Integration of State of the Art Simulation Software Tools for Guidance and Control of an Under-actuated Surface Autonomous Vessel

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Abstract
In recent years significant effort have been devoted to the development of Autonomous Underwater Vehicles (AUV) and Surface Autonomous Vessels (SAV) largely driven by scientific investigations pertaining to marine biology and environmental studies involving ocean atmosphere interactions. Development of low-cost satellite navigation systems, new and improved sensors, communication and computer technology, and new and improved digital control algorithms have made the realization of such autonomous platforms feasible.

This paper reports simulation studies for guidance, navigation and control of a low cost under-actuated SAV in the presence of wind and ocean current disturbances. The complex nonlinear dynamics and the disturbance due to wind and ocean current are modeled using the virtual prototyping capability of Working Model 2D software package from MSC.Software. The control of thruster force and direction with realistic constraints is implemented in MATLAB. The Dynamic Data Exchange (DDE) capability of the two software tools provide a powerful integrated platform for implementation and visualization of SAV motion and control performance. The algorithms have also been implemented in C. NCARR graphics package has been utilized in conjunction with the C-program for visualization purposes.

1. Introduction

The study reported in this document is the result of preliminary investigations and simulations conducted by the primary author, who is a faculty member in Department of Engineering and Aviation Sciences and two graduate students in the Department of Mathematics and Computer Sciences at University of Maryland Eastern Shore(UMES) in collaboration with a NASA colleague at NASA Wallops Flight Facility(WFF) of the Goddard Space Flight Center(GSFC) during a ten week fellowship program co-sponsored by NASA, ASEE and Maryland Space Grant Consortium(MSGC). The research focused on modeling and simulation of an Underactuated Surface Autonomous Vehicle (USAV). The small, low cost USAV development forms an integral part of the Ocean Atmosphere Sensor Integration System (OASIS) project led by the NASA scientist who is also a co-author of this paper. The discussion is not exhaustive but provides a starting point for the design and real-time control efforts that will follow to develop a fully functional small and low-cost USAV.

Significant research efforts are being devoted to the design and control of Uninhabited Aerial Vehicles (UAV)[1] and Autonomous Underwater Vehicle (AUV) [2-4] largely driven by scientific exploration of the depths of space and ocean. Surface Autonomous Vehicles

(SAV) compliment such exploratory efforts on the surface of the land and sea. UAVs and AUVs are typically fully actuated, often with redundancies in actuation for specific degrees of freedom. However, due to practical considerations small SAVs are frequently not fully actuated. Underactuated Surface Automonous Vehilces(USAV) have a variety of scientific and commercial applications but poses significant engineering challenges with regard to design and control. The six degrees of freedom of AUVs are surge, sway and heave corresponding to translation in the three coordinate directions and roll, pitch and yaw representing the rotations around these coordinate directions. The initial studies reported here involve dynamic modeling and control efforts for a marine surface vessel with only the surge, sway and the yaw degrees of freedom subjected to wind and ocean current disturbances. The vessel is actuated by a single thruster at the rear which can provide variable thrust constrained by a pre-set upper limit. The direction of the thruster force can be controlled by rotating it about a pivot within pre-set limits of the thruster angle. Due to the nature of the actuation the motion dynamics of the vessel becomes coupled giving rise to a challenging problem for control efforts. Extensive research is underway focused on USAV control throughout the world. References [5-7] are some of the many articles that the authors have consulted while performing the work reported here. USAV development efforts can benefit largely from autopilot and automatic digital control effort of modern ships and ocean vehicles. Interested readers are encouraged to peruse references [8 - 10] for more information.

2. USAV Motion Dynamics: Kinetics and Kinematics

Figure 1 illustrates the relevant kinematic parameters, the wind and current magnitude and direction (V_w and V_c) and the control forces (F) acting on the small USAV. It may be noted that the "single thruster" provides the surge force (F_u), sway force (F_v) and the torque (bF_v) for yaw motion, where b is the perpendicular distance from the thruster location to the center of gravity G of the USAV.

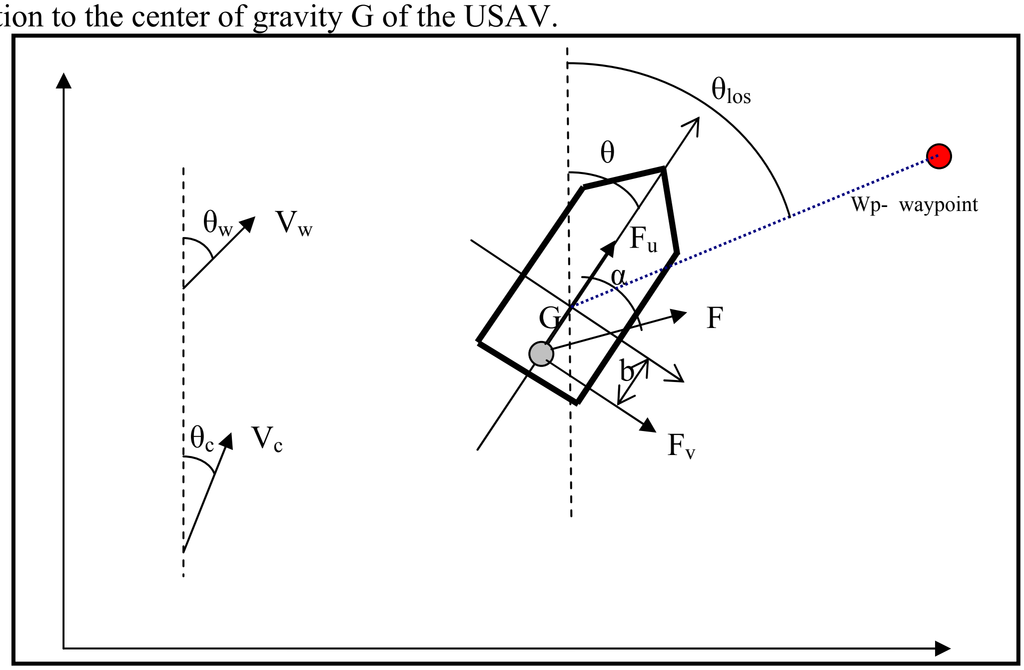

Figure 1: USAV kinematic parameters, environment and control forces

Since USAV motion can be represented conveniently using the surge, sway and yaw dynamics in a frame of reference attached to the USAV, it is necessary to perform relevant linear transformation to map the relevant motion attributes (velocities) to the world or inertial frame of reference for simulation and analysis.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} V_c \cos\theta_c \\ V_c \sin\theta_c \end{bmatrix} \tag{1}$$

$$\dot{\theta} = r$$

where x, y, and θ are the planar position and rotation variables in the world or inertial frame of reference and u, v, and r are the surge velocity, sway velocity and yaw rate with respect to a reference frame attached to the USAV.

In Equation (1) V_c and θ_c represent the ocean current magnitude and direction. The ocean current directly modifies the velocities in the inertial frame as evidenced from Equation (1).

Exact dynamics of marine vessels becomes extremely complicated if all the added inertia and first and higher order hydrodynamic effects are considered. Since the USAV considered in this study is a small and compact sensor platform the following simplified dynamics was deemed to be appropriate for preliminary simulation analysis. The interested reader is encouraged to consult reference[8] for an elaborate discussion on hydrodynamic forces and moments for "Ocean Vehicles".

$$F_u = m\dot{u} - mvr - X_u u - K_{ax}\cos(\theta_w - (\theta + \pi)).V_w^2$$

$$F_v = m\dot{v} + mur - Y_v v - K_{ay}\sin(\theta_w - (\theta + \pi)).V_w^2 \tag{2}$$

$$-bF_v = I\dot{r} - N_r r - K_{an}\cos(\theta_a - (\theta + \pi)).V_w^2$$

In the system of equations above m and I are mass and mass of moment of inertia of the USAV. The various terms in the equation corresponds to inertia forces, Coriolis forces, simplified hydrodynamic and aerodynamic effects. The centrifugal terms are not included since it is assumed that origin of the body fixed coordinate system is located at the center of gravity (G). V_w and θ_w represent the magnitude and direction of the wind. It can be observed from Equation (2) there exists significant coupling among the dynamic equations in the surge, sway and yaw direction for the USAV giving rise to a challenging problem with regard to way-point tracking as well as dynamic positioning.

3. Dynamic Simulation and Control

Motivated by the success of simulation efforts for a variety of mechanical systems as reported in reference [11] by the principal author, the integrated platform of Working Model 2D[12] and MATLAB[13] was chosen as the simulation environment for the preliminary simulation effort. The dynamic data exchange (DDE) capability of the two software packages as illustrated in Figure (2) allow computation of control action utilizing the computational engine of MATLAB while the kinematic and kinetic parameters are developed in Working Model 2D. The hydrodynamic and aerodynamic effects as well as the ocean current are incorporated from within Working Model for a realistic visualization of the motion and control simulation of the USAV.

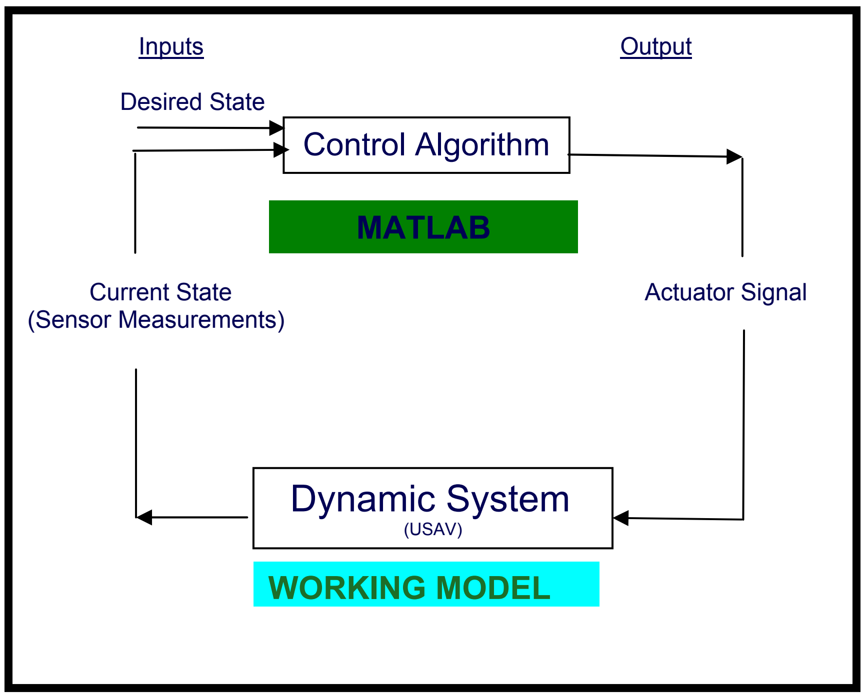

Figure 2: Dynamic Data Exchange between the softwares

Results of initial simulation studies involving course-keeping, course maneuvering and way-point tracking control are reported here. No attempt is made to perform trajectory tracking but a time free parameterization involving appropriate heading and line of sight control for a planar path following effort is deemed to be sufficient.

The simplified control problem therefore is to automatically correct the thruster force magnitude (F) and direction (α) so that the USAV traverses a sequence of way-points to arrive at a pre-specified destination with realistic constraints on both F and α. When the USAV reaches within a circle of acceptance region of a way-point the next way-point in sequence is made the target till the way-point corresponding to the final destination is reached. At the final destination the control action involves station-keeping or dynamic positioning with due regard to effects due to wind, current, and other environmental disturbances that may be present.

The primary focus of the study reported here involves the line of sight control (LOS) that assumes that a satellite navigation system (GPS – Global Positioning System) will be used as a position sensor to determine the x and y coordinates of the USAV and a gyrocompass will provide the orientation or heading angle θ of the ship with reference to the world or inertial frame of reference.

Assuming the way-point location to be $[x_{wp}, y_{wp}]$ and the position of the USAV as reported by the GPS to be [x,y] the line of sight angle θ_{los} can be computed as :

$$\theta_{los} = \text{atan2}(y_{wp} - y, x_{wp} - x) \tag{3}$$

The on-board microcontroller on the USAV will need to continuously compute the θ_{los} compare it with the heading angle θ using the gyrocompass and correct for the error, $(\theta_{los}-\theta)$ by appropriately controlling the single thruster force magnitude and direction, F and α, using suitable control algorithm (see Figure 1).

Researchers are exploring a variety of control algorithms to achieve desired performance for SAVs, USAVs, and other marine vehicles. Few additional references[14-16] provide a sample of the several algorithms that are currently being explored in this very active research area.

The preliminary study performed by the authors included primarily a decoupled digital Proportional plus Integral plus Derivative(PID) control algorithm for independent control of the thruster angle α for correcting the heading with respect to the line of sight angle and thruster force F for controlling USAV speed and station keeping. More needs to be done with control simulations involving dynamic positioning (DP) and station keeping.

The digital algorithm utilized is as follows :

In the continuous domain the PID algorithm is typically represented as:

$$u(t) = K_p E + K_v \dot{E} + K_I \int E dt \tag{4}$$

where, K_p, K_v and K_I are the proportional, derivative and integral gains that can be tuned for a particular system ; E and $\dot{E}$ are error and derivative of error of the controlled variable and u(t) is the actuator signal corresponding to α or F as the case may be

The following MATLAB function implements the control algorithm in Equation 4 in discrete time:

```
function u = pidctrl(e,u1)
 global e1

  h =n ; kp = n1; ki=n2; kd =n3;
 c1 = kp +(h/2)*ki + (1/h)*kd;
```

```
c2 = (h/2)*ki – (1/h)*kd;
c3 = ki;
u = c1*e + c2*e1 + c3*u1;
e1 = e;
```

where, h is the update rate and e and u1 are error and actuator signal of the prior step that provides the input values to the MATLAB function (pidctrl) which computes the actuator signal for the subsequent step to be used by the Working Model software for dynamic updating (Figure 2). The numbers corresponding to n1, n2 and n3 are tuned appropriately with due consideration for performance requirements.

4. Simulation Results

Figures 3 and 4 below are screenshots of the monitor screen during the execution of USAV control simulation using Working Model 2D and MATLAB. The plane of the screen represents the sea surface, the default gravity force has been turned off to simulate a floating mass of the USAV. The red rectangle represents the USAV the solid arrow at the back of the USAV represents the thruster force whose magnitude and direction is modified by MATLAB using appropriate control algorithms. Results using PID control is shown , however, fuzzy control was also explored. The embedded graphs can be easily developed from within Working Model, the two graphs represent the heading error versus time and distance from way point against time during the execution of the simulation.

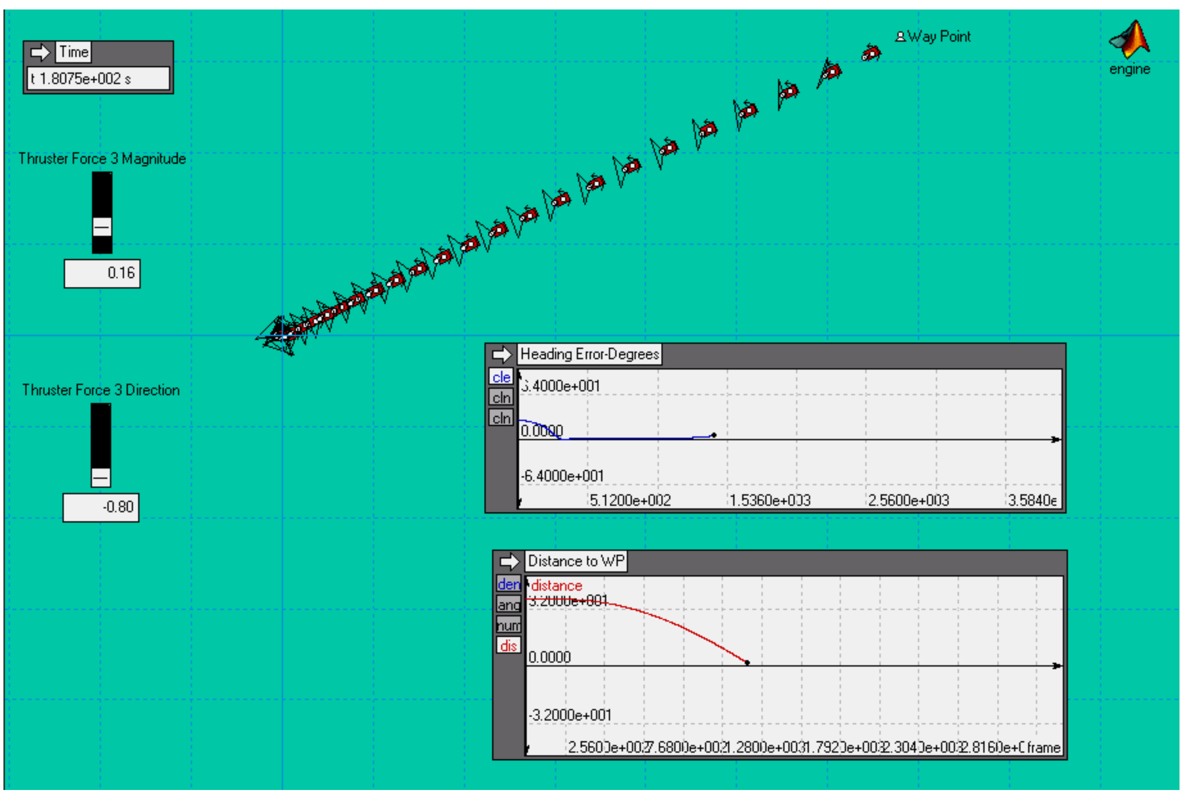

Figure 3: USAV way point tracking results for a small initial heading angle error

Working Model also allows the user to track frames at suitable frame intervals, this feature has been utilized during simulation and the USAV has been tracked every 50 frames during the simulation runs.

All environment effects (wind and current) and simplified hydrodynamic effects have been incorporated.

Figure 3 represents way point tracking effort for a relatively small initial heading angle as given by the way point location relative to the starting point of the USAV. The USAV achieves desired heading angle and tracks the way point without difficulty. However, for larger heading angle error as shown in Figure 4 the USAV has to maneuver within the realistic constraints of the thruster angle (+/- .8 rad ~ +/-45 degrees) and thruster force magnitude limit of 0.6 N and achieves the desired heading after some manipulation as clearly evidenced in the simulation results. (The mass of the USAV is 200 Kg and moment of inertia is 60 kg-m^2). In this case the way point is vertically above the USAV which is facing in the horizontal direction with the thruster aligned with the longitudinal axis of the USAV at the start (initial USAV position and thruster orientation is the same in Figure 3 as well). Some of these results were reproduced using C and NCARR graphics.

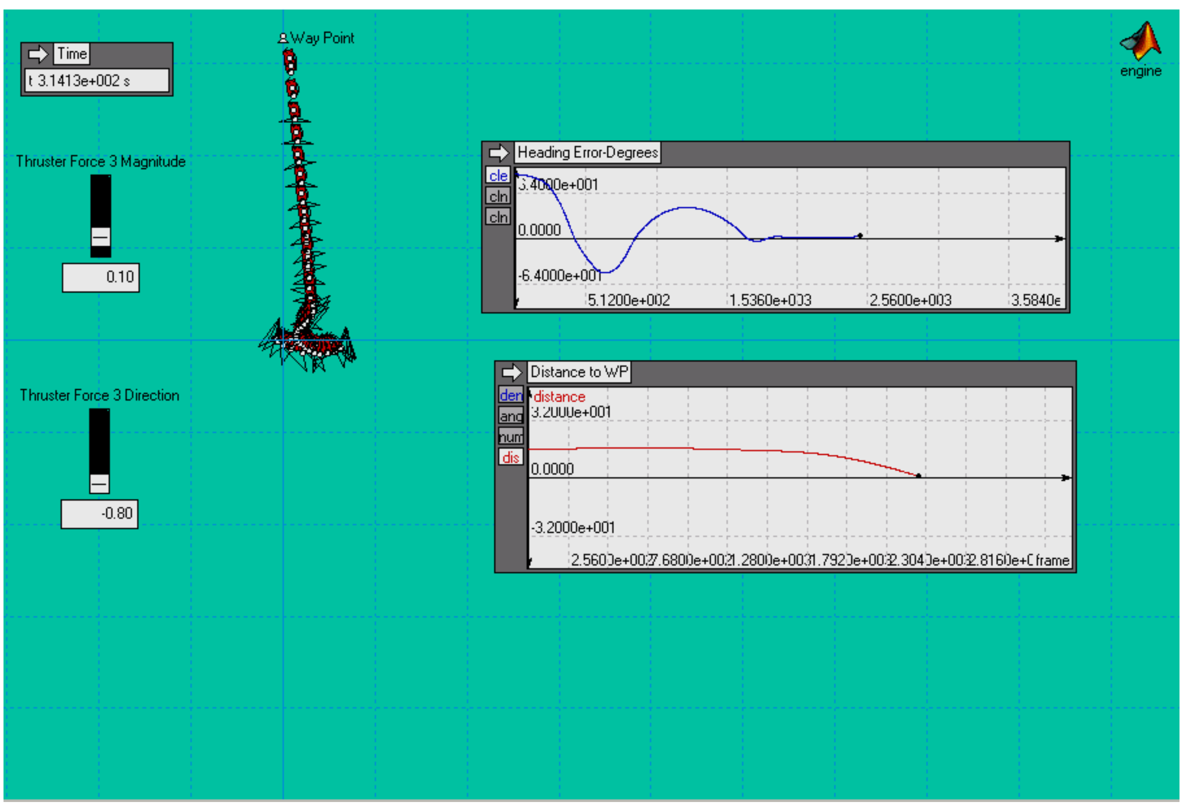

Figure 4 : USAV way point tracking results for a large initial heading angle error

5. Conclusion.

The study reported in the previous sections
is the result of the primary author's participation in the NASA/ASEE Faculty Fellowship Program (NFFP) for a period of 10 weeks in the summer of 2003. Maryland Space Grant Consortium offered to support two graduate students to assist with the efforts during the period and the NASA colleague and co-author assigned to the primary author for the NFFP was willing to accommodate. Although the primary author is a faculty of the engineering program at UMES since UMES does not offer a graduate program in engineering the students were selected from the graduate program in the Department of Mathematics and Computer Sciences at UMES. The NASA colleague is an active researcher in the field of oceanography and marine sciences. Ten weeks is certainly not enough to contribute significantly to the active field of research reported here, however, the interdisciplinary collaboration resulted in a lot of positive outcomes. Some of them are listed below:

(i) The NASA scientist heads the Ocean Atmosphere Sensor Integration System (OASIS) project. The preliminary study performed over the 2003 summer has shed light on the design and development of the SAV that forms the sensing platform for the marine and oceanography research component of the OASIS project.
(ii) The primary author is an active researcher in the field of applied mechanics, robotics and control systems. The exposure allowed him to explore simulation of USAV using Working Model 2D and MATLAB along the lines of previous investigations performed by him for other mechanical systems[11]. It also provided an exposure to a new and related avenue to expand the scope of his research involvement.
(iii) The two graduate students learned fundamentals of dynamics and control related to the USAV and could quickly implement the dynamics and some of the control algorithms discussed in C and NCARR graphics using their programming skills with appropriate guidance from the primary author and NASA colleague.
(iv) Effective win/win/win collaboration among UMES, NASA GSFC WFF and Maryland Space Grant Consortium.

6. Acknowledgment

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