

Multi-Domain Modeling of the Dynamics of a Hovercraft for Controller Development

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Abstract

This paper discusses the modeling and simulation of a hovercraft vehicle for the purposes of developing a vehicular motion control system. A multi-domain modeling approach is applied through the use of The MathWorks product Simulink®. The model includes the full powertrain, rack-and-pinion steering, ground effects and electric power generation. This model has been created to assist in the development of a vehicular motion control system that employs classic continuous control methods. Use of these methods will draw upon linearized mathematical models of the system that are generated by this full non-linear model. This full non-linear model will then be used to evaluate the performance of the controller prior to the availability of the fully-integrated hovercraft hardware.

I. Introduction

In this paper we present a model of a hovercraft for the purpose of developing an embedded control system. Model-Based Design is a proven process for successfully developing such systems¹. A key to successful employment of this process is to have a useful model of the vehicle being controlled, which is called the plant. The usefulness of the model should be judged in terms of completeness, accuracy, simulation speed, and easiness to build. In this paper we describe a model of a hovercraft system that employs a detailed description of the powertrain, steering system, and ground effects. This model predicts the expected motion of the hovercraft and can interface with the vehicle's motion controller. This solution is implemented through the commercially available product Simulink, which is a successful platform for employing Model-Based Design. Through the Simulink platform, we employ a hybrid modeling approach that combines first-principle with data-driven modeling approaches.

II. Modeling Approaches

There are two basic approaches to developing plant models: 1. implement a solution to the physical governing equations that expresses the relevant dynamics of the plant, or 2. collect data through experimentation and correlate it with a suitable mathematical expression that expresses these same dynamics. We will refer to these as a first-principle approach and a data-driven approach, respectively. By reducing reliance on hardware prototypes of the vehicle, the first-principle approach offers a significant advantage that enables early testing of a system and thorough exploration of design options. The data-driven approach, however, offers confidence in the accuracy of the model, and possibly provides a more efficient model building process.

Within the first-principle approach there is an additional subdivision. One approach is to derive the governing equations from the first principles of physics and to directly implement a solution to these equations. The other approach is to employ commercially available software tools that automate the formulation and solution of the governing equations based upon a description of the physical structure of the plant. We will refer to these approaches as a mathematical approach and a physics-based approach, respectively. The mathematical approach offers great flexibility, but usually requires significant knowledge, skill, and effort from the modeling team to implement a general and useful solution. The physics-based approach offers significant efficiency by eliminating the need to derive equations and implement a solution. Commercially available physics-based tools, in general, are very good for representing a single physical domain, like mechanics, but lack the capability to represent a system characterized by multiple physical domains. Another disadvantage of the commercially available tools comes from the inability of the toolmaker to anticipate all of the components in your system that contribute significantly to the dynamics of the system, which can make it difficult to include the unanticipated components.

The various strengths and weaknesses of the mathematical, physics-based, and data-driven approaches, and the way these approaches might complement each other, suggests that a hybrid approach would provide the most useful

model. In this paper, we describe a process that successfully employs the techniques of all three approaches to deliver a useful model of a hovercraft.

III. Description of the Hovercraft

A conceptual image of the hovercraft is shown in Figure 1. Four engines provide the power for the hovercraft. This power drives seven outlets of power, which includes four vertical lift fans, two horizontal thrust fans, and an electric generator. The driveline employs planetary gears to converge the power of the four engines into one line, and then additional planetary gears to split this power for distribution among the seven outlets of power. It employs mechanical friction clutches to control the engagement of the outlets with the power source.

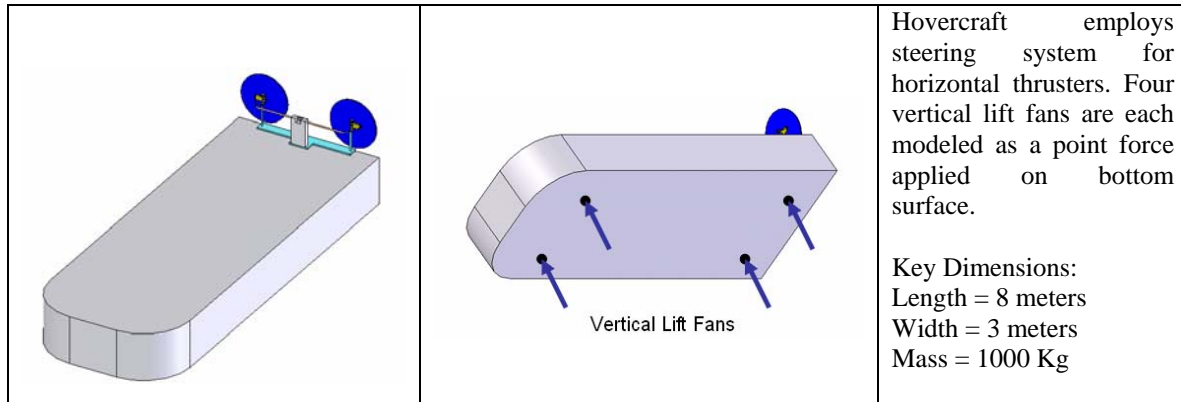


Figure 1. Conceptual Image of Hovercraft Vehicle

The driveline system connects the electrical power generator to the four engines. The generator converts the mechanical power delivered by the driveline into electrical power. Because the generator draws power from the same source that lifts and propels the vehicle, its operation can impact the motion of the vehicle, and, therefore, needs to be accounted for by the motion control system.

The hovercraft includes a rack-and-pinion steering system that is actuated by a ball screw and an electric motor. It is lifted by four vertical fans and propelled by two horizontal thrust fans. The lift from the vertical fans falls off sharply as the vehicle is elevated significantly above the ground. The physical reasons for this fall-off are complicated as they include turbulent flow and an unusual boundary condition on the air flow that is imposed by an elastic skirt attached along the perimeter of the bottom surface of the vehicle.

IV. Employing physics-based tools to model the vehicle, powertrain, and electricity generation

The hovercraft model in Simulink is shown in Figure 2. This figure shows that the two primary components are the powertrain and the vehicle model. The vehicle model captures the motion of the vehicle. It represents the hovercraft as a body with mass and inertia with point forces applied to represent each vertical lift fan and each horizontal thruster. The mechanics of the steering linkage is modeled directly and accounts for the dynamics of pivoting of the thrusters to redirect the horizontal thrust vector. The powertrain includes the engines, driveline and the electric power generator. The driveline delivers power from the engines to the electric generator and to the fans that lift and propel the vehicle. It is through these fans that the powertrain model connects to the vehicle model. Through the Simulink platform, physics-based tools are applied for modeling and simulating the mechanical and electrical components. The tools for mechanical components are SimMechanics and SimDriveline. The tool for electrical components is SimPowerSystems.

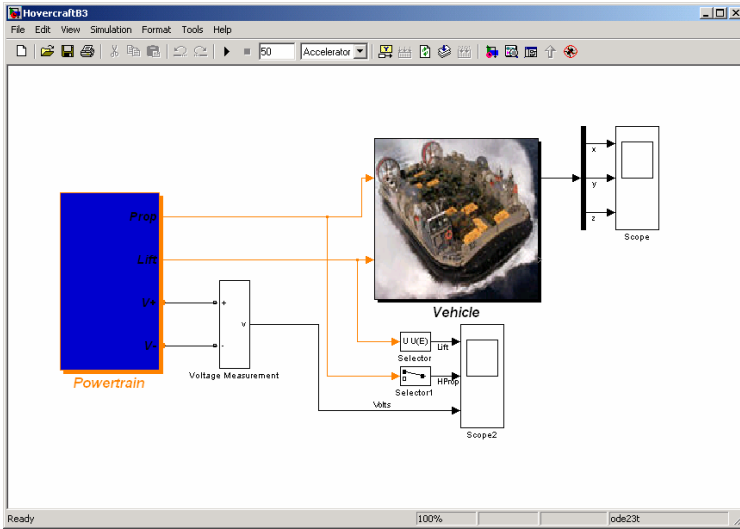


Figure 2. Simulink System Model of Hovercraft

a. Modeling vehicles and mechanical linkages with SimMechanics

SimMechanics enables efficient modeling and simulation of full 3-dimensional mechanical systems. It is based upon the principles of rigid-body dynamics and designed for general motion analysis of mechanical assemblies containing internal linkages. It employs an Order (n) method that is described in the paper by Wood and Kennedy².

i. SimMechanics modeling and simulation environment

Figures 3 and 5 show the models of the vehicle and the steering linkage, respectively. These figures display the block diagram modeling environment of SimMechanics. This modeling environment offers blocks for defining bodies, joints, and constraints to describe the structure of a mechanical assembly. The joint blocks are defined by assigning the orientation of the relevant revolute and prismatic axes of the joint. The body blocks are defined by assigning mass and inertia properties for the body, and by assigning local coordinate systems which mark locations for joint attachments and provide a reference for joint orientations. The lines that join blocks simply represent connection, unlike traditional Simulink models, where lines represent the unidirectional flow of numerical information that is being passed between transfer function blocks.

The modeling environment also provides blocks for actuation and sensing. The sensing blocks extract mechanical performance data from the simulation and make it available through numerical flow lines to traditional Simulink blocks. The actuation blocks receive numerical flow lines from traditional Simulink blocks and apply it to actuate motion through assignments for forces, torques or prescribed motions. It is through the sensing and actuation blocks that a subsystem employing SimMechanics blocks is configured to form a transfer function that can interface with a controller, as well as other components that might be included in a system-level model. Further information describing the components, capabilities and use of this tool are available in the SimMechanics user manual³.

ii. Defining the vehicular motion model with SimMechanics

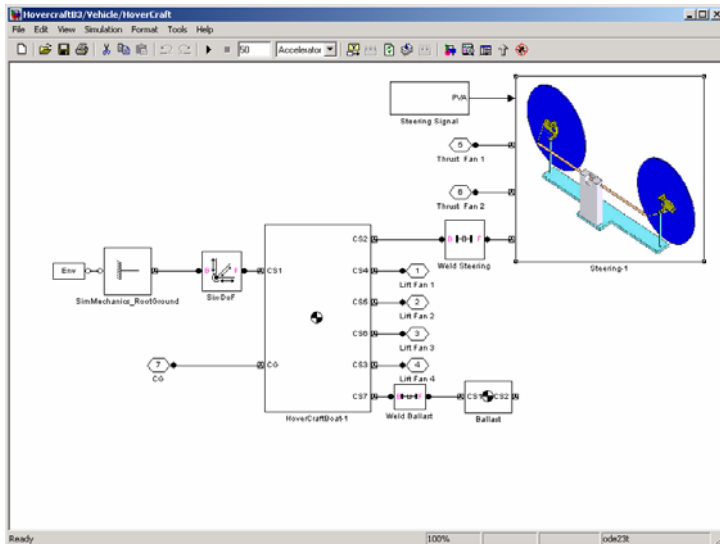


Figure 3. SimMechanics model of hovercraft boat with steering linkage

The vehicular motion model is shown in Figure 3. It shows that a single body block represents the boat and that it is connected to the steering system and ballast mass through welds, and to a world reference through a 6-DOF joint. The 6-DOF joint, which stands for six degree-of-freedom, provides the positional reference to the world coordinate system, but imposes no constraint on the motion of the boat. The properties for this body block are shown in Figure 4. These properties show the mass and inertia values and key assignments for local coordinate systems. The local coordinate systems are used in a number of roles for marking critical locations on this body. Here, local coordinate systems mark the locations for the center of gravity (CG), the attachment points for the steering system and the ballast, the application points for the lift fan forces, and the point used in the positional reference of the 6-DOF joint.

Block Parameters: HoverCraftBoat-1

Body
Represents a user-defined rigid body. Body defined by mass m , inertia tensor I , and coordinate origins and axes for center of gravity (CG) and other user-specified Body coordinate systems. This dialog sets Body initial position and orientation, unless Body and/or connected Joints are actuated separately.

Mass properties
Mass: 1000 kg
Inertia: [810.6671 0 0, 0 5890.8697 0, 0 0 5240.8698] kg*m²
* with respect to the CG (Center of Gravity) Body coordinate system

Body coordinate systems

Show port	Port side	Name	Origin position vector [x y z]	Units	Translated from origin of	Components in axes of
<input checked="" type="checkbox"/>	Left	CG	[0.068769 0.5 0]	m	WORLD	WORLD
<input checked="" type="checkbox"/>	Right	CS2	[-4 1 1.5]	m	WORLD	WORLD
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<input checked="" type="checkbox"/>	Right	CS5	[3 -0.5 1]	m	CG	CG
<input checked="" type="checkbox"/>	Right	CS6	[-3 -0.5 1]	m	CG	CG
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<input checked="" type="checkbox"/>	Left	CS1	[0 0 0]	m	ADJOINING	ADJOINING
<input checked="" type="checkbox"/>	Right	CS7	[-4 0.5 0]	m	CG	CG

OK Cancel Help Apply

Figure 4. Property assignments for hovercraft boat body

iii. Defining the steering linkage model using SolidWorks, a 3D CAD tool

SolidWorks⁴ is a 3D CAD tool that runs on the Windows operating system. Its interface is shown in Figure 6. It offers a 3-dimensional graphical environment for defining mechanical assemblies. The MathWorks, the maker of Simulink and SimMechanics, has built a translator that reads SolidWorks assembly models and creates a SimMechanics model that represents that assembly⁵. The visual context of SolidWorks is very valuable in defining joints, and the tool's ability to represent general part shapes and deliver calculations of their mass and inertia properties offers great value in the SimMechanics model building process.

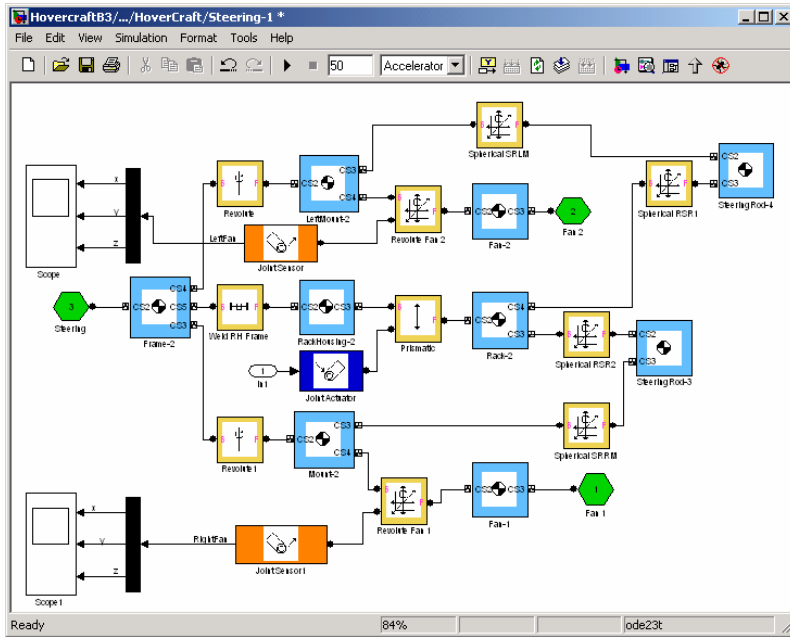


Figure 5. SimMechanics model of steering linkage

As is shown in Figure 6, the steering system employs a rack-and-pinion mechanism. The rack can be moved in the direction defined by the orientation of its own major axis. The rack is connected to the two horizontal thrust fans via mechanical linkages. Each fan is mounted on a link that can pivot with respect to the hovercraft through a revolute joint. This link connects to the rack through a tie rod. At each end of the tie rod, the connection to each part is made through a spherical joint. The material assignments for each part are made in SolidWorks, which implies the material density used in the mass properties calculation.

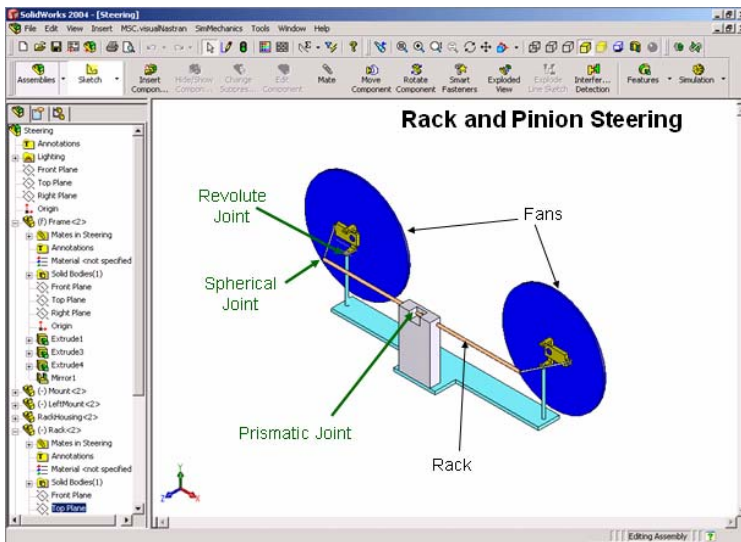


Figure 6. SolidWorks model of steering linkage

b. Modeling the powertrain using SimDriveline

SimDriveline⁶ enables efficient modeling of 1-dimensional rotational mechanical systems. Mechanical power transmission systems are a key application for this area of mechanics. An important example of such a system is in the automobile, where the driveline transmits power from the engine to the tires. The automotive driveline consists of the torque converter, transmission, driveshaft, differential, clutches and wheel axles. SimDriveline provides blocks that model these types of components, which are composed of gears, clutches, shaft inertias, and components that enforce general torque or motion relationships between connected shafts. The lines in SimDriveline models represent ideal massless rotating shafts. It is possible to model a driveline in a full 3-dimensional environment, like SimMechanics, but a specialized driveline tool provides advantages by offering a more efficient model building environment and a faster simulation.

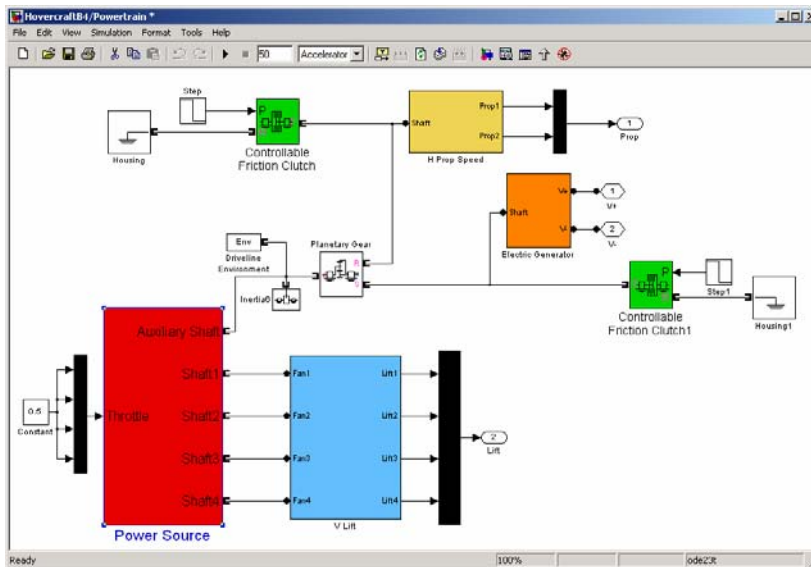


Figure 7. Simulink subsystem model of powertrain

The powertrain for the hovercraft is shown in Figure 7. It includes a power source that drives five shafts: one for each lift fan and an auxiliary shaft whose power is split between the horizontal thrusters and the electric generator. Throttle position is an input to this block and is available for assignment from the controller. The power from the auxiliary shaft is split through the actions of a planetary gear to serve its two outlets. The actual engagement of this power by these outlets is controllable through a friction clutch for both the generator and the thrusters.

The detailed block diagram of the power source is shown in Figure 4. This figure shows the employment of four engines, each of which is connected to a planetary gear. Each planetary gear splits the power of its respective engine and distributes it to a vertical lift fan and to a line that ultimately converges with lines from the other engines to deliver power to the auxiliary shaft.

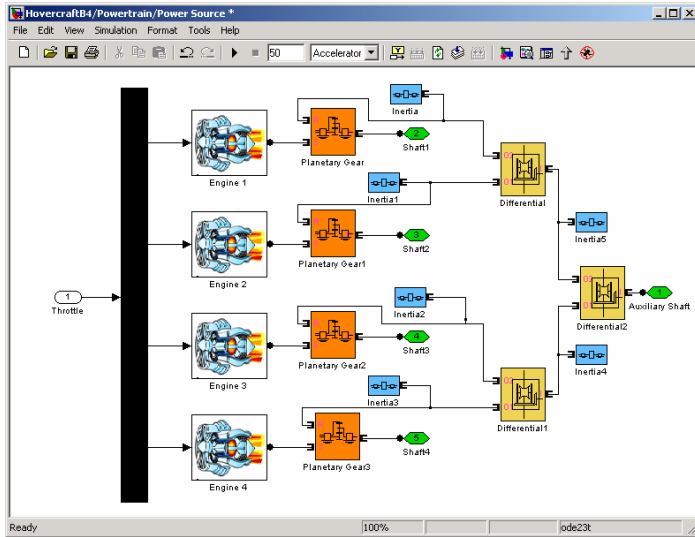


Figure 8. Power source model implementation using SimDriveline

It is an important design choice to associate each engine with a single fan because it offers options to the controller to minimize oscillations in the roll and pitch of the vehicle. Although the driveline connects all four engines with all four fans in a way that each of these components influences all of the others, the direct connection of each engine to a single fan through a planetary gear allows that engine to more strongly influence the power delivered to that fan. Oscillations in the roll or pitch of the vehicle, therefore, can be addressed by the controller by adjusting the throttle to the various engines, which based upon the location of each, allows the controller to generate moments that oppose the oscillations.

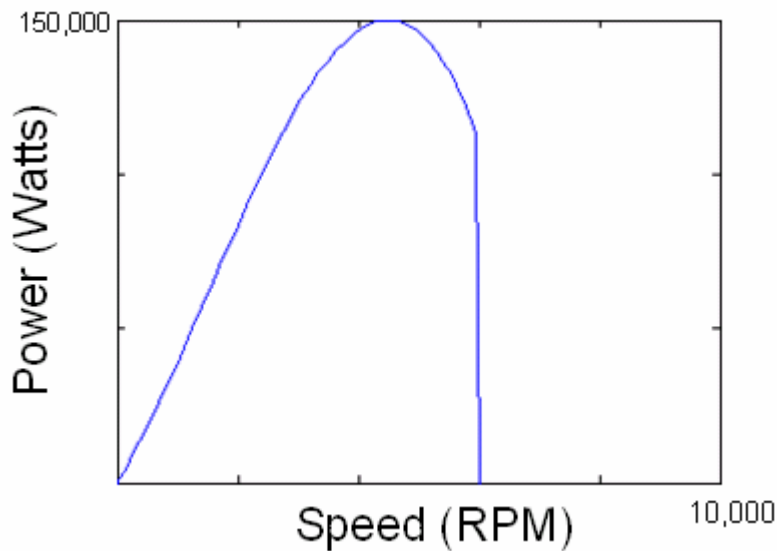


Figure 9. Engine power vs. speed curve

The engine is represented by a simple model that defines a relationship between the throttle position, engine speed, and torque. The power vs speed curve for this engine is shown in Figure 5.

c. Modeling electric power generation with SimPowerSystems

SimPowerSystems enables efficient modeling of electrical power systems and basic electric circuits. With SimPowerSystems, electrical systems are described through electrical circuit schematic diagrams, like that shown in Figure – 10. This figure also shows how electro-mechanical devices, such as an electric generator, are created through interfacing SimPowerSystems with SimDriveline, or SimMechanics. The capabilities of SimPowerSystems,

of course, are much broader than what is shown in this figure. It is a tool with rich libraries that enable production level modeling of power systems that generate, transmit, distribute, and consume electrical power, and also convert it into mechanical power. These broader capabilities will be valuable if this model is extended to elaborate upon the complete power system of the hovercraft to include the electrical loads that will be served by this power generation. Additional information describing the components, capabilities and use of this tool are available in the SimPowerSystems user manual⁷.

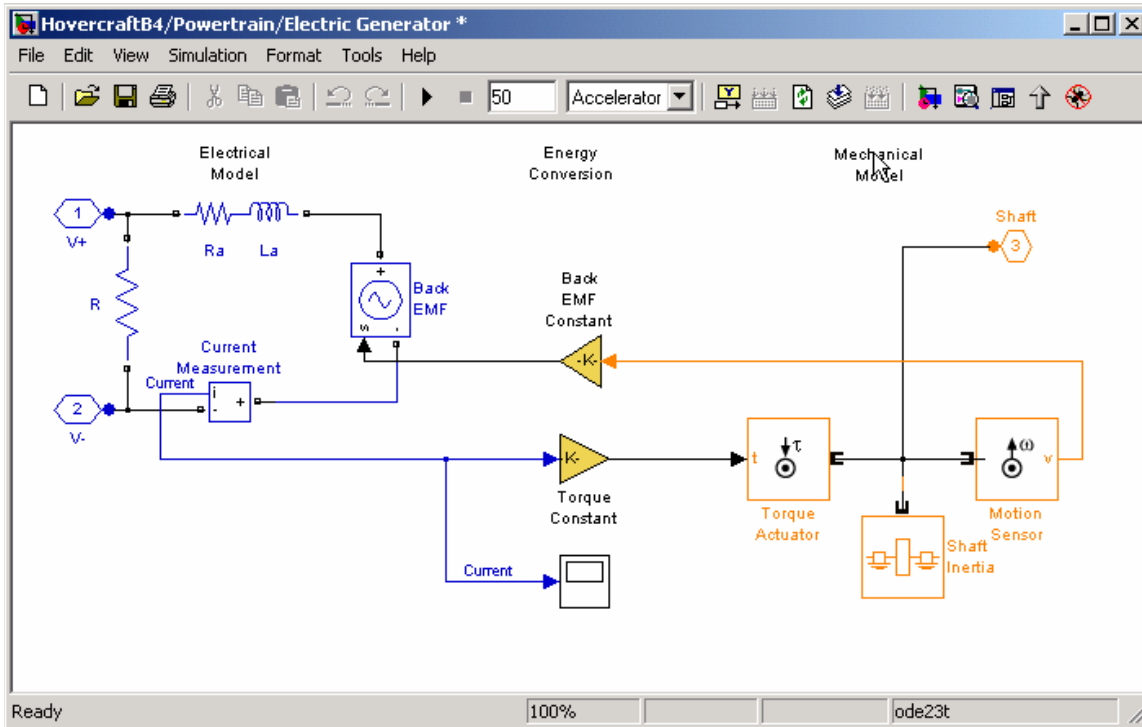


Figure 10. Electric generator model

Figure – 10 shows that the electric circuit of the generator consists of two voltage terminals that are in series with a resistor, inductor and a back EMF source. The electric generator exerts a torque load that is proportional to the current flow through the circuit. The voltage delivered to the circuit through the back EMF is proportional to the speed at which the shaft of the generator turns. The shaft speed is measured from the mechanical model, which is accessed through SimDriveline components shown in this figure, and includes a port for connection into the hovercraft’s powertrain. The torque generated by the electric motor is applied to the mechanical model through a SimDriveline torque actuator block, which is also shown in this figure.

V. Modeling the thrust of the lift and horizontal propulsion fans

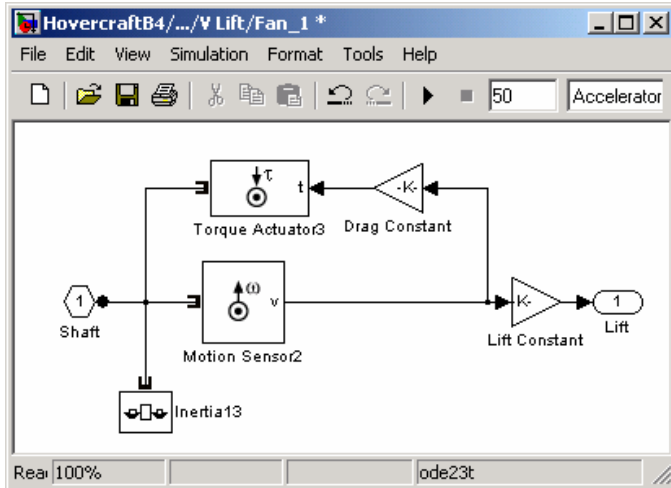


Figure 11. Fan thrust algorithm as implemented in Simulink

All six fans of the hovercraft are modeled in a similar way to determine the thrust each produces. The generic algorithm for the thrust calculation for each fan is shown in Figure – 11. This figure shows that the algorithm begins with a shaft speed measurement from a port connection to the driving shaft that powers the individual fan. The thrust exerted by the fan is simply proportional to this speed, and its calculated value is delivered as a numerical signal to an output port, which delivers this signal to the vehicle model. There is also a drag exerted on this shaft that is proportional to this speed, too. The calculated drag is fed back and delivered to the shaft through the same port connection via a SimDriveline torque actuator block.

VI. Employing a data-driven approach to model ground effects on lift

An empirical approach is suggested to augment the calculated lift to account for the complicated interaction between the air flow from the fans and the ground. Direct modeling of this turbulent flow interaction is extremely challenging, and the intensity of such a calculation would severely limit the usefulness of this model in an iterative process for controller development. For these reasons, a method is advised that employs experimental data to characterize an empirical expression for the force delivered by the vertical fans. This suggested expression needs to capture the strong relationship between the force and the position of the fan above the ground. Least-squares techniques would be used to fit the data to identify the proper parameterization of the formula that most efficiently expresses the vertical lift. This method is only suggested because it requires access to a real hovercraft and its thruster to be implemented, which we do not have.

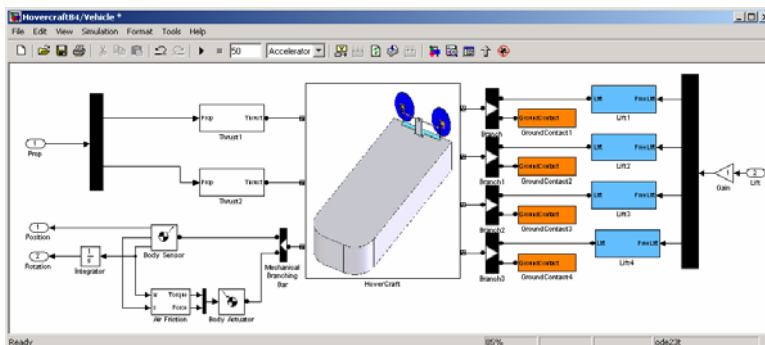


Figure 12. Hovercraft vehicle motion model

The algorithm for the lift discussed in section V, should be considered a calculation for the maximum available lift, l_{max} . To account for the fall-off in the lift as the hovercraft moves further above the ground, we suggest use of the following formula:

$$lift = l_{max} \bullet e^{-\left(\frac{y}{\sigma}\right)^2}$$

The exponential component of this equation can be considered a fall-off factor that is parameterized by the variable σ . Because it would be very difficult to evaluate this parameter accurately through a first-principle approach, we would choose an experimental one. The approach would be to mount a lift fan to a test stand that can vary the elevation of the fan. Measurements on thrust would be made during a test where the stand executes a trajectory that varies the elevation of the fan through a suitable range.

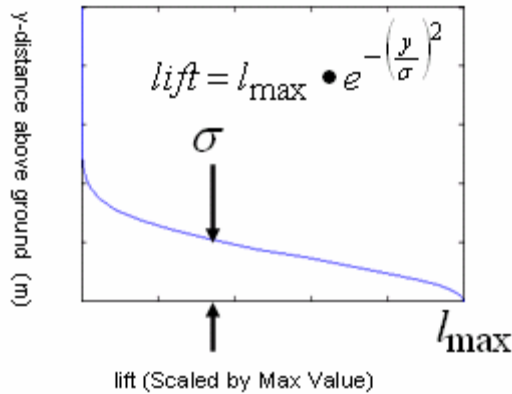


Figure 13. Lift force vs. elevation relationship

We can use Simulink to automate the setting of the parameter σ . The first step is to build a model that emulates the actual test. This means that both the test stand and the lift fan would be modeled, and that the modeled stand is programmed to replicate the elevation trajectory that is executed in the real test. By comparing the thrust predicted by the simulation with the real test data, the parameter σ can be tuned to make the simulation fit the data. The tool Simulink Parameter Estimation is available to automate the tuning process. This tool employs data fitting and optimization techniques and can fit a function characterized by multiple parameters. Additional information describing the components, capabilities and use of this tool are available in the Simulink Parameter Estimation user manual⁸

VII. Employing a mathematical approach to model ground contact

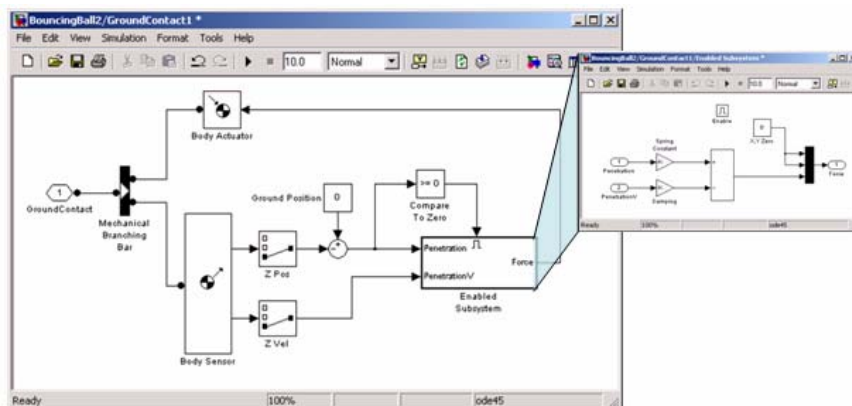


Figure 14. Ground Contact Model

The model accounts for the vehicle's contact with the ground. Figure – 12 shows the contact model is applied to the vehicle through the same four points that define the locations for the forces of the lift fans. The contact model, which is shown in Figure – 14, tracks the position of a single point on the surface of the hovercraft and applies a

contact response at that point if it attempts to penetrate the ground surface. It characterizes the response force with a spring-damper formulation. We chose the same four points that locate the vertical lift fan thrust mostly for modeling efficiency. We recognized that at least three points are required to represent the approximately planar shape of the bottom surface of the hovercraft, and the choice at these 4 locations seemed appropriate for suitable spatial distribution. The use of Simulink's enabled subsystem in this contact model represents the valuable flexibility that is offered by complementing physics-based and data-driven models with mathematical formulations.

VIII. Simulation results

Results are presented for a simulation of 50 seconds with the vehicle resting on the ground initially and the engines off. At $t=0$ seconds, full throttle is applied to the engines with full power delivery to the vertical lift fans. At 15 seconds a clutch is actuated to deliver power to the horizontal thrusters. At 35 seconds another clutch is actuated to split this power between the horizontal thrusters and the electric generator. At 30 seconds the steering system is actuated to turn the vehicle to the left; at 40 seconds, to the right.

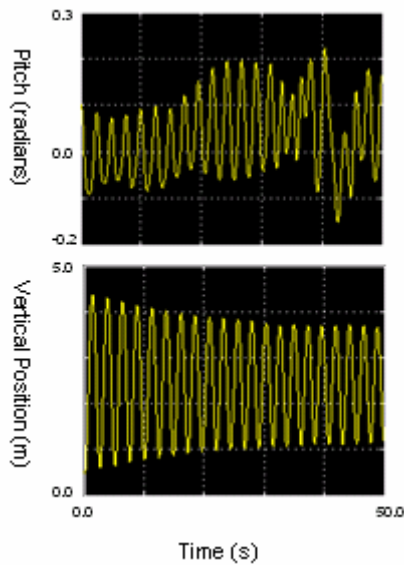


Figure 15. Vertical position and pitch oscillations from simulation

Figure – 15 shows that oscillations occur in the pitch and vertical position of the vehicle. There certainly is a strong dependence of the magnitude and duration of the oscillations on the parameter σ , which was defined in section VI of this paper. Lacking real data on the vertical lift fan to calibrate this parameter, our arbitrary choice for its value affects these oscillations. As is suggested in section VI, a rigorous data-driven modeling approach should be used to estimate this parameter properly.

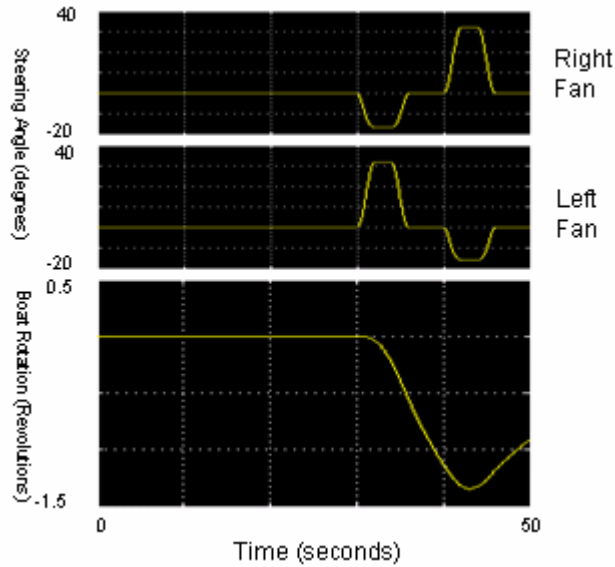


Figure 16. Steering fan angles and boat orientation from simulation

Figure – 16 shows the steering angles for each fan, and the resulting rotation of the vehicle to the steering. The figure shows nearly one and a half full revolutions occur when the vehicle attempts to turn left. Because hovercrafts encounter minimal friction, or any other dissipative influences, the turning strategy must account directly for the removal of the angular momentum associated with the turn. This strategy would be implemented through the controller.

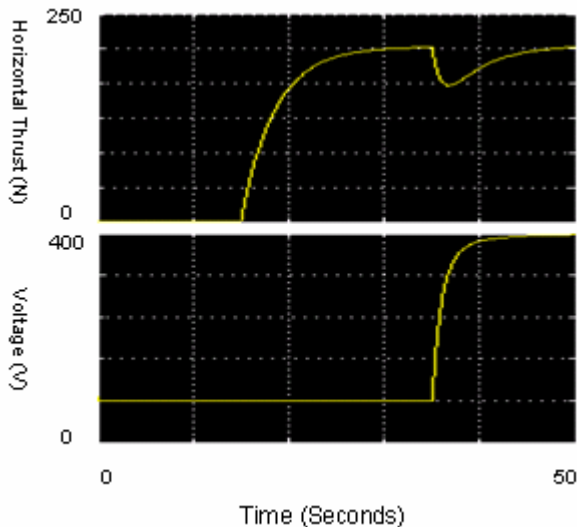


Figure 17. Horizontal thrust and generator voltage from simulation

Figure – 17 shows the horizontal thrust and voltage measurements. These figures show clearly that the horizontal thrust suffers a deficient supply of power when the electric generator is first delivered power. Re-emphasizing what was stated earlier – the vehicular motion controller must account for this in guiding the vehicle to an optimal motion trajectory.

IX. Concluding Remarks

The description of a hovercraft requires concepts from multiple physical domains, which include 3-dimensional mechanics, driveline mechanics, fluid mechanics and electrical circuits. This description also requires inclusion of

complicated phenomenon, such as turbulent flow and ground contact. The point of this paper is to present a method for modeling such systems. The conclusion of this paper is that the efficiency of physics-based methods in delivering a first-principle model makes the use of these methods highly desirable for the majority of the modeling. The most useful modeling approach, however, will include mathematical and data-driven methods, also, to deliver the most accurate, complete, computationally efficient, and easily built models.

X. References

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