Modeling and Control of a Torpedo Shaped Autonomous Underwater Vehicle with a 3 Degree of Freedom Manipulator

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***Abstract*—This paper focuses on the modeling and discusses the control of a torpedo shaped Autonomous Underwater Vehicle (AUV) with a 3 degree of freedom manipulator attached. This paper is purely simulation based using Matlab and Simulink to simulate the movement of rigid body models. Different control schemes will be discussed. Simulation results of AUV movement using a classical control scheme will be shown.**

***Index Terms*— Dexterity manipulation, Motion coordination, Manipulator Control, Marine Robotics, Underwater vehicle-manipulator systems**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUV) have become increasingly popular in military, commercial, and hobby use. With a large customer being the oil and gas industry [4]-[6]. Thet ability to use unmanned or autonomous vehicles to perform task greatly increase the range of capabilities to be performed underwater. There exist AUVs with two manipulators on them. One manipulator meant for grabbing and stabilizing and the other meant for work [6]. This method only works if there is a stable point that the AUV can attach itself to. On the seabed or rock face there is no way to reliable attach for stabilization.

Manipulators in industrial applications are typically anchored to stable surface as the motion generates forces and moments on the base. While attached to a submarine these forces and moments are now exerted onto the vehicle. The vehicle then must counteract those forces to remain stationary or the manipulator end point will be skewed.

Autonomous Underwater Vehicle Manipulator Systems (AUVMS) are kinematically redundant [1][6]. This means when solving end effector joint positions there are an infinite number of solutions. To establish solutions, they will need to be within the vehicle frame while being the closest to the previous frame. The motion of the vehicle will need to be considered so the solution will be with respect to where the expected position of the vehicle body position will be in the next time step.

The goal of this project is to create a combined model for a torpedo shaped submarine and a simple manipulator, and then show through simulation the stabilization of the vehicle during manipulator motion. There exist many different control schemes for controlling an AUV with a manipulator. There is focus on control of the underwater manipulator itself and control of the vehicle motion. This project aims to look at the control of vehicle motion.

The most straightforward approach for control is to decouple the manipulator and submarine into two different controls [1][6]. The downside is this requires the vehicle controller to be very robust for stabilization. For a larger submarine in which the forces of the manipulator can be negligible and the thrusters have adequate power this scheme is more appropriate.

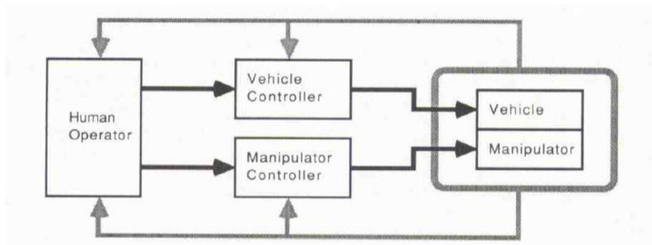

Figure 1. Decoupled manipulator and vehicle control [1].

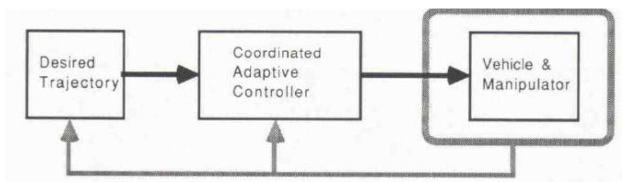

Figure 2. Coupled manipulator and vehicle adaptive control scheme [1].

With a smaller submarine the coupling effects of the manipulator cannot be ignored, and the complete dynamic model of the submarine must be accounted for. Dynamic force equations will be used to track center of mass (COM) for the system as it changes based on motion [1][2][6].

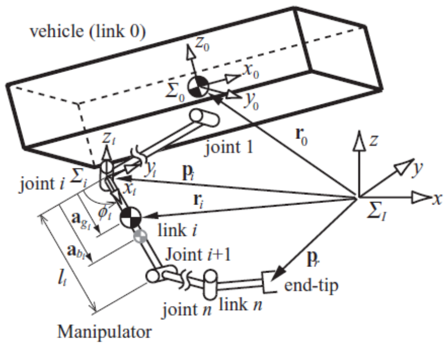

Figure 3. n-link manipulator vehicle [2]

II. Modeling

Every model is defined as rigid body model. It is a combination of simple shape geometries and assigned densities. The use of a simple rigid body structure allows the use of COM and moment of inertia calculations without needed to provide a CAD design. This allows variability in size of the models. The sizes being variables mean the comparative size of the AUV to manipulator can be dynamically tuned.

A. World Definition

A global frame to reference all the rigid body parts to. A value for gravity of 9.81 m/s is applied to all the bodies. For the system to be neutrally buoyant an opposing buoyant force is applied in the -Z direction.

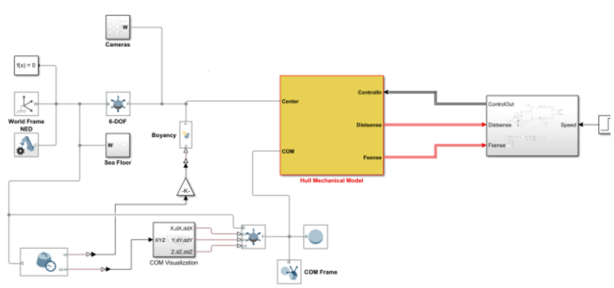

Figure 4. World frame established in Simulink.

To track and visualize the COM an inertial sensor was used. The inertial sensor is measuring with respect the global frame, so the output coordinates are the COM of the entire AUVMS system. To visualize the COM the first and second order derivatives are applied to the coordinate measurement of the inertial sensor. Those are then applied to a 6-DOF ball that will follow the movement of the center of mass based on the position, velocity, and acceleration inputs. In the simulations this will visualize as a red ball.

During simulations with movement inputs a stationary reference is needed for visualizing AUVMS movement. To do this a grid is created with square tiles measuring 4m by 4m. To track movement three cameras are positioned to track the system as it moves through the world.

B. AUV Model

The submarine model used in these simulations are similar in size to the Teledyne Gavia AUV [5]. The length of the vehicle comes to 2m. The density of the materials for the rigid body are 1500 kg/m^3 which is similar to that of CPVC.

The main differences from typical torpedo submarines are the main thrusters are beneath the sub center. The purpose of this applies for attaching the manipulator to the submarine system. The thrusters are now closer to the shifted total COM producing less of a moment during surge motion.

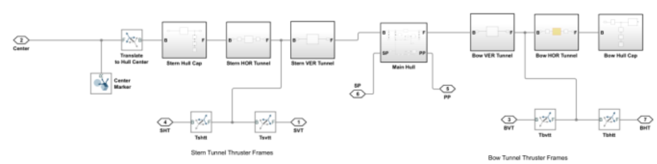

Figure 5. AUV body diagram connections

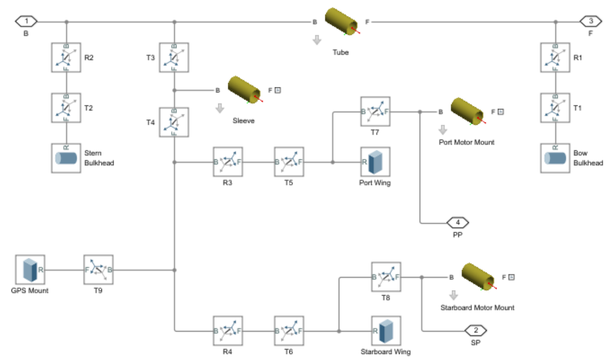

Figure 6. Main Hull rigid body diagram

To simplify the model, propeller designs were ignored. To produce thrust a force was directly applied to where the propellors would be to simulate their thrust. The submarine has a total of 6 thrusters for actuation. Two for main thrust, two vertical tunnels for pitch control, and two horizontal tunnels for yaw control.

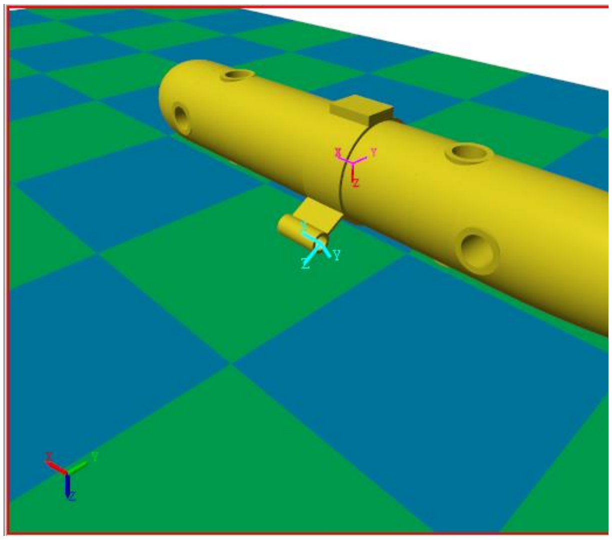

Figure 7. Main thruster force frame for actuation (blue) and sub center frame (red)

C. Manipulator Model

The most common material used in underwater manipulators is aluminum [7]. The density of aluminum is 2700 kg/m^3 which means that for manipulator of close to the same size as the submarine it will weigh much more. The chosen length for this manipulator is 1.5m as this is a common size for underwater manipulators [7].

The manipulator is a 3 DOF manipulator. All the joints used are single axis rotation. The arms connect at the rotating joints allowing for planar movement. The end-effector joint axis is rotated from the other two joints 90˚ to allow for end effector orientation change. The method of control for the manipulator will be torque inputs for each joint.

Figure 8. Rigid body tree of 3 DOF manipulator

D. Combined Model

The purpose of using the rigid body tree method is it allows for a singular connection to be formed for the combination of manipulator to submarine. The manipulator is attached to the sub center as to align the manipulator COM with that of the COM and therefore center of buoyancy (COB). This allows for the submarine to be horizontally stable without the need for external actuation.

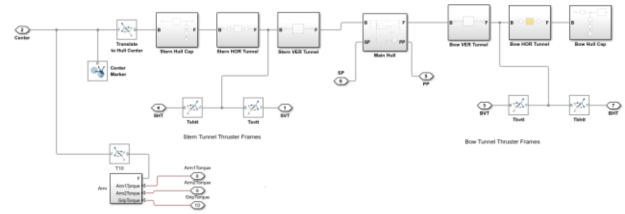

Figure 9. Rigid body tree of combined model.

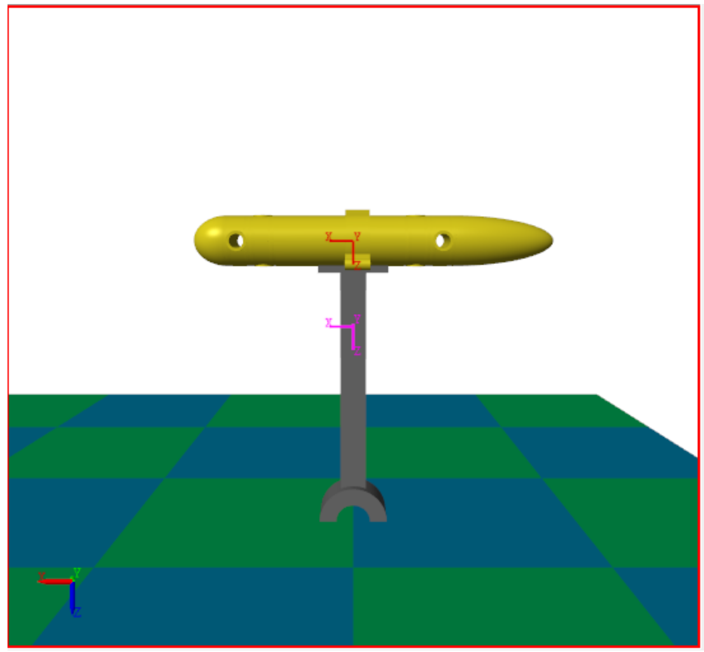

Figure 10. Visualization of AUVMS

III. Inverse Kinematics

Due to the kinematic redundancy, all the inverse kinematics are done with respect to the base of the manipulator. Which is directly connected underneath the center of the submarine. This allows for end effector points to be generated in the body frame. The weights for the inverse kinematics solver determine the leniency of the solution in terms of position and pose. Th weights for this application are strict for position solution however it can be in any pose.

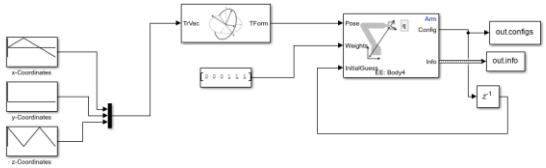

Figure 10. Inverse kinematic solver diagram

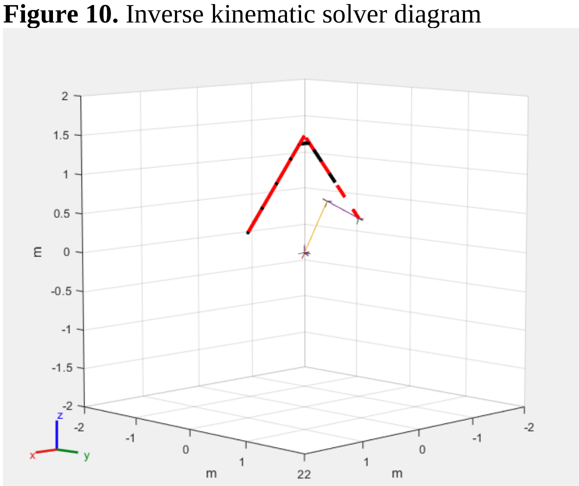

Figure 11. Planned path (red); Followed path (black)

IV. CONTROLS

A. Combined Control

An example of combined control uses a kinematic approach and Lagrange formulations for dynamic control [7]. The main issue with combined control is it is computationally intensive. To limit this computation the problem can be broken down into classical control schemes.

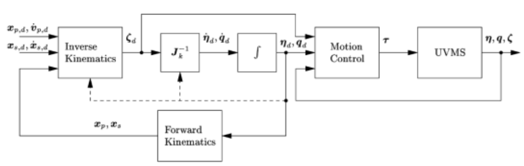

Figure 12. Example diagram of combined control [7]

B. Motion control

Each thruster corresponds to a control input for motion of the UVMS. The input dynamics solved from the inverse kinematics will be used to decouple the motion of the manipulator from the submarine. So that way they both can operate independently.

TABLE 1

CONTROL INPUTS AND SURFACES

Control Input	**Control Surface**
Speed x-direction	Main Thrusters
Heading	Horizontal Tunnels
Depth	Vertical Tunnels
End Effector Position	Arm Torques
End Effector Angle	End Effector Torque

C. Speed Control

Speed is measured with respect to the submarine center body frame. This allows tracking of sub movement and not COM movements. A PI controller was used to amplify the error between the reference speed and the measured speed. It was tuned based on the transfer function of the model of the UVMS. The step response has an overshoot of around 15% and it takes 10 seconds to get to steady state.

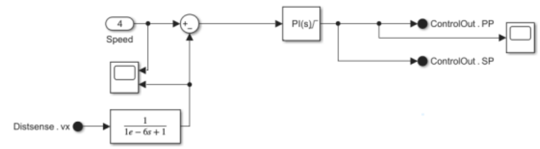

Figure 12. PI control in Simulink. The transfer function is there for continuity of the controller to avoid singularity.

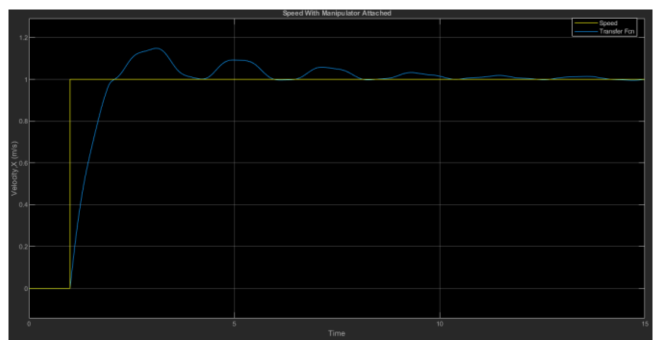

Figure 13. Step response input for speed

V. CONCLUSION

This paper sets preliminary groundwork for future research and experimentation. It allows for exploration of size ratios between manipulator and submarine. A greater DOF manipulator can be used in these simulations. This will only complicate the inverse kinematics though as all of the control will be based on COM position and movement. This leads to an exploration of how the COM will be sensed in a physical system.

Further simulations need to be done with added controls to fully encompass the combined control. The only controls implemented in this paper are the horizontal speed control. This only applies to the motion of the AUVMS to which the manipulator coupling does not effect.

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