Guidance, Navigation and Control of Autonomous Vessels: 
An Implementation using a Control-Based Framework

Ships have been sailing around the world for many centuries. Navigation, Guidance and Control (GNC) of vessels has always been the responsibility of humans, whom determined their own position and intuitively set out routes. The helm was continuously manned to execute subtle course corrections. Over time, individual GNC subsystems have been automated, resulting in GPS for reliable navigation and autopilots for course-keeping. As a result, the human role aboard vessels has become less critical and perhaps, in the future, obsolete. The benefits of unmanned ships could be substantial. Crew cost are mitigated and vessels could be built without crew accommodations, saving weight and costs. On top of that, automation may lead to safer shipping as accidents and casualty situations are often the result of human errors.

This thesis report proposes a framework to implement GNC algorithms that enable point-to-point autonomy for displacement vessels. A model-based control approach is chosen as the basis of the GNC systems. The resulting algorithms are implemented for verification in a 1:25 scale model of a Azimuth Stern Drive 3111 Damen tug named “Damen Autonomous Ship”, aka DASh, which was specially built for this project.

First, a maneuvering model that captures relevant dynamics of displacement vessel is formulated. The dynamic model of DASH is identified using system identification. The propulsion, surge dynamics and sway-yaw dynamics are identified separately by performing bollard pull tests, straight-line acceleration tests and zigzag tests. The parameter estimation problem is formulated as a nonlinear optimization and is solved in Matlab. The identified model is able to correctly predict short term output.

Secondly, the guidance system is automated such that it connects an initial state to a goal state with a collision free path that satisfies all input and differential constraints of the vessel model. To this end, the kinodynamic Rapidly-exploring Random Tree (RRT) path planning algorithm is extended to use a maneuver automaton and optimal motion primitives in its steering function. Special attention is paid to the notion of distance in the state space of a dynamic system. Several distance metrics are discussed and implementing in the kinodynamic RRT planner to compare their performance when generating paths.

Lastly, the navigation and control systems are implemented on DASH. Due to disturbances present in real world environments, the paths must be tracked using feedback control. State estimation based on position and heading measurements is performed by implementing an observer using an Extended Kalman Filter (EKF). Non-linear model predictive control (NMPC) in combination with thrust allocation is used to control the vessel during path execution. Due to real time requirements of the GNC systems, the EKF, NMPC and the thrust allocation algorithm are directly embedded on the board computer of DASH in efficient C/C++ code. Model tests were performed which showed DASH was able to successfully track paths generated by the path planner. Therefore the identified model is deemed suitable for use in model-based control. The NMPC feedback law showed superior tracking performance compared to more traditional non-linear PD control. Overall, the real time implementation using the control-based framework enabled point-to-point autonomy of DASH and can be used to automate the GNC systems of other vessels in the future.