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Preliminary Design of an Autonomous Amphibious System

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ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Unmanned Systems Advanced Development Branch (Code 71720) of the Advanced Systems & Applied Sciences Division, Space and Naval Warfare Systems Center Pacific (SSC Pacific), San Diego, CA. The Naval Innovative Science and Engineering (NISE) Program at SSC Pacific provided funding for this Applied Research project.

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EXECUTIVE SUMMARY

This report describes the design of an autonomous amphibious system and associated software architecture being developed under the Space and Naval Warfare Systems Center Pacific (SSC Pacific) Naval Innovative Science and Engineering (NISE) Program to augment the manned amphibious force. Amphibious landings and assaults are inherently dangerous and complex military operations, especially on a congested shore in an A2/AD environment. An unmanned amphibious capability is desirable to reduce the risk to the warfighter.

The preliminary autonomous vehicle design described accelerates the exploration of autonomy development by leveraging commercial off-the-shelf hardware, the Gibbs Quadski XL amphibious vehicle, and existing land and sea autonomy algorithms, allowing the primary focus to be on developing the autonomy software required for challenging sea to land transitions where perceptions sensor outputs will vary drastically and changing vehicle dynamics will require innovative new autonomy algorithms.

The developed software architecture, drive-by-wire kit, and supporting electronics will provide the capability to develop new autonomy software required for successful amphibious landings in the challenging transition state between land and sea.

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1. INTRODUCTION

1.1 BACKGROUND

Amphibious landings and assaults are inherently dangerous and complex military operations, especially on a congested shore in an anti-access and area denial (A2/AD) environment. Vehicles that are designed to survive and operate effectively while conducting 90% of their mission on land are not high-performance watercraft. The currently fielded assault amphibious vehicles (AAVs) were designed in the 1960s and manufactured in the 1970s (Figure 1). They are slow in the water, with a maximum speed of 7 kts, which makes them vulnerable to shoreline defenses. The U,S, Marine Corps (USMC) has pursued a higher speed platform, the Expeditionary Fighting Vehicle (EFV), which included a separate turbine engine for the marine propulsion and had a maximum over-water speed of 25 kts, but was ultimately deemed too expensive and too difficult to maintain. As a consequence, the USMC continues to employ the antiquated AAVs and is initiating a program to upgrade them with new powertrains. Unfortunately, this still leaves the USMC with a slow and vulnerable amphibious assault capability.

The U.S. Navy Science and Technology (S&T) community is once again taking up the challenge of looking for alternative solutions to the amphibious assault/ship-to-shore connector mission. One potential approach being investigated is the use of autonomous platforms to augment the manned amphibious force. Autonomous platforms could be used as advanced scouts looking for mines in the shallow water and on the beach, for logistics resupply, deception, or full first assault to soften beach defenses.

Figure 1. USMC assault amphibious vehicle.

1.2 PURPOSE

1.2.1 Autonomy Capability for AAV

The autonomous amphibious capability described in this report is being developed first on a low-cost surrogate platform, the Gibbs Quadski XL (Figure 2). The Quadski XL is a commercial off-the-shelf (COTS) platform that enables the development and experimentation of the core amphibious autonomy architecture and software without the logistical burden of a full-size AAV.

The autonomy capability developed initially on the Quadski XL will be transitioned and adapted to the AAV. The Naval Surface Warfare Center Panama City Division (NSWCPD) is developing the drive-by-wire (DBW) actuation for the AAV in parallel to the SSC Pacific autonomy development effort. Although there are obvious differences between the two platforms, the underlying architecture and transition state logic are being designed to transition between them.

The autonomous AAV is scheduled for demonstration in late Fiscal Year (FY) 2018, conducting operations at sea, through the surf zone, on land, and return to sea through the surf. By demonstrating these basic functions, this program will allow the USMC leadership to develop concepts of operation and tactics for employing autonomous AAVs in the future.

Figure 2. Gibbs Quadski XL.

1.2.2 Low-Cost Autonomous Amphibious Swarm

In addition to its use as a surrogate for the AAV, the Quadski will be used by SSC Pacific and Office of Naval Research (ONR) Code 30 Expeditionary Maneuver Warfare and Combating Terrorism Department to demonstrate the concept of a low-cost amphibious assault swarm. The fundamental theoretical advantage of a swarm of autonomous systems is to change the cost imposition to the enemy. Using large numbers of relatively cheap autonomous systems to first engage the objective causes the enemy to react and expend energy and resources dealing with autonomous expendable systems. Those same expendable systems will be providing intelligence, surveillance, and reconnaissance (ISR), mine countermeasures (MCM), electronic warfare (EW), and Fires capabilities to help soften the objective prior to a manned assault.

1.3 APPROACH

To advance the exploration of a new amphibious autonomous capability this research and development (R&D) project is focused primarily on the development of new algorithms that address vehicle control in the surf zone and transition states between sea and land. To achieve this goal, the project is leveraging as much COTS hardware and existing software as possible.

The Autonomous AAV software is composed largely of code adopted from the ONR 30 TIA autonomous ground vehicle software architecture, a code base managed by the Unmanned Systems Branch at SSC Pacific and developed by a variety of organizations, including SSC Pacific, the Southwest Research Institute (SwRI), the Jet Propulsion Laboratory (JPL), and Neya Systems, LLC. Surface vehicle capabilities from prior SSC Pacific unmanned surface vessel (USV) projects will be ported into the ONR 30 TIA architecture. These capabilities include a bathymetry server, a nautical chart server, and a surface waypoint navigation controller. This code, developed under legacy architectures, will be ported to the Robot Operating Systems (ROS) architecture and adapted to ONR 30 TIA conventions and standards.

New software research and development efforts will focus on the amphibious transitions (ground-to-surface and surface-to-ground).

2. AMPHIBIOUS AUTONOMY SOFTWARE

2.1 STRATEGY OVERVIEW

The Unmanned Systems Branch has a decades-long history in the development of autonomy software, from research and development to software used on programs of record, which includes autonomy for both land and surface vehicles. The design for AAV autonomy software is leveraging this existing codebase, with little modification needed for basic land or surface navigation.

However, there is little existing demonstrated autonomy capability—at SSC Pacific or anywhere else—for handling the transition between ground and surface modes required for amphibious operations. The bulk of new software research and development will focus in this area.

The software strategy for the Autonomous AAV project is to establish a baseline capability with existing software, and then incrementally add AAV-specific capability.

2.2 SOFTWARE ARCHITECTURE

The core architecture used is an instance of the ONR 30 Autonomy Transition Technology Architecture (TIA), based on the Robot Operating System (ROS). This architecture is designed for on and off road navigation by medium and larger sized ground vehicles. Existing vehicles include retrofitted High Mobility Multi-purpose Wheeled Vehicles (HMWWVs) and a custom vehicle, RaDER, based on a Polaris all-terrain vehicle (ATV) drive train. These vehicles are capable of autonomous navigation in a variety of on and off road environments, and have undergone extensive developmental testing to establish well-defined baselines for system and subsystem performance. This architecture provides the autonomous AAV with an almost out-of-the-box ground navigation capability.

Some surface autonomy capability is provided by porting software from prior unmanned surface vessel (USV) research and development performed with funding from the Office of the Secretary of Defense Joint Robotics Program. This R&D includes capabilities such as providing software interfaces to digital nautical charts, performing bathymetry, and investing prior work in tuning waypoint navigation planners.

Figure 3 demonstrates how the AAV autonomy effort software architecture relates to the overarching Reference Model for Unmanned Systems architecture model—developed at SSC Pacific to provide a concise description of autonomy software architectures. The Reference Model decomposes the vehicle architecture into subsystems. Rows in the figure correspond to “levels.” The lowest level (bottom row) corresponds to low-level subsystems, such as sensor drivers or motor controllers. The highest level subsystems along the top row correspond to subsystems that perform high-level tasks such as multi-vehicle coordination or wide-area mission planning. The columns indicate membership in four broad capability categories: sensing, modeling, behaviors, and mission payloads. The subsystem may correspond to an actual software module, but can also be just a logical description of the capability provided, i.e., the subsystems may be implemented as multiple software modules. Subsystems outlined in yellow (Figure 3, larger landscape image in Appendix A) indicate areas of significant software development under the Autonomous AAV project.

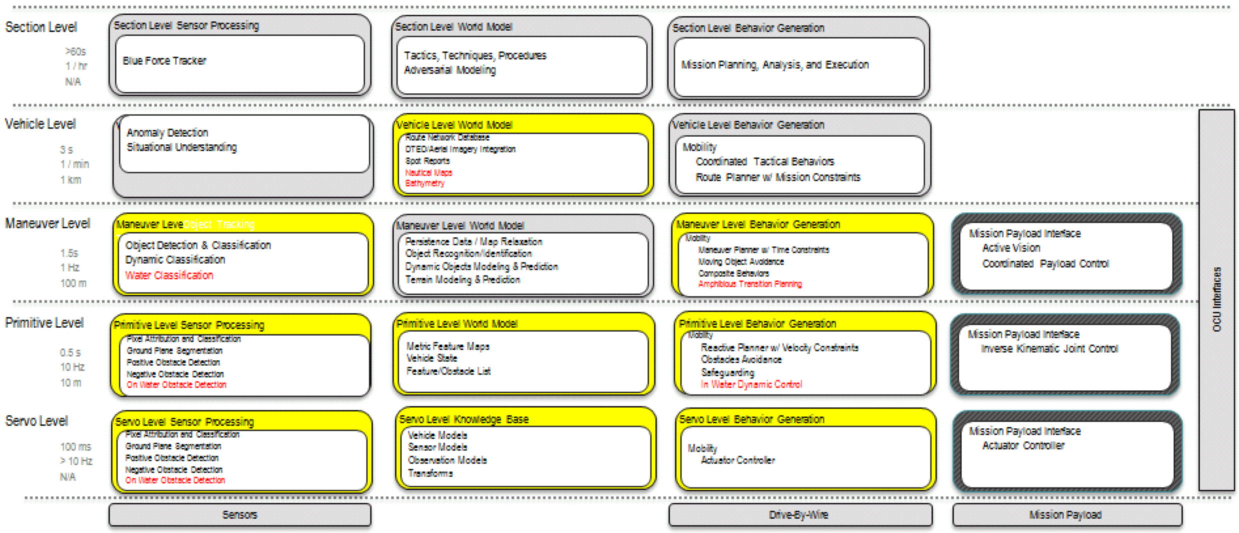

Figure 3. Software Architecture Reference Model.

2.3 LOCALIZATION

Effective autonomy requires the ability to maintain precise, smooth, and accurate estimates of the position of a vehicle relative to objects in its immediate surroundings as well as its position in wide-area or global coordinate systems. Localization is a key capability of the Autonomous AAV, with some unique requirements compared to most autonomous vehicles. The Autonomous AAV must localize effectively on land, surface, and in the surface-land transition zone, without interruption. This is challenging because different sets of sensors are used in each zone. For example, a water velocity sensor is used to measure velocity during surface navigation, while a wheel velocity sensor is used to measure velocity on land. Vehicle dynamics vary considerably in each zone as well. For example, on land Ackermann or skid-steer control models govern motion, meaning that the vehicle turns on well-defined arcs based on the steering-wheel angle, and most translation occurs along the forward axis of the vehicle (e.g., it generally does not slip sideways [other than the known slip of skid-steer geometry] or hop up in the air). However the Ackermann or skid-steer models are not sufficient predictors of surface dynamics. Water currents, vehicle momentum through a liquid, and wave effects result in a far less constrained model of vehicle dynamics. To further complicate matters, the transition zone—where neither the water velocity sensor nor the wheel velocity sensors may be reliable—involves a challenging mixture of dynamics.

There are further requirements placed upon the localization subsystem by the different consumers of localization data. Some localization consumers, such as path-planners, require smooth, continuous localization estimates that are locally consistent at the possible expense of large-area or global inaccuracy. Others, such as the operator control unit, require position estimates that are as globally accurate as possible to render over aerial imagery, even at the expense of allowing sudden jumps in position when an accurate global position measurement is acquired. To handle these conflicting requirements, the Autonomous AAV architecture will partially comply with the ROS “REP 105” convention (REP 105), with some project-specific modifications. REP 105 specifies the use of four well-defined coordinate frames, each with specific characteristics, as well as coordinate-frame transforms between each frame. The Autonomous AAV architecture varies with REP 105 only on the global coordinate frame. REP 105 specifies the use of a frame called “earth.” The origin of the “earth” frame is the ECEF (earth-fixed, earth-centered) frame. The Autonomous AAV architecture instead uses the frame “UTM,” another global coordinate system. The UTM coordinate system is convenient because it is a flat plane coordinate system convenient for use in distance and vector calculations. However, at some point the Autonomous AAV architecture may add the ECEF “earth” frame to bring it into complete REP 105 compliance. The Autonomous AAV architecture also introduces a new frame, “depth,” to estimate water depth.

The implementation of the Autonomous AAV subsystem will use three distinct implementations of unscented Kalman filters. The core filter implementation is that provided by the open source ROS “robot localization” package originally developed by Charles River Analytics (Robot Localization). One filter is used to generate the smooth continuous estimates. This filter only uses sensors that provide smooth continuous measurements with well-defined noise characteristics, such as inertial measurement units (IMUs) and velocity sensors. A second filter uses all the sensors as the first, but also uses estimates from sensors subject to large jumps or having poor noise characteristics, as opposed to the mean-centered Gaussian noise “preferred” by Kalman filters. For example, accelerometer and gyroscope measurements tend to have zero-mean noise well-described by a normal distribution. However, Global Positioning System (GPS) measurement error tends to follow a distributed Levy distribution in the presence of a GPS signal multipath, which can lead directly to bias in the filter output. The third filter will use estimates of water depth as sensor measurements, including sonar depth and depth estimates from bathymetric charts—either charts taken from public sources or custom-generated charts for local use.

The localization subsystem must have a mechanism of “knowing” which sensors to use at any given time, e.g., when to use the water velocity measurement vs. wheel velocity. In addition, the other vehicle subsystems must “know” the appropriate time to use mode-specific estimates, e.g., the depth estimate. This mechanism will be described in Section 2.6.

The sensors used will be as follows:

1. A “tactical grade” 3-axis fiber-optic gyro and 3-axis accelerometer, used to provide very accurate pitch, roll, and yaw data
2. A lower-cost, consumer-grade IMU for redundancy
3. A gyro-stabilized marine compass used to provide accurate global heading
4. An impeller-based water velocity sensor
5. A wheel odometry-based wheel velocity sensor on at least two wheels
6. Commercial GPS
7. Sonar-based depth sensor
8. Bathymetry chart lookup based on global position estimates.

This combination of position estimators and sensors will provide the Autonomous AAV architecture with a robust, accurate set of localization estimates.

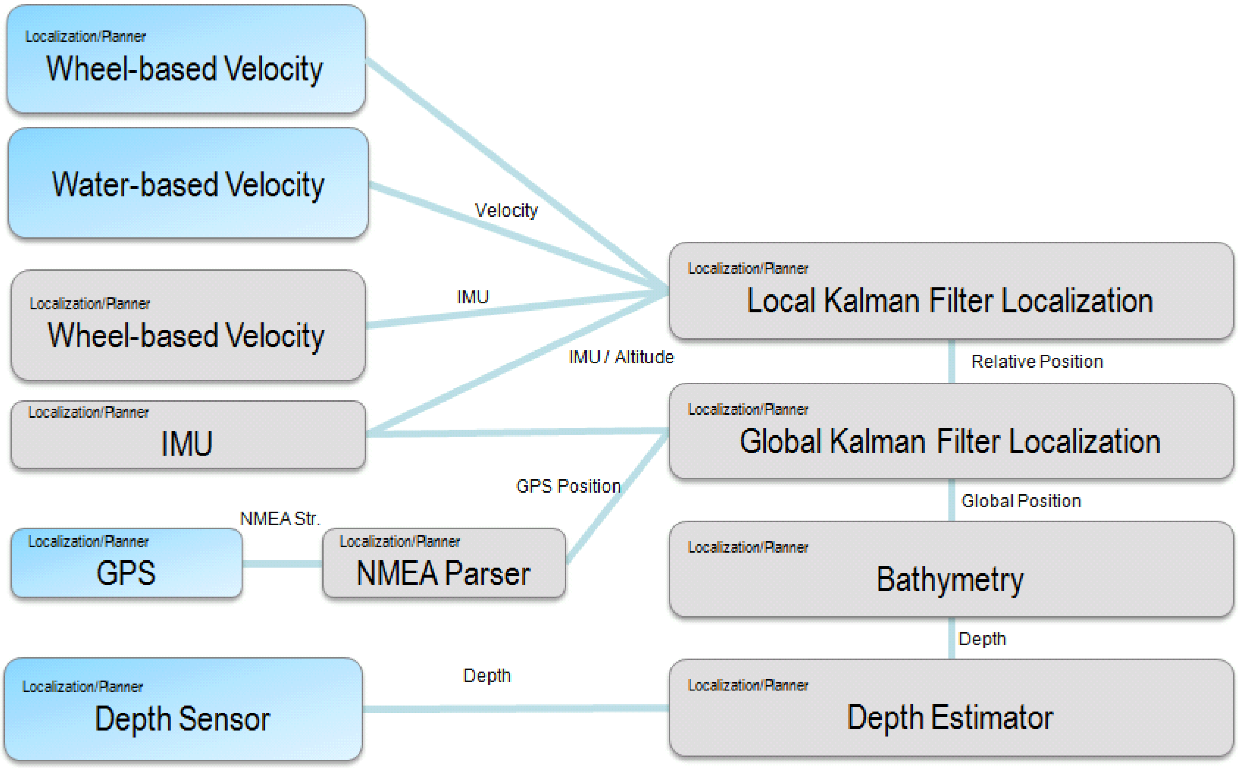

Figure 4. Localization architecture.

2.4 PERCEPTION/SENSOR FUSION/WORLD MODEL

The Autonomous AAV perception and world modeling subsystem will borrow heavily from the ONR 30 TIA architecture. Like the existing ONR 30 TIA vehicles, the Autonomous AAV architecture will use stereo and Light Detection and Ranging (LIDAR) data for sensing objects in the surrounding environment. The Carnegie Robotics *MultiSense S21* stereo camera will provide a dense, short-range, three-dimensional (3-D) view of the world immediately in front of the vehicle, with an effective range of approximately 40 m. The *Velodyne HDL-32E* LIDAR will provide a wider area, long-range (approximately 80 m), and more accurate representation of the environment, but with less density than the stereo camera. In addition, the Autonomous AAV architecture may also employ one or more rear-facing LIDARS to provide coverage in areas that are blind spots for the stereo and *Velodyne* LIDAR. Another key input to the world model subsystem is the output of the localization subsystem described above.

The method of fusing the data and providing a central coherent model of the world for use by other subsystems is the ONR 30 TIA “world model” system, a ROS node with a ROS “plugin” mechanism for both adding the output of an arbitrary number and type of 3-D sensors, as well as an arbitrary number and type of modules for processing the raw sensor data into actionable data. The core world model was developed by the Southwest Research Institute (SwRI), with additions and modifications by the Jet Propulsion Laboratory (JPL), SSC Pacific, and some influence by Neya Systems, LLC. The world model architecture concept also has lineage to the ROS *OctoMap* package developed at the University of Freiburg (OctoMap).

The primary world model capability is the conversion of high volumes of 3-D data into a CPU and memory-efficient voxel representation, using an octree-based data structure, which converts very high volumes of data (potentially on the order of gigabytes per second) into a compact data structure that provides low-cost spatial queries and other operations. It also provides a mechanism for sensor fusion, e.g., the “occupancy” of a given voxel in the world may be influenced by multiple sensors simultaneously. The voxels are probabilistic in nature, with both the fusion step and the resulting degree of occupancy having an associated likelihood to allow consumers of world model data an estimate of the reliability of the voxel data.

The world model subsystem can also accept input from other processing ROS nodes or subsystems. For example, a ground-plane estimation algorithm is used to segment raw stereo disparity images into ground and non-ground regions. Similar algorithms are used to segment LIDAR point clouds. This segmentation provides data convenient for use by the path-planning subsystem tasked with finding reasonable trajectories to navigate and avoid obstacles.

The Autonomous AAV architecture will use the already-developed baseline capabilities of the world model and also develop additional capabilities to support AAV-specific functions. For example adding a representation of water-surface pixels by processing stereo and/or LIDAR data to estimate which data is reflected off water may be very useful, improving the ability of the architecture to estimate the land-water transition area. Perception data will be used in conjunction with the localization output to estimate the location of and proximity to transition zones.

2.5 PLANNING/CONTROL

The planning and controls subsystems are responsible for using the data from the localization and perception/world model subsystems to generate appropriate paths to navigate through the world by controlling the various motors that control the amphibious vehicle.

The lowest-level subsystem is the drive-by-wire subsystem. This subsystem converts steering, throttle, brake, reverse bucket, and other basic movement commands into commands to control the various motors on the vehicle. The drive-by-wire system can be used as an interface for autonomous control of the vehicle, but can also be used as the interface to a game controller or other means of teleoperating the vehicle. The drive-by-wire subsystem is also used to implement a number of safety features. For example, the drive-by-wire system subscribes to “emergency stop” signals from the “e-stop” module, and places the motors in a safe state before cutting off control from either the autonomy subsystem or teleoperation. This feature is an addition to safety features already implemented at the hardware and electrical level that can cut off control independently of the software, e.g., cutting power to motors or turning off the engine. The drive-by-wire controller can also use message timestamps to ensure that only very recent commands are used to produce motion, reducing the risk of communications latencies causing inappropriately delayed motion by the vehicle.

Most drive-by-wire commands for an amphibious vehicle can be re-used from existing land-vehicle commands. Additional commands for the Autonomous AAV and Autonomous AAV surrogate are used to control the reverse bucket and the articulating suspension system.

During autonomous operation, the low-level controller commands the drive-by-wire subsystem. The low-level controller uses a control algorithm to convert requested vehicle velocity and steering angle commands from higher-level controllers/planners into drive-by-wire commands. The algorithms used in the low-level controller are variations on the PID (proportional – integral – derivative) controller. The outputs of the localization and drive-by-wire subsystems are used to calculate the error between desired and measured velocities and steering angles. There are two different implementations of a low-level controller available for use as part of the ONR 30 TIA architecture, one implemented by the Southwest Research Institute, and another developed at SSC Pacific.

A low-level controller needs to be tuned both to the vehicle controlled as well as to the mode of operation. Therefore, an amphibious vehicle will need different tuning parameters for land and surface use. In addition a possible third set of tuning parameters may be needed during the land-surface transition where neither water nor land dynamics are dominant. The low-level controller reacts accordingly to the state reported by the Mode Controller described in Section 2.6 and shown in Figure 5.

Providing input to the low-level controller are the reactive and maneuver planners. The reactive and deliberate planners take data from the localization and perception/world model along with a goal point or goal path and produce a path that seeks to achieve the goal while satisfying a number of constraints. The constraints include avoiding obstacles and limiting deviation from the goal path. The reactive planner operates at a high rate, and produces simple arc-based trajectories in a timely fashion in response to obstacle and other cost data produced by the world model subsystem. The deliberative planner is allowed more time (e.g., seconds) and can produce more complex trajectories that attempt to produce optimal paths around obstacles to the desired goal point. The deliberative trajectories can include multi-point turns or other more complex maneuvers. The reactive and deliberative planners exist in a subsumptive relationship where the reactive planner can override the deliberative planner in commanding vehicle motion. This relationship exists because the reactive planner can respond more quickly to the sudden presence of new obstacles or unplanned changes in vehicle behavior such as hitting an unseen bump.

The land-mode planners for the amphibious vehicle will likely remain unchanged from the existing planners developed by Neya Systems, LLC. Surface-mode planners will likely use the land-mode planners with some existing parameters and possibly some modification. However, adding in planning for the land-to-surface and surface-to-land transitions will be a significant addition to the amphibious vehicle architecture. Due to the importance of this additional planning, the Mode Controller subsystem that performs this role is described in Section 2.6.

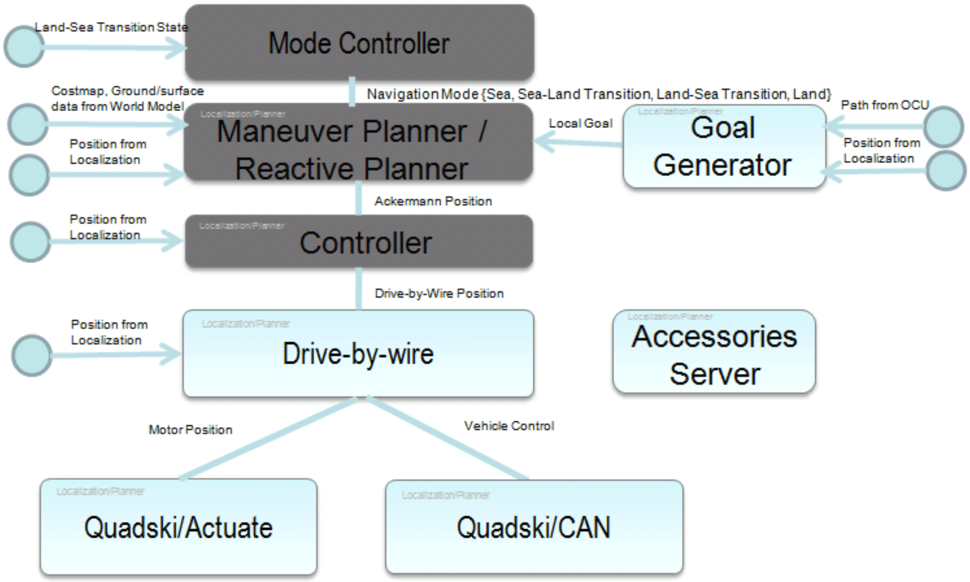

Figure 5. Planning and Control Subsystem.

2.6 MODE CONTROLLER

The land-to-surface and surface-to-land transitions are the riskiest and most complex areas for the navigation of an amphibious vehicle—either manned or autonomous. Timing is important in transitioning to the appropriate method of steering, propulsion, and braking. Maintaining a desired heading is important as approaching a surf zone with a heading orthogonal to oncoming waves is important. Maintaining appropriate velocity is important because surface vehicles generally require a minimum velocity to turn to a heading. Mistakes in control during the transition can result in an aborted attempt or place the vehicle in a vulnerable state.

The trajectories for these transitions will likely be reasonably straightforward in the first phases of the amphibious vehicle project where such transitions will only be attempted in areas with sea state 0 (glassy water). However, an amphibious vehicle will also have the additional responsibility of planning the states of additional actuators, such as articulating suspension or reverse bucket. Correct and timely raising/lowering of the suspension during a transition is critical to a successful transition. The planners and controller must also use the appropriate methods for achieving braking, velocity, and steering during a transition, e.g., switching from water jet to wheel velocity during a surface-to-land transition. It is possible that both jet and wheel velocity propulsion be used simultaneously during a transition. Constructing an amphibious planner capable of performing this transition reliably and in a wide range of conditions will be a core area of research and development in the software development of the Autonomous AAV. A notional Mode Controller subsystem is shown in Figure 6. The Mode Controller acquires position and land-sea state from the localization and perception/world model subsystems. When an operator-provided goal route results in a path plan that traverses a known transition zone, the Mode Controller produces and publishes a strategy for effectively transitioning through the transition zone while actuating suspension at the appropriate times, using the appropriate localization sensors and output, and using the appropriate methods low-level controller and drive-by-wire configurations.

The likely architectural mechanisms for achieving this control strategy are the ROS Action Server (actionlib) and State Machine (smach) tools (ActionServer, StateMachine). The Action Server is a ROS tool used for defining and controlling actions that may take a relatively long time to complete, and that can provide regular updates such as percent completion. The navigation through a transition zone fit these criteria. The State Machine mechanism, often tightly coupled with Action Server, allows the explicit definition of states and the events that trigger transitions between states. The use of these tools, or other algorithms and tools, to successfully achieve amphibious transitions will be a core area of research and development in the second year of the Autonomous AAV project.

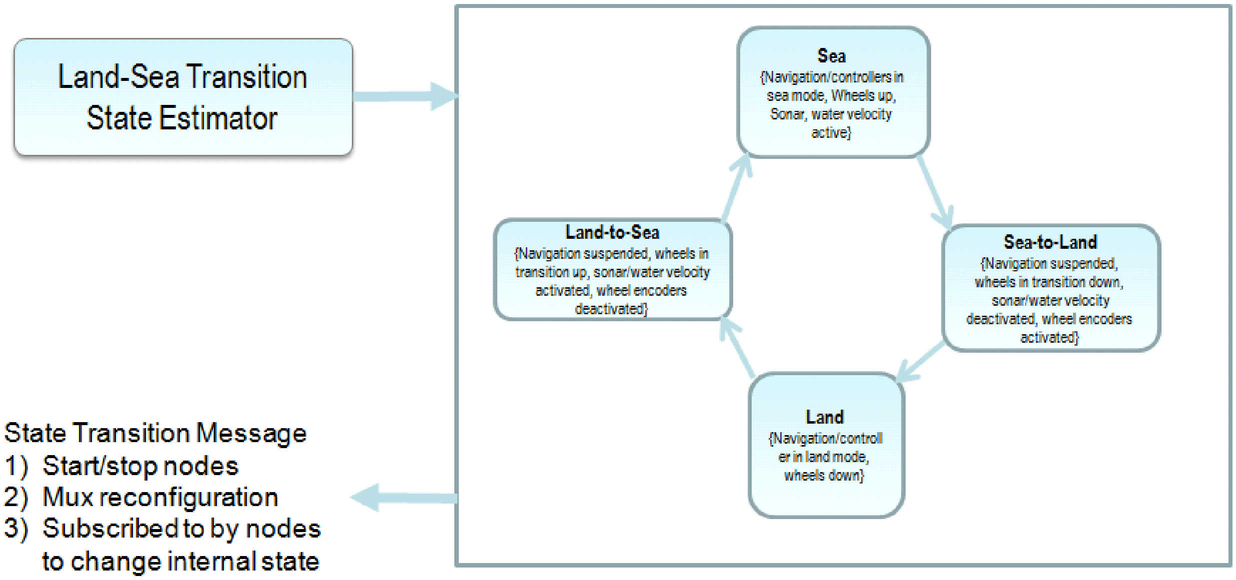

Figure 6. Mode Controller architecture.

3. AMPHIBIOUS AUTONOMY HARDWARE

3.1 AMPHIBIOUS SURROGATE VEHICLE SELECTION

To develop an autonomous amphibious system it was desirable to leverage a commercially available vehicle that was less expensive, less complex, and could be tested in more locations than the 29-ton amphibious assault vehicle. A market survey was performed to identify potential candidates that met critical criteria such as land and water speed, cost, and availability. The summarized results of the survey (Table 1) clearly showed that the Gibbs Quadski XL provided the best match to the desired criteria at the time of the survey. The table does not include all amphibious vehicles just the ones that were closest to meeting critical criteria.

Table 1. Simplified Amphibious Vehicle Market Survey.

Model	Make	Land Speed (mph)	Water Speed (mph)	Cost ($K)	Max Payload (Pounds)	Availability (Months)
Quadski	Gibbs	45	45	41	264	*
Quadski XL	Gibbs	45	45	48	405	*
Humdinga	Gibbs	55	30	650	1320	6-9
Python	Watercar	55	44	155	700	6-8
Max IV	Max all-terrain	25	3	7	500	0
8x8 XTD	ARGO	17	3	38	840	0

*At the time of the survey these vehicles were in stock at local suppliers.

3.2 HARDWARE COMMUNICATIONS ARCHITECTURE

Computers, sensors, and actuators were added to the Quadski XL to facilitate autonomous control. The components used and the method of communication between them is illustrated in Figure 7. Sensors are shown in green boxes and include stereo vision, LIDAR, wheel encoders, IMU, GPS, fiber optic gyro, compass, water depth and speed sensor, and brake fluid pressure. Additional sensor input that is native to the Quadski, such as fuel level, rpm, vehicle speed, and steering position, is received from the CAN bus port on the vehicle.

Three computers (shown in blue with other data processing devices) are used to perform high-level autonomy functions; the sensor fusion computer collects, processes, and passes on information from the stereo vision and LIDAR sensors; the localization computer collects data from most of the other sensors on the system and provides control to the drive-by-wire actuators and to a relay board that controls low level native functions on the vehicle such as transitioning the suspension between water and land modes, engine start, engine kill, and shifting; the world model computer processes data from the other computers and integrates them into a common “world model” that is used for path-planning and higher level sensor processing. The micro-computer is used for miscellaneous low-level functions such as controlling safety lights.

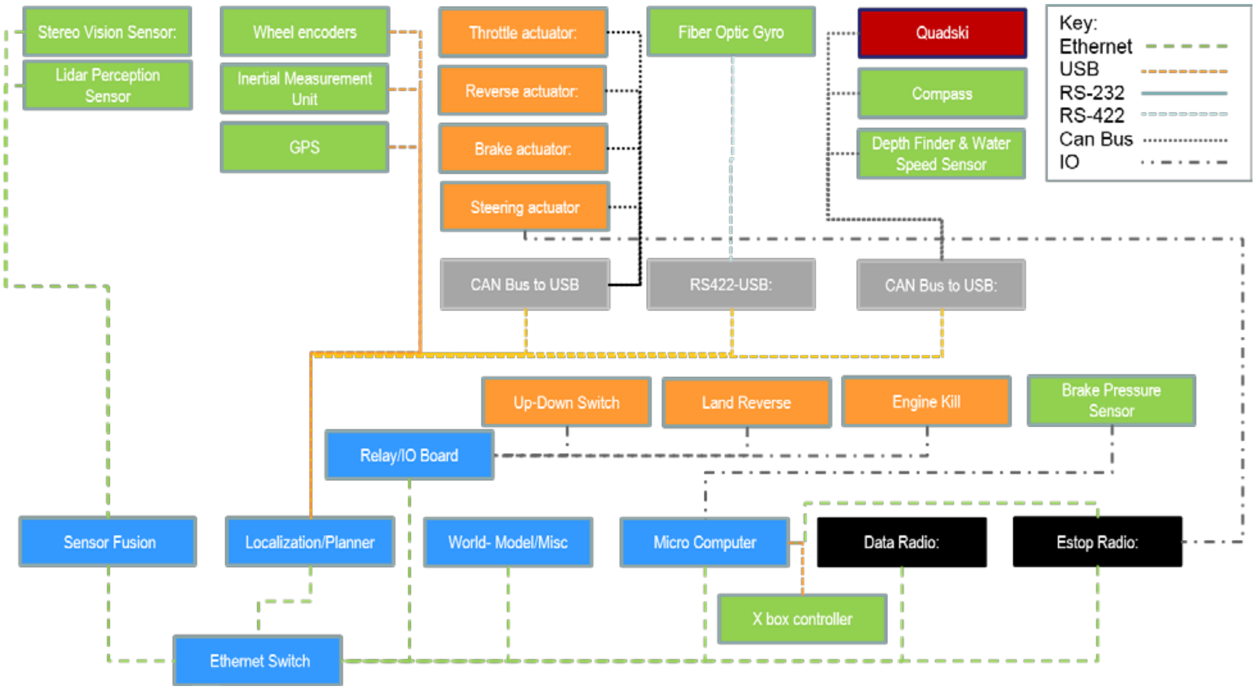

Figure 7. Autonomy System Communication architecture.

3.3 DRIVE-BY-WIRE DESIGN

The drive-by-wire system replaces a human as the controller of the vehicle. It consists of three main subsystems that include a CAN bus interface, electro-mechanical actuators (Figure 8), and a relay interface board. The CAN bus interface provides native Quadski vehicle information that is collected by the vehicles stock computer (ECU), such as fuel level, rpm, and steering column angular position.

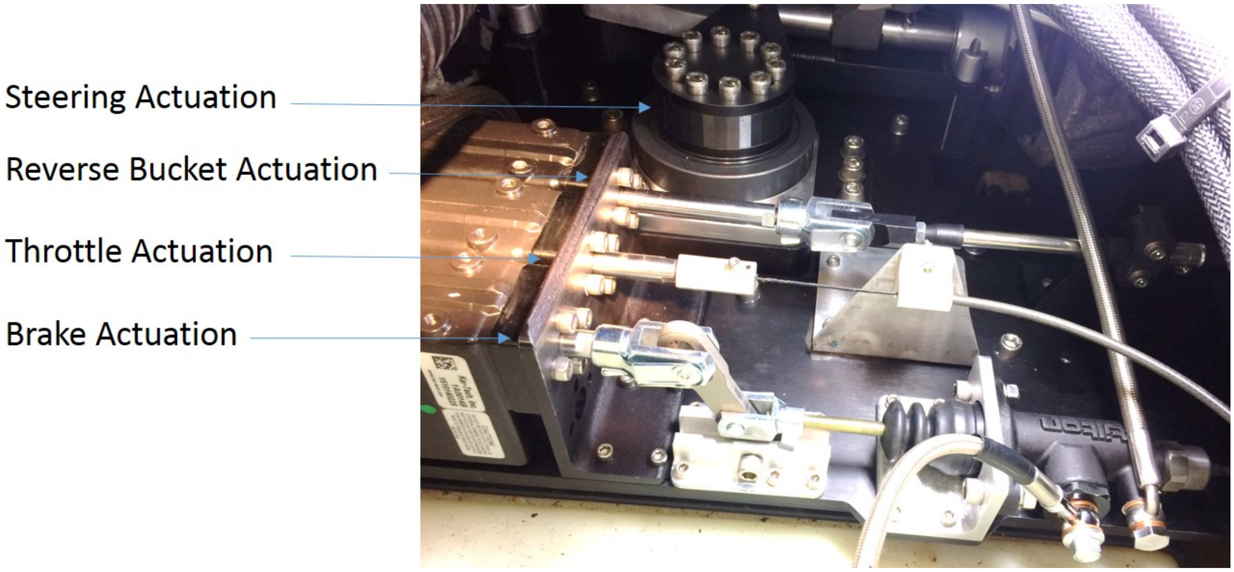

Figure 8. Drive-by-wire actuators.

The electro-mechanical actuators move parts on the vehicle that are normally controlled by a driver; they include a steering actuator, brake actuator, throttle actuator, and reverse bucket actuator. The steering actuator (Figure 9) shown in red drives a linkage (also shown in red) that pushes a shaft (shown in green) left or right to change the steering angle.

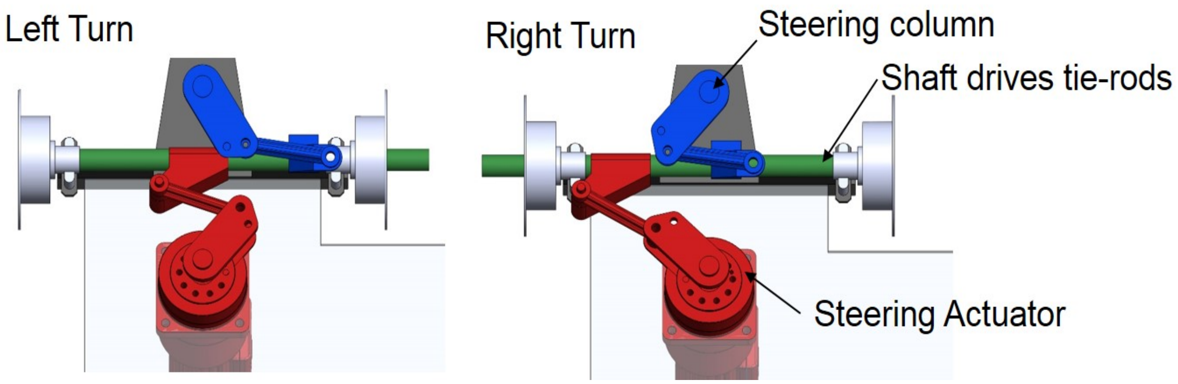

Figure 9. Steering actuation.

Analysis and dynamic simulation performed during the design process found that the required torque for an actuator to steer the vehicle with a left to right response time of less than one second was in excess of 1000 inch-pounds. (Figure 10) in worst case conditions. The simulation shows that at time zero when the steering was completely turned to the right it took about 690 inch-pounds to start turning the handlebars. When the handle bars reached the straight position at 0.5 seconds, actuation torque peaked at just more than 1000 inch-pounds. As the handle bars continued to toward the left turn position the required torque began dropping. The steering motor and gear-reducer were selected to achieve this level of torque plus a specified safety factor to ensure the drive-by-wire system would be able to turn the vehicle in all conditions.

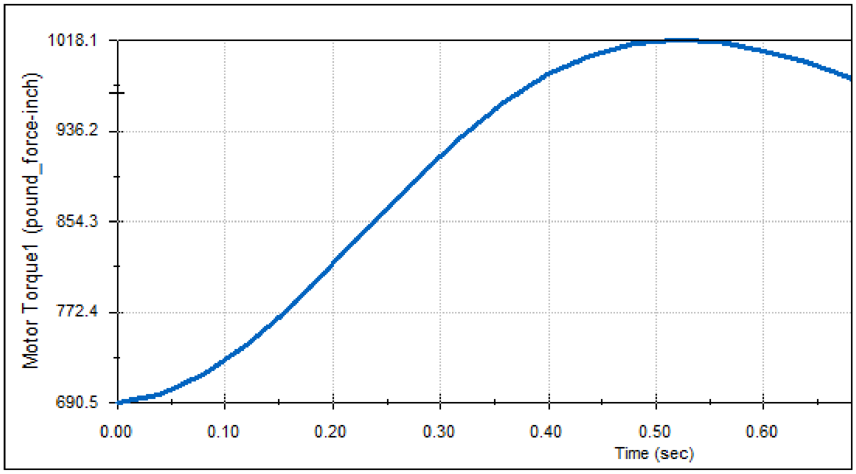

Figure 10. Required steering torque simulation.

The vehicle brake is actuated by a CAN Bus-controlled linear actuator with digital position feedback. The actuator pushes on a lever arm that moves the input rod of a brake master cylinder, which then pressurizes the vehicles existing brake lines and activates the brake calipers to stop the vehicle. A pressure sensor on the back of the master cylinder reports the brake pressure providing closed-loop brake control for safe effective stopping and monitoring of brake failure. Figure 11 illustrates some of the key components and shows the on and off positions of the brake actuation.

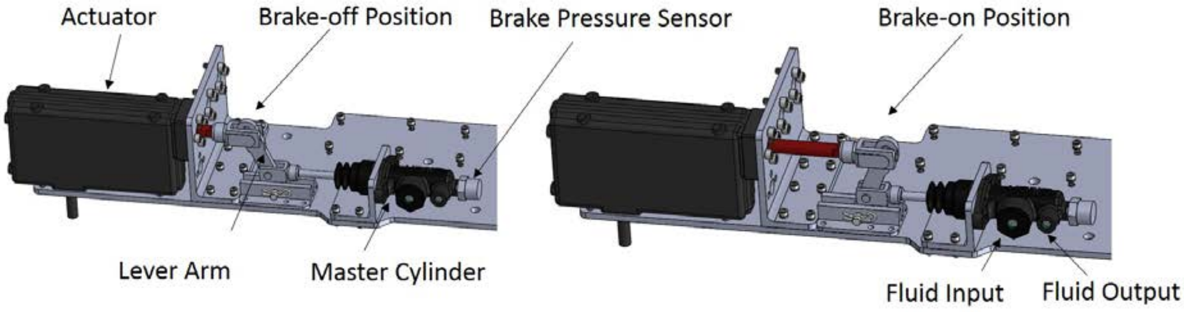

Figure 11. Brake actuation.

The same type of actuator that is used for the brake is also used for the throttle and reverse bucket. The reverse bucket moves a reflector "bucket" in front of the waterjet on the vehicle to redirect water thrust, allowing the vehicle to move in reverse while in the water. In both of these cases, the actuator (Figure 12) is directly linked to the cable that drives the throttle and reverse bucket to actuate these systems. The moving shaft on each of the actuators is illustrated in red.

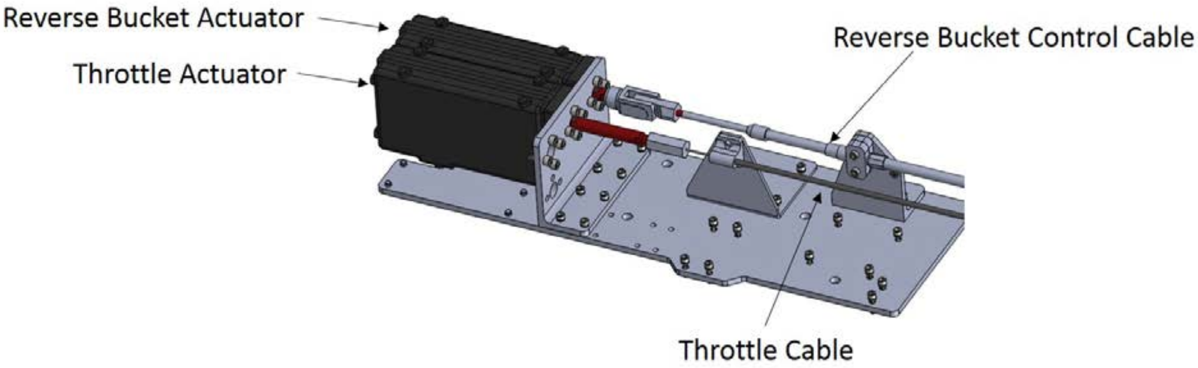

Figure 12. Throttle and reverse bucket actuation.

Functions controlled by an electrical signal on the Quadski are engine start, engine kill, head lights, suspension up-down, land reverse, shift up, and shift down. All of these functions are controlled by adding inline connectors that run signal input lines to a computer controlled relay board. This method preserves the ability of a driver to manually control these functions while also allowing access to the autonomy system.

3.4 AUTONOMY ELECTRONICS

A temporary prototype electronics enclosure (Figure 13) was designed and fabricated to allow autonomy software development to begin before a ruggedized waterproof enclosure could be designed. The temporary enclosure includes all the components required for autonomous vehicle control, including radios, computers, inertial sensors, power distribution components, and signal processing electronics. For electronics cooling, the enclosure relies on filtered air being cycled into and out of the enclosure.

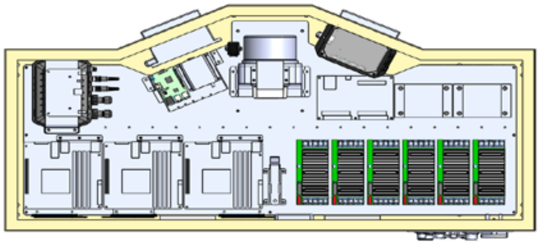

Figure 13. Temporary electronics enclosure (top view, lid removed).

4. FUTURE WORK

4.1 AUTONOMY SOFTWARE MATURATION PLANS

The core area of software maturation will be in providing effective and reliable autonomous navigation through surface-to-land and land-to-surface transitions. This work involves developing and maturing the Mode Controller Subsystem described in Section 2.6 as well as work in most other software subsystems. The initial work in this research and development effort will be extensive data collection using the initial surrogate AAV vehicle to collect and characterize a sufficient body of sensor data from teleoperated transitions. This data characterization will be used to select appropriate algorithms and construct the logic used in the transition state estimator and Mode Controller. Subsequent testing will be required to tune and refine the autonomous amphibious transition capability.

Additional work will be done to support the drive-by-wire refinement and low-cost amphibious swarm plan. The drive-by-wire refinement will involve incorporating additional safety features to drive-by-wire operation, such as ensuring that a remote e-stop cannot throw a manned drive-by-wire operator from the vehicle. Additional work for the low-cost amphibious swarm will be providing an easily-deployable software release system using a standard software package management system to deploy software vs. the current system of hand-constructing software builds for each vehicle.

4.2 DRIVE-BY-WIRE PLANNED REFINEMENT

Refinements to the drive-by-wire actuation system design is underway to allow the vehicle to be easily switched between manned control and autonomous control. All four electro-mechanically actuated subsystems will be impacted by these design changes. Manual actuation by a driver is critical for testing, safety, and logistics reasons. For example, if an electronics failure occurs in the autonomy enclosure while the vehicle is on range, an operator will need to drive the vehicle to a safe location for repair.

Currently, the steering system actuator can be turned off and the operator can steer the vehicle through the original steering column and steering linkages. However, with the autonomy steering motor in place and unpowered, significant force is required to back-drive the motor during manual steering. Because of this steering is cumbersome and only safe at very slow speeds. To allow effective manned steering the steering autonomy motor will need to be completely disengaged either through a clutch or other mechanical device.

A preliminary design for a throttle mechanism that passes both manned and autonomy inputs to the vehicle engine has been developed (Figure 14). The mechanism provides a throttle cable output to the engine while the manually actuated throttle cable and the autonomy system motor actuation are completely uncoupled. Springs within the system return the system to a safe zero throttle position in case of power loss to the autonomy motor.

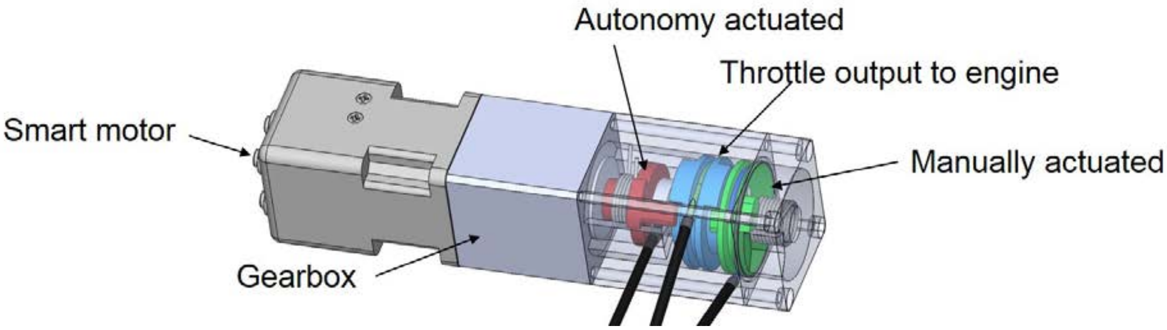

Figure 14. Dual input throttle mechanism.

A dual input brake that facilitates autonomy and manned control has been designed and all the parts ordered. Installation and testing in the Quadski was completed in November 2016 and the design works as intended. To achieve a dual input brake system two master cylinders and a special component called a shuttle valve are required. One master cylinder provides braking from the human driver and the other from the autonomy system. The shuttle valve is required so that the pressure created by the active master cylinder does not create fluid flow back through the inactive master cylinder to the fluid reservoir. If this were to happen, no pressure would build in the brake lines to stop the vehicle, and it would simply flow in a circle from the fluid reservoir through the two master-cylinders back to the reservoir. Figure 15 illustrates this design in a simplified block diagram. As shown, the manually driven actuator is pressurizing the brake system to activate the brake calipers. The ball shown in the shuttle valve shifts over to the left to close off flow back through the actuator-driven master-cylinder to the reservoir.

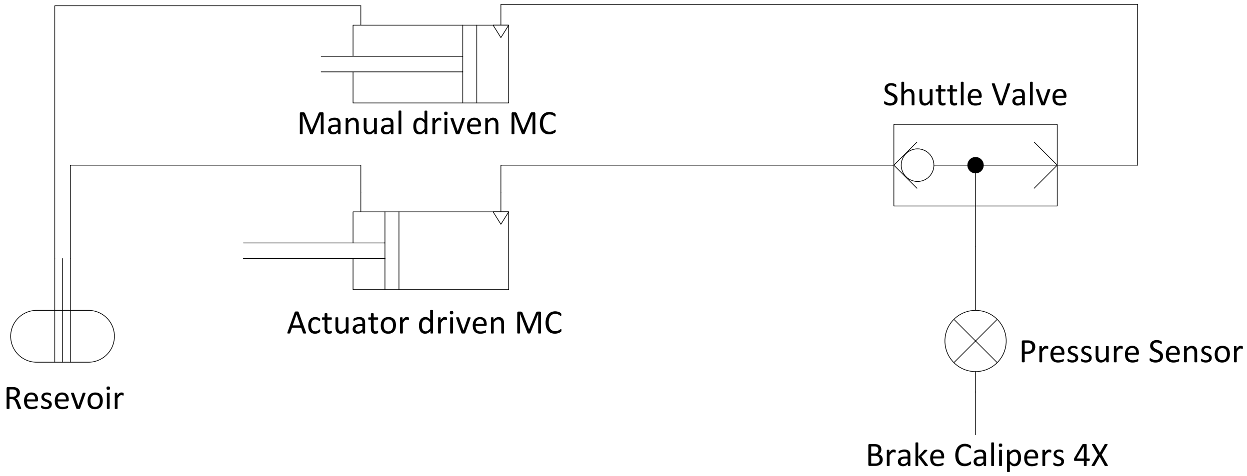

Figure 15. Dual input brake system block diagram.

A dual input design for the reverse bucket actuation is planned, but has not been started at this time.

4.3 AUTONOMY SYSTEM ELECTRONICS PACKAGING PLAN

Design efforts on a fully waterproof electronics enclosure have started, and early computational fluid dynamic simulation results (Figure 16) have helped establish a path ahead for a thermal cooling solution. To achieve effective cooling in a completely sealed enclosure, the highest heat generating components have heat paths to the outer edge of the enclosure where heat fins transfer heat to exterior air. To achieve this goal, the DC-DC power regulators are mounted directly to the left side of the enclosure in contact with a surface directly connected to the heat fins. On the left side of the enclosure, the primary computers use heat-pipes to transfer heat from the processor to the heat fins on the side of the enclosure. In addition, waterproof (Figure 17) fans under the enclosure blow air up through the heat fins to speed heat transfer to exterior air.

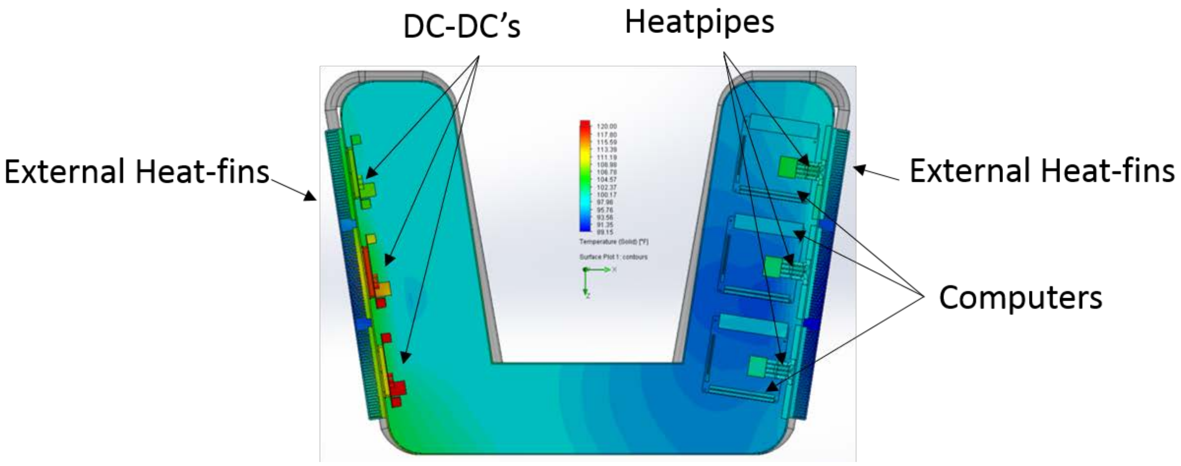

Figure 16. CFD results for conceptual waterproof electronics enclosure (top view, lid removed).

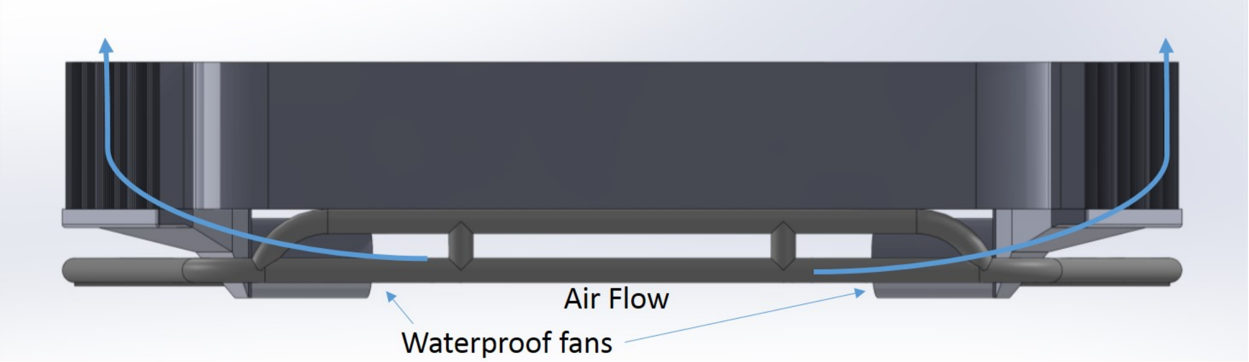

Figure 17. Waterproof enclosure exterior fans (rear view).

4.4 TRANSISTION TO AAV

Transition of the autonomy system from the Quadski XL to the AAV will require the following:

- Development of a drive-by-wire kit for the AAV; Naval Surface Warfare Center Panama City Division is undertaking this effort

- Development of software controls for new drive-by-wire kit functionality; the AAV has many more control features than the Quadski, such as a parking brake, bilge pumps, fuel control, a bow plane, and a rear door/ramp, that need to be actuated and controlled
- Tuning of the autonomy system vehicle model to match AAV dynamics for vehicle control in land, sea, and transition modes
- Integration of the autonomy computers and electronics into the AAV.

5. SUMMARY

The preliminary design for an autonomous amphibious vehicle has been completed to advance the development of autonomy software that provides for effective mobility through the transition zone between land and sea during landing operations. The design includes the Gibbs Quadski XL as the mobility platform, a custom-made, drive-by-wire kit that allows computer control of the vehicle, and an electronics payload to provide sensing, processing, power distribution, and vehicle control. The system will allow for data collection and autonomy development on land and in calm sea-states while a refined drive-by-wire capability and waterproof electronics enclosure are developed.

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APPENDIX A

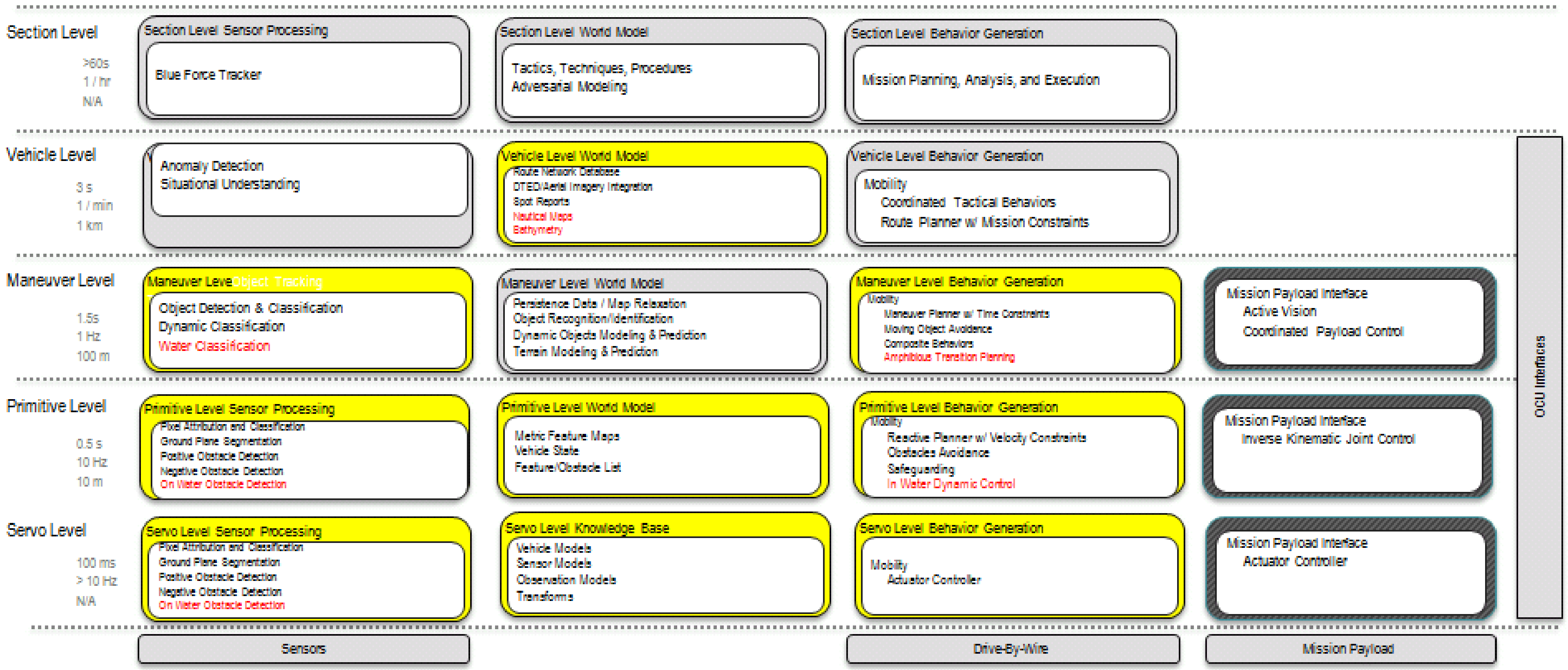

Figure A-1. Software Architecture Reference Model (Landscape).

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14. ABSTRACT

This report describes the design of an autonomous amphibious system and associated software architecture being developed under the Space and Naval Warfare Systems Center Pacific (SSC Pacific) Naval Innovative Science and Engineering (NISE) Program to augment the manned amphibious force. Amphibious landings and assaults are inherently dangerous and complex military operations, especially on a congested shore in an A2/AD environment. An unmanned amphibious capability is desirable to reduce the risk to the warfighter.

The preliminary autonomous vehicle design described accelerates the exploration of autonomy development by leveraging commercial off-the-shelf hardware, the Gibbs Quadski XL amphibious vehicle, and existing land and sea autonomy algorithms, allowing the primary focus to be on developing the autonomy software required for challenging sea to land transitions where perceptions sensor outputs will vary drastically and changing vehicle dynamics will require innovative new autonomy algorithms.

The developed software architecture, drive-by-wire kit, and supporting electronics will provide the capability to develop new autonomy software required for successful amphibious landings in the challenging transition state between land and sea.

15. SUBJECT TERMS

autonomous amphibious system; amphibious landings and assaults; A2/AD environment; land and sea autonomy algorithms; amphibious autonomy hardware/software; drive-by-wire kit; autonomy electronics

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