDS was successfully demonstrated and validated from the skateboard testing and is ready to be implemented on the ASV once available. Further development needs to be done including calibration of the sensor suite to account for different types and usages of ASV in the current industry. The implementation of additional sensors and video equipment on the vehicle is also deferred for identification of interference to the disabled ASV to minimize the system's false positive rate. Further investigation needs be done to study different methods of collecting ASVs' thrust input and its corresponding dynamical performance data, considering different environmental factors that affect the ASV dynamics, such as vegetation type, density, water depth, temperature, and geographical location. The goal is to get the best result of the Digital Twin table (ideal condition) design and data collection.

8. References

B. Bulletin. (2022). *Bay's underwater grasses see slight rebound.* Chesapeake Bay Magazine. Retrieved, 24-Jul-2022 from https://chesapeakebaymagazine.com/bays-underwater-grasses-see-slight-rebound/.

Blankenship, K., and Harp, D. (2010). Chesapeake Bay Grass Beds Decline for second year in a row. *Bay Journal.* Retrieved, 29-Jul-2021 from https://www.bayjournal.com/news/fisheries/chesapeake-bay-grass-beds-decline-for-second-year-in-a-row/article_e6f097fa-e568-11eb-a573-9766d206b1a9.html.

Chesapeake Bay Program. (n.d.). *Underwater grasses. Retrieved from* https://www.chesapeakebay.net/issues/whats-at-risk/underwater-grasses#:~:text=In%202021%2C%20an%20estimated%2067%2C470,needed%20for%20a%20restored%20Bay

M. Staff. (2019). How to wirelessly transmit data on Arduino. *Digi.* Retrieved, (22 Apr 2019) from https://www.digikey.com/en/maker/blogs/2019/how-to-wirelessly-transmit-data-on-arduino.

MarketsandMarkets (2021). *Unmmaned Surface Vehicles Market. Retrieved from* https://www.marketsandmarkets.com/Market-Reports/unmanned-surface-vehicle-market-220162588.html

Trembanis, A., and McPherran, K. (2019). *Challenges and Innovation in Ocean In Situ Sensor.* Retrieved from https://www.sciencedirect.com/topics/earth-and-planetary-sciences/surface-vehicle