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Monte Carlo Analysis

Monte Carlo analysis allows engineers to generate expected results for systems with a large number of free or uncertain variables. Monte Carlo simulations are often used to help engineers determine the range of expected behavior for uncertain systems.

Monte Carlo simulations can also function as a method of indirect optimization for a design given several alternatives. By simulating system performance of various alternatives against some cost function, be it cost, weight, or otherwise, engineers can rule out alternatives that do not yield the required performance within the required confidence interval, then choose whatever alternative minimizes their applicable cost.

To begin a monte-carlo, uncertain variables are first modeled using a probability distribution functions. Common choices for these probability distribution functions are uniform distributions and normal distributions. After the uncertain variables are chosen, a model simulation is then run to completion assuming the chosen variables as truth values. This process is then repeated a large number of times. With appropriately chosen parameter distributions and a large enough number of trials, the simulation results will regress to a normal distribution. From this distribution, the engineer can estimate average, best case, and worst case system performance to their desired confidence interval.

Monte Carlo analysis is used within this thesis as the main basis for comparison of results between different simulation configurations. This style of analysis is well suited to the problem due to:

1. The flow velocity field uncertainty due to the turbulent nature of the flow field
2. The large number of model configurations available within the developed simulation, and
3. …

3DOF and Modeling

Advantages of Simulation Based Approach

…

One of the main advantages of a simulation based approach to this analysis is that it is not dependent on dedicated lab space. While initial efforts on this project were conducted in Prof. Cataldo’s civil engineering lab, physical testing became … after that lab space became unavailable. Subsequent efforts for physical testing were made using a pool in Prof. Sidebotham’s lab. While initial tests looked promising, it was eventually concluded that due to the small scale of the flow available, as well as the relatively large scale of the boat to the flow, that any results gathered would be largely inapplicable to the larger bodies of water this project aims for.

A second advantage of simulation based testing is the time difference between simulation testing and hardware testing. While there is a substantial initial time cost in simulation development and testing, this cost is largely marginal when the time difference between simulation and hardware testing is taken into account. While all testing on physical hardware must be conducted in real time, with test points taking between tens of minutes for initial system verification and up to several days for endurance testing, these same tests can be conducted in simulation in minutes. Furthermore, simulation based testing does not require constant supervision once established, allowing the engineer to focus on other aspects of the project.

A third key advantage of a simulation and modeling based approach is the agile nature of software development. Since, as stated above, testing can be conducted at a much faster pace in software, the boat’s control architecture and routing algorithm can be matured at a much more rapid pace. (add more here)

Finally, an advantage specifically of Simulink testing in this case is autocode-ability. The boat software developed can be autocoded using the Embedded Coder functionality native to Simulink. This allows the user to take the modules of their simulation which constitute the boat software, and have code generated for each block that can be uploaded directly to a wide variety of microprocessors. The code that is generated is optimized for the chosen hardware, allowing for more efficient processing uning low level functions and eliminating user errors.

Overall Structure

The simulation developed for use within this project is a three degree for freedom simulation (3DOF). As such, there are several implicit assumptions about the boat/water system which dictate its applicability:

1. The boat is assumed to be stable in its roll and pitch axis.
2. Waves and their effects on boat velocity and energy consumption are assumed to be negligible relative to the energy cost of traversing the planned trajectory.
3. …

The simulation is broken out several sub-modules as described below. All of these sub-modules have various versions, ranging in fidelity and complexity. …

Plant Modeling

The Boat as a Point Particle

Assume a boat small relative to the length scale of the flow field it navigates within. In this case, the boat is assumed to be a spherical point mass with the same mass and moment of inertia as the physical boat. Both motors are also assumed to have the same moment arm about the yaw axis as they have on the physical system. Under these assumptions, the boat is well modeled by the following set of differential equations:

M(xdd) = -b\_x(xdot)(xdot) + (T\_l + T\_r)

Izz(th\_dd) = -b\_th(th\_dot)(th\_dot) + (T\_l – T\_r)

where: …

While drag coefficient can be allowed to vary as a function of speed, most of these non-linear effects are not demonstrated due to the low relative velocity between the fluid and boat. Linear drag coefficients …

The Boat as an Airfoil

One of the main hydrodynamic effects not well captured by a point particle model of the boat is passive alignment of the boat with a flow. To capture this effect, the boat can be modeled as a symmetric airfoil. The center of pressure of the airfoil is assumed to be coincident with the aerodynamic center of the airfoil for all angles of attack. Furthermore, the center of mass of the boat is assumed to be aft of the center of pressure so that the hydrodynamic forces acting on the boat tend to provide a restoring moment about the yaw axis, passively aligning the boat with the flow field. …

Actuator Modeling

Both boat drive motors are modeled according to the second order motor model:

(add motor model)

The DC motors used on the boat, as stated above, are … According to the manufacturer’s data sheet for the motors (see Appendix …) …

Navigation Block

Navigation, in the sense of Guidance, Navigation, and Control (GNC), refers to the determination of a vehicle’s state at a given time. (source wiki)…

Navigation often requires the use of Kalman Filtering or other forms of sensor fusion to develop a state estimate for use within the Guidance and Control modules…

The Navigation sub-module within the 3DOF simulation takes two forms. The first is a direct pass-through, where state information is passed directly from the plant model to the guidance and control modules. While not necessarily realistic, this form of navigation module has several testing benefits. The first major benefit is that it allows for pure performance testing of the embedded guidance and control sub-modules. Since the “estimated” state in this case is just the truth value for the state, this gives an upper bound for vehicle performance at a given set of conditions. It also allows for verification testing of the functionality of sub-modules, since they are acting on uncorrupted state data. …

The second and final form of Navigation modeled is a sensor fusion between inertial measurement unit (IMU) data and pseudo-GPS data. The pseudo-GPS sensor modeled replicates the overhead camera found in the lab setup, giving absolute positions of the boat’s center of navigation in the lab frame. Use of an actual GPS data like that found on the boat would follow similarly, however a conversions would be required… (detail below)

The accelerometer and pseudo-GPS are modeled using the same refresh rates and noise levels as expected by the physical hardware as outlined in the table below:…

(insert table…)

The accelerometer and pseudo-GPS data were fused using a Kalman Filter. …

Guidance

Guidance, in the GNC sense, refers to the determination of the desired path between the vehicle’s current position and desired position, including desired changes to velocity, rotation, and acceleration along that path. (source wiki) Guidance provides these signals to the controls module as the desired reference point to track. In the case of this thesis, distinction is made between overall routing and waypoint planning, which is addressed in Section XXX: Energy Optimal Routing, and the determination of speed and rotation references which is addressed here. …

Control

Control, in the sense of GNC, refers to the manipulation of forces by way of steering controls, thrusters, etc., needed to execute guidance commands whilst maintaining vehicle stability. (source wiki)

The control module can be broken down into two distinct sections, control effort determination and control surface allocation. Control effort determination refers to the sub-module which takes in references from the Guidance module and uses a control algorithm to generate closed loop axial and rotational accelerations. The control effector allocation module, often called the ‘mixer’, then takes these closed loop accelerations and determines appropriate surfaces commands to achieve these accelerations.

(details)

In the case of this boat, there are two accelerations to track and two control effectors the surface allocation is relatively trivial; however in more complex cases the mixer can be designed to be robust up to a certain number of control effector failures…

Details on the baseline controllers used, and the modifications to these baseline controllers to improve energy efficiency, can be found in Section XXX: Energy Efficient Control Methods.