ONR 30 Autonomous Ground System Program Overview

Michael Bruch*, Leah Kelley, Chris J. Scrapper
SPAWAR Systems Center Pacific, 53560 Hull Street, San Diego, CA, USA 92152-5001

ABSTRACT

In 2010 the ONR Code 30 Irregular and Expeditionary Warfare Department began a long-term strategic investment in ground system autonomy focused on supporting our Expeditionary forces, namely the United States Marine Corps (USMC). The Marine Corps' mission and challenges are unique and as such require unique capabilities of the autonomous systems they will employ. For the past six years ONR Code 30 has been executing the Multi-role Autonomous Ground Vehicle (MAGV) program which has focused on developing core technologies to enable the operation of autonomous ground vehicles in expeditionary environments. The key overarching tenets of the program have been to develop a ground autonomy system that is affordable, can operate in those expeditionary (off-route) environments, and which will be the technological foundation for future DoD programs both in S&T and acquisition. Those three key tenets have driven many of the investment decisions of the program including a focus on low-cost sensors and computation (e.g., vision systems), congested environment motion planning, operation under degraded GPS conditions, multi-vehicle coordination, and using a rapid development and evolutionary systems engineering approach with rigorous and consistent performance evaluations. This paper describes the goals and objectives of the ONR 30 ground autonomy program and provides an overview of the technical accomplishments that have been achieved over the past six years.

Keywords: Ground vehicle autonomy, integration, autonomous navigation, perception, coordinated behaviors

1. KEY TENETS OF THE PROGRAM

The Office of Naval Research (ONR) Code 30 Multi-role Autonomous Ground Vehicle (MAGV) program sought to develop an autonomous expeditionary ground vehicle system that was capable of operating in a variety of off-road environments under a variety of weather conditions, was affordable, easily maintained, used open-source software architecture and code, and could serve as a technical base for future DoD programs.

1.1 Expeditionary navigation

Commercial automakers such as Tesla, Ford, BMW, Volvo, Nissan and GM, as well as companies such as Google and Uber, have spent billions of dollars on acquiring and/or developing self-driving car technologies for consumer/commercial use[1-3]. Urban driving in a structured environment on paved roads with signage, lane markings, and GPS-assisted navigation is challenging, and the capabilities such companies have achieved are impressive. However, typical expeditionary military operations take place in unstructured environments, where GPS data may be denied, maps may be inaccurate or non-existent, and the line between what is and isn't an obstacle is blurry. Expeditionary navigation refers to negotiating a path through an unconstrained space where the possibility of directly traversing from point A to point B is not guaranteed. Additionally, one cannot make the same assumptions about the behaviors of pedestrians and other vehicles in an expeditionary environment. For example, vehicles may not obey local traffic laws, if they exist, and pedestrians and other vehicles may be allies or enemies. Finally, it may be necessary to operate covertly, relying on passive sensing alone for navigation. The MAGV program has developed capabilities to address the challenges of autonomous navigation, including perception, obstacle avoidance, route planning, and coordinated behaviors between autonomous vehicles.

1.2 Get off-road

Roads are continuous planar surfaces that are traversable, generally free of obstructions, well-defined, and frequently include traffic control devices (e.g. signs, lights, lane markings). Paved roads have distinct edges and other features that aid machine perception. This provides a structured environment that permits the system to make assumptions about the environment which eases the sensor processing, world modeling, and behavior generation problems. These assumptions

*bruch@spawar.navy.mil

Unmanned Systems Technology XIX, edited by Robert E. Karlsen, Douglas W. Gage, Charles M. Shoemaker,
Hoa G. Nguyen, Proceedings of SPIE Vol. 10195, 101950E · © 2017 SPIE
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2267705

do not hold when driving in off-route, expeditionary environments. Off-road navigation requires perception and detection of clear, traversable spaces, which may have surfaces consisting of, but not limited to, dirt, rock, sand, grass, mud and ice. Environments may be constricted, such as in woodland areas, but still passable. Terrain may be rough (e.g. rocky, covered in low-profile debris, full of long grass), but still navigable for certain classes of larger vehicles. Thus, more detailed models of the support surface and probabilistic sensor fusion capabilities to reason about which sensor noise an autonomous vehicle can safely ignore and which sensor "noise" represents a solid object hiding on an undulating surface are needed.

1.3 Day/night capable

Expeditionary activities for the military are not limited to daylight hours, and hence providing the proper sensing capability for night operations and for low-visibility conditions is necessary. Furthermore, the vehicle must be able to navigate using only those sensors which provide useful information under low visibility. Use of Light Detection and Ranging (LIDAR) or other active sensing may make vehicles too easily detectable by night vision equipment, so during covert operations, vehicles will require signature management or must rely solely on passive sensing. The ability for the autonomous vehicle to perform in a gracefully degraded manner under a variety of both environmental and operational environments is critical to the utility of such systems for the military.

1.4 Affordability

Historically, the autonomous ground vehicle community has relied on the use of many high-cost sensors and computers to enable autonomous navigation capabilities[4-6]. While such individual systems may function well, it is cost-prohibitive to build, field, and maintain large quantities of expensive systems. Additionally, such systems are more fragile and vulnerable as well as expensive to retrofit with new sensors as they become available. By using low-cost sensors, open architectures, and maintaining Government-purpose rights to source code, autonomous systems can be more easily transitioned to and deployed with the military.

1.5 Low-cost sensors

The state-of-the-art color stereo vision systems, long-wave infrared (LWIR) cameras, ultrasonic range finders, LIDAR sensors, and Inertial Navigation Measurement (IMU) packages have become much more affordable in recent years such that retrofitting vehicles is economically feasible, and such sensors are readily available from the commercial sector. Thus, the focus of the MAGV program has been capability development using existing sensors, not fundamental research in sensor technology. However, such sensors are not perfect and have their limitations. One of the key challenges in this program has been properly fusing sensor information and accounting for uncertainty in sensing so that decision-making algorithms perform robustly. For example, under certain circumstances, such as in low-visibility situations, images from visible-spectrum stereo cameras may provide little information and so data from LIDAR and LWIR cameras may be more dependable. However, in daylight, it may be beneficial to rely more heavily on RGB camera data. An autonomous expeditionary vehicle requires an appropriate sensor package that facilitates perception regardless of the level of visibility and operational environment.

1.6 Maintainability

In addition to using low-cost components, an expeditionary autonomous vehicle needs to be easily maintainable when fielded. Developing a completely new platform is cost-prohibitive, thus the MAGV program used a commonly available expeditionary vehicle, the HMMWV, and added autonomous capabilities to it. In addition to cost savings, using previously fielded platforms ensures our forces already have experience maintaining such platforms in the field, along with the necessary supply chains that provide replacement parts. Additionally, the autonomy applique' kit components should be modular and easily replaced when necessary. The MAGV perception sensor head shown in Figure 1 is modular and permits easy replacement of damaged sensors.

Figure 1. MAGV perception sensor head mounted on a HMMWV.

Maintenance of the software systems will be equally important for a fielded autonomous ground vehicle. Calibration of the sensor and software systems on such vehicles has long been a tedious and arduous process even for the scientists and engineers that develop them. The MAGV program has invested in the development of more streamlined processes for some components of the system such as stereo vision calibration but much more remains to be done is this key area.

1.7 Government source code rights

Government-purpose-rights (GPR) to all source code ensures that the Government does not get locked into exclusive contracts (vendor lock), and also ensures that features of capabilities developed by one performer can be used by another (within the Government program). The availability of the source code to all performers means that well-functioning features can be leveraged by all, and speeds up overall development. It also gives the Government the flexibility, insight, and agility needed to respond to uncertainty in the challenging S&T environments and permits the Government to transition the software to other programs and organizations. The GPR paradigm does allow the performers to maintain their IP in the commercial sector and therefore an additional incentive to develop well formed, transition-ready software.

1.8 Future technology base

One major outcome of the MAGV program has been the development and implementation of a highly modular suite of autonomous capabilities and behaviors that have been tested, verified, and validated in a realistic expeditionary environment. This suite of autonomy behaviors and capabilities can now be readily leveraged by both future S&T programs across the DoD R&D enterprise and military programs ready to transition today's capability into the field. Figure 2 shows one of the HMMWV test platforms. The MAGV autonomy applique' kit has been designed to be vehicle agnostic so that it could be installed on a large range of vehicles with minimal vehicle-specific tuning required to account for vehicle geometries and dynamics and actuation response times.

Figure 2. One of three HMMWV testbeds used in the MAGV program.

2. PROGRAM STRUCTURE AND PERFORMERS

The MAGV program structure consisted of performers from both the U.S. Naval Research and Development Enterprise (NRDE) and private industry responsible for developing individual capabilities, and a U.S. Naval laboratory responsible for integration, test, and experimentation of the capabilities on Government furnished platforms. By structuring the program so that individual performers are responsible for the development of well-defined individual functional capabilities, all using a common architecture maintained by the Government lead integrator, dependencies between performers were minimized. This reduced overall risk in that a delay by one performer did not hold up development from others. It also encouraged cooperation between the performers since they were not competing against each other but rather against the previous baseline capability of the overall system.

2.1 Government lead systems integrator, test and experimentation

SPAWAR Systems Center Pacific (SSC Pacific) has served as the Government's lead systems integrator, as well as its testing and experimentation lead. During this program, SSC Pacific developed a systematic process for integrating, testing and validating capabilities for unmanned vehicles that facilitates rapid and agile development of capabilities while decoupling the technology maturation and integration processes. SSC Pacific also developed automated test tools for use during developmental testing which provided performers with quantitative feedback immediately after each test event, enabling performers to make improvements, sometimes even between successive test events on the same day.

2.2 NASA Jet Propulsion Laboratory (JPL)

The NASA Jet Propulsion Laboratory (JPL) served as the primary developer of advanced perception capabilities. Perception capabilities include ground and object segmentation, negative obstacle detection, terrain classification, roughness detection and fusion of this information into the vehicle's world model. Under this effort, JPL developed novel methods for calibrating LWIR stereo cameras and for cross-calibrating color stereo and LIDAR sensors, negative obstacle detection, roughness detection, terrain classification and stereo map evaluation. In addition to leading perception capability development, JPL, in collaboration with SSC Pacific, developed a novel mission planning framework for coordinated control of heterogeneous teams of unmanned and manned systems with associated mission-specific payloads, based on business process logic. JPL and SSC Pacific were awarded a provisional patent on this framework.

2.3 Southwest Research Institute (SwRI)

The Southwest Research Institute (SwRI) was the primary developer of the world model. They leveraged previous work from the Small Unit Mobility Enhancement Technology (SUMET) program, and refined the world modeling capability developed therein. In this program, SwRI enhanced the three-dimensional voxel representation of the world used in the SUMET program by adding persistent data into the world model, and introducing *a priori* side-slope detection based on elevation map and vehicle trajectory data. In addition to maintaining a model of the system's operating environment, the world model is used to generate cost maps used by the navigation planner.

2.4 Neya Systems

Neya Systems was the primary developer of vehicle behavior generation. Neya breaks up autonomous navigation planning into higher-level maneuver planning (route planning) and lower-level reactive planning (obstacle avoidance). As part of behavior generation, Neya developed an adaptive traversability capability that mitigates world model and cost map noise and errors that adversely affect path planning. Neya also enhanced its path planning capability by implementing a wheel placement strategy for generating safe and efficient planned trajectories for negotiation of complex, rough terrain at low speeds.

3. KEY TECHNICAL ACCOMPLISHMENTS

Accomplishments made by individual performers and the government lead integrator under the MAGV program include advancements in sensor fusion, IR camera calibration, improved world modeling using persistent data, advancements in vehicle motion planning incorporating explicit wheel placement, implementation and demonstration of coordinated maneuvers with multiple vehicles, and development of a strategy for agile and rapid evolution of platform-based system-of-systems. These key accomplishments are described below.

3.1 Perception

In order to successfully navigate autonomously in any terrain, a vehicle must know its pose, orientation and the locations of obstacles it must maneuver around while traversing a route. Further, explicit detection of roads and paths is critical for missions which require the system to stay within a prescribed lane, such as when performing route clearance. Perception requires fusion of data from on-board sensors in real time to extract information about the vehicle's environment, as well as its location and orientation within the environment. On-board sensors used in the MAGV program include color stereo cameras, LWIR stereo cameras, and LIDAR for perception and IMU, odometry, and GPS for localization. During passive mode, only the stereo color and LWIR cameras are used for perception.

Key technical accomplishments in perception include novel calibration methods for LWIR cameras and extrinsic LIDAR-to-camera calibration, negative obstacle detection, terrain classification, roughness detection, stereo map evaluation and fusion of perception data into the world model for use by the navigation planner.

Proper sensor operation requires calibration. During the course of this program JPL developed novel LWIR stereo camera and extensive LIDAR-to-camera calibration methods. The LWIR calibration method follows a procedure similar to that used for visual-spectrum cameras[7], but uses "active" calibration targets that generate thermal signatures in dot and checkerboard patterns using low-resistance resistors and standard white LEDs, respectively[8]. The LIDAR-to-camera calibration method matches points from color or LWIR stereo camera-produced 3D point clouds to points in a LIDAR-scan point cloud using a two-part correspondence method as described[8].

Even when properly calibrated, low-cost cameras can have poor dynamic range, presenting problems for the stereovision algorithms, such as loss of texture, resulting in low disparity densities which in turn results in incomplete or noisy cost maps. Fusion of LWIR camera stereo disparity helps compensate for holes in the color camera disparity. The auto-exposure algorithm has also been optimized for the stereovision algorithm requirements, including for texture, stability, and synchronization.

Pre- and post-filters were developed to improve stereo accuracy. The pre-filters condition the imagery for improved disparity density. For LWIR images, a subsampling pre-filter step mitigates the low signal-to-noise ratio in the data. Post-filters remove spurious disparity points to decrease the number of false positives in the range data. Finally, a multi-resolution consistency check compares the disparities at multiple resolutions to mitigate noise from repeated textures. Figure 3 shows an improved cost map with fused sensor data.

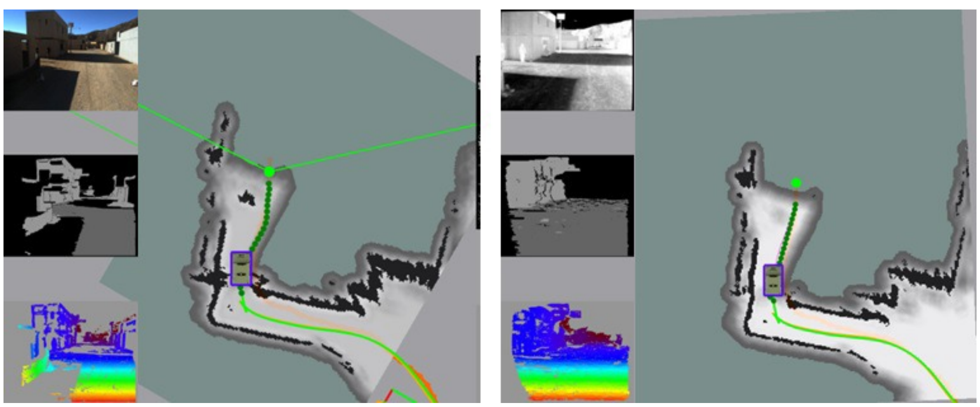

Figure 3. Comparison of cost maps with independent data handling (left) and probabilistic sensor fusion, including IR data (right). The map on the right is cleaner and has fewer false detections of obstacles.

JPL used color stereo imagery for terrain classification and detection of both surface roughness and negative obstacles. Though not yet implemented on the autonomous vehicle, JPL demonstrated a deep convolutional neural network approach to terrain classification using the MultiNet architecture[9] and a dataset of 1492 labeled images where the labeled images were not precisely annotated, rather, general areas were marked. Though quantitative results are not yet available, qualitative results are available[8] that show the CNN classifier learns dense labeling through sparse annotations and produces more accurate classifications than ground truth comparison images.

To detect surface roughness, local height variances are estimated from each disparity image, and these attributes are provided to the world model. Detection of negative obstacles, specifically steep declines off trail edges and abrupt drop offs, was accomplished by identifying the horizon in each color stereo image and then identifying no-range pixels below the horizon in each image. After additional processing, regions determined to be drop-offs or steep declines were marked as having increased/high cost in the vehicle's cost map. Details on methods for segmentation, terrain classification, surface roughness detection and negative obstacle detection are available[8].

To segment sensor data into ground and object groups, data from each sensor is first segregated separately and then aggregated into 2D (ground) and 3D (object) grids in the world model. Once the data is segmented and pre-processed into the knowledge products described above, JPL used inverse sensor models and a log odds update function to probabilistically fuse stereo color camera data, stereo LWIR camera data, and LIDAR data into the world model. This approach enabled the vehicle to intelligently model the support surface and to decide what is traversable in off-route environments through cost-map generation.

3.2 World Model

Key accomplishments in world modeling include incorporation of persistent data into the vehicle's cost map, and incorporation of elevation data for *a priori* slope detection. Terrain features not directly observable due to sensor geometry or absence of clear indicators (e.g. side slopes) represents a unique challenge for unmanned systems. Limited sensor horizon impedes the ability of an autonomous vehicle to select optimal trajectories for negotiating congested environments. Persistent data extends the sensor horizon by continuously fusing sensor and map data into a persisted map structure and re-optimizes the global map to maintain consistency and improve accuracy.

Persistent data is added to the world model as follows. Initially, the vehicle starts out with a rudimentary map, such as generated from the OpenStreetMap route network[10], and a set of waypoints it must follow. As it traverses an area for the first time, the initial data collected from its sensors populates its world model with features such as obstacles. This information is used for subsequent route planning. As the vehicle makes multiple trips through a given terrain, current sensor data is continually registered with older data using phase correlation techniques, and is fused into the persistent map using polygon decomposition and nonlinear least-squares optimization. This continuous fusion of data helps mitigate the exacerbation of the data association problem related to registration of overlapping but non-sequential maps caused by position uncertainty. It also improves localization in GPS-degraded environments. Figure 4 shows cost map improvements with persistent data.

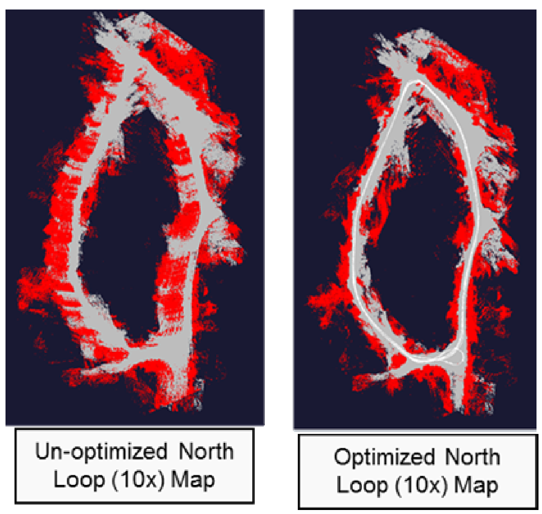

Figure 4. Vehicle cost maps with (right) and without (left) persistent data. The North Loop is a test route.

An additional enhancement developed during this program was the incorporation of elevation data into the world model. In the approach taken here, SwRI obtained the three-dimensional paths the vehicle took from its inertial measurement unit data and registers it on an existing elevation map, again using phase correlation. This provided robust absolute position estimates, as well as estimates of slopes that can be used for later route planning.

Details on these accomplishments are available[11].

3.3 Behavior generation

Key accomplishments in behavior generation include development and demonstration of a hierarchical planning system and kinematic models, development of an adaptive traversability capability, and inclusion of wheel placement planning. These capabilities are required for the vehicle to execute behaviors such as multi-point turns and precise wheel placement in off-route, congested, expeditionary environments. The planning system also provides hard and soft constraints that enable the vehicle to drive off a prescribed path and circumvent untraversable objects and features.

The higher level of the hierarchical planning system is the maneuver planner. In the maneuver planner, an “anytime incremental search” is performed on a multi-resolution dynamically-feasible lattice state space[12-13]. The lattice state space is a discretization of the configuration space into a set of states and connections between these states, where every connection represents a feasible path. A receding horizon model-predictive control (RHMPC) is used to generate the feasible actions between states[14]. Given an initial and a goal state (e.g. a starting waypoint and ending waypoint), an Anytime Dynamic A* search[15] is used to generate a trajectory. This approach successfully generates trajectories for maneuvers in congested environments, such as k-point turns, while minimizing the number of segments and durations of the maneuvers.

The lower level of the hierarchical planning system is the reactive planner. Given the trajectory from the maneuver planner, RHMPC is used to track the trajectory from the lattice planner while avoiding obstacles. It does this by repeatedly simulating vehicle behavior using imperfect models of the vehicle and the world over a small time horizon to determine the “best” control inputs (e.g. velocity and steering angle) by evaluating the generated trajectories based on a heuristically-derived cost function. One of the key additions to this cost function during the MAGV program is the inclusion of terms in the cost function to account for wheel motion and acceleration for explicit wheel placement. Additions include terms that account for the jolt of each wheel, vehicle roll and pitch, and underbody clearance. Figure 5 shows a wheel placement experiment. Details on wheel placement reasoning are available[16].

Figure 5. HMMWV testbed during wheel placement planning test.

Both levels of the hierarchical planner require information from the vehicle’s cost map and world model. Noise and errors in both contribute to inaccurate planning, or plan generation failure. Neya Systems developed an adaptive traversability capability that uses an online learning strategy to improve cost map estimation. Passive sensor data collected during successful vehicle traversals is used as a training signal. Dynamic features perceived by the vehicle, such as ground smoothness, vertical smear, and mean height are combined with the fixed-perception cost map to generate an improved cost map. Details on adaptive traversability are available[17].

3.4 Coordinated tactical behaviors

During this program, SSC Pacific and NASA JPL developed a novel mission planning framework to coordinate the control of heterogeneous teams of unmanned and manned systems with associated mission-specific payloads. This framework leverages business process logic to develop executable mission models to coordinate tactical behaviors. In the Mission Modeling, Planning, and Execution Module (M2PEM) framework, the mission planner defines how a mission should be executed using an existing library of (low-level) tasks and actions. For the FY16 ONR 30 Modular Explosive Hazard Defeat System (MHEDS) program demonstration, the MAGV program implemented a number of vehicle tasks and actions specific to route clearance including route sweeping, formation following, bridge traversal, re-shuffling, stop-on-detect, and controlled stop. Also included were payload actions, such as observe area, observe point, observe route, suppress detections, and enable neutralizer. The execution engine performs the mission described by the mission planner. The modeling component, still under development, will provide formal validation by formulating the system described by the mission planner, ensuring that the mission is feasible given the system and that the mission plan satisfies a set of requirements. SSC Pacific and JPL have submitted a provisional patent on this framework. Details on M2PEM are available[18].

SSC Pacific also developed a cooperative path planning framework for the adaptive formation control of multiple vehicles navigating along a desired, unknown route where spatial and temporal objectives must be considered. This includes the ability to cooperatively navigate in complex, constrained environments in multiple formations such as staggered, line haul, and echelon. In the approach taken here, lateral and longitudinal planning occur independently. The lateral planning keeps each vehicle in a “lane-like” position with respect to the route, but permits vehicles to adjust their formation to avoid obstacles. Hence, coordination, kinematic, and spatial constraints are bounds on a single variable. The longitudinal planner employs reactive speed control to maintain spacing between vehicles. This permits incorporation of well-established techniques for coping with sluggish dynamics of large vehicles, and can be run at a much higher rate than lateral planning to ensure collision avoidance. Details on cooperative planning and coordinated behaviors are available[19].

The SSC Pacific team demonstrated cooperative fixed formation behavior and formation reconfiguration triggered by detection of a hostile entity during demonstrations at Fort A.P. Hill for the MEHDS program. The fixed formation behavior demonstrates the benefits of independent lateral and longitudinal path planning. In this demonstration, the leading autonomous vehicle traversed a route determined by waypoints, while the trailing vehicle maintained a safe distance behind it. Should the forward vehicle stop, the reactive speed control forces the trailing vehicle to stop. If the trailing vehicle stops or falls too far behind, the forward vehicle will wait for the trailing vehicle to catch up. Thus, the vehicles retain a bounded, safe distance from each other.

3.5 Unmanned Systems Integration, Test and Experimentation (UxSITE)

One of the challenges of MAGV program was coordinating the integration, testing, and validation of capabilities developed by several different performers on shared vehicle platforms. Under this program, SSC Pacific developed an Unmanned Systems Integration, Test and Experimentation (UxSITE) strategy that enables agile and rapid evolution of platform-based system-of-systems. The method smoothly incorporates capabilities developed by different performers and permits continuous vehicle maturation. In the system development V-model, the integration stream follows a unit testing – subsystem testing – system testing – verification – validation process that implies that all smaller pieces of a subsystem must be tested and verified individually before the larger, complete system can be verified. Under this model, one may assume that late development of a capability, unit or subsystem may hold up verification and validation of the entire system. In the UxSITE strategy, the same testing, verification and validation process occurs, but in a wave-like fashion rather than as a single maturation push (see Figure 6). Rather than wait for all components to be ready before integration and testing commences, integration and testing becomes a continuous, cyclic process in which a baseline system evolves. This baseline system remains functional throughout this process.

In this approach, the integration platform serves as a baseline testbed. When a performer develops a new capability, it is implemented on the testbed and the performance of the testbed under the new capability is compared with the baseline performance. Not only is performance assessed, but comparison against a baseline also facilitates understanding of performance tradeoffs and associated costs and provides a method of assessing whether functional requirements are being met. When the performer’s capability meets the functional requirements and demonstrates improved testbed performance, it is then integrated into the baseline testbed. Thus, the testbed continuously evolves and improves. Key to successful implementation of this methodology is the single lead integrator, who maintains the testbed and manages the interfaces and system architecture. Lessons learned and best practices for autonomous vehicle configuration management are detailed here[20].

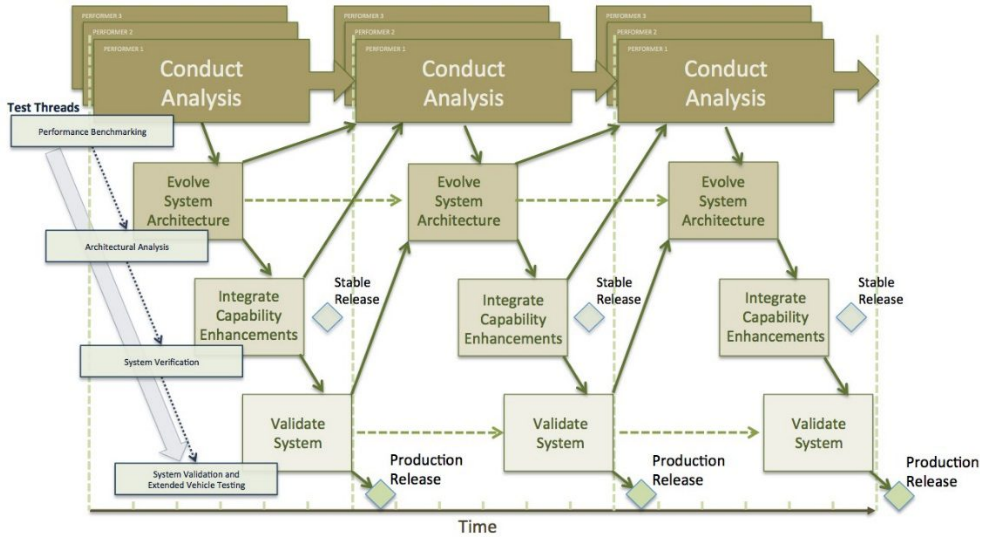

Figure 6. UxSITE integration wave model.

One of the core features of the UxSITE strategy is the incorporation of automated test tools that provide instant feedback to the performers and government team immediately following a test event (see Figure 7). The automated tool incorporates test data, a test and evaluation ontology for unmanned vehicles, and a web front end into its automated test framework. The ontology contains the test campaigns, test methods, test trials, types of events (e.g. safety stop, planner time-out), and auto-trigger configurations that are relevant to autonomous vehicles. During testing the automated test framework triggers events when their auto-trigger conditions are met, along with a timestamp and, in some cases, an image of the associated test data. The triggered events are put into the test timeline and the user has the ability to manually annotate the events. Once a single test run is complete, a report containing a timeline with events that occurred during the test can be automatically generated. The report can be configured to include statistics and comparisons of results from multiple tests of the same type (e.g. 10 runs of a given test type).

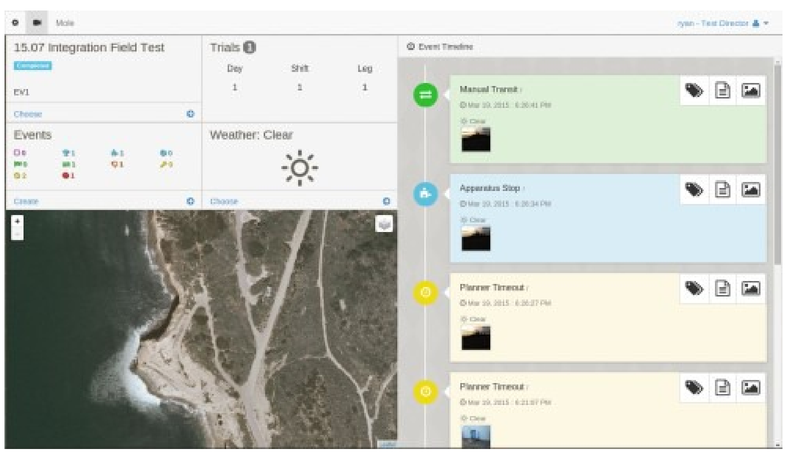

Figure 7. Web-based front-end of the Automated Test Tool.

Details on the UxSITE strategy and automated test tools are available here[21].

3.6 Key demonstrations

Two demonstrations in fiscal year 2016 showcased the autonomous expeditionary vehicle capabilities developed under the MAGV program.

3.7 May 2016 at Camp Pendleton

Capabilities developed under the MAGV program were demonstrated to the ONR Code 30 Department Head and Military Deputy at Camp Pendleton, CA in May of 2016. This demonstration included single autonomous vehicle navigation on both dirt trail and congested urban-type environments. This demonstration featured improved sensor fusion and improvements to the cost map from incorporation of persistent data. It also highlighted the vehicle's ability to perform congested maneuvers using the lattice planner. Two HMMWVs driving in staggered formation through an obstacle course with a 4-meter lateral offset was also demonstrated (see Figure 8).

Figure 8. Staggered formation control demonstrated at Camp Pendleton, CA.

3.8 September 2016 at Fort A.P. Hill

Key capabilities developed under the MAGV program were also highlighted at the Mobile Explosive Hazard Defeat System (MEHDS) technical demonstration at Fort A. P. Hill, VA, in September 2016. Attendees at the demonstration included a large number of senior military and DoD officials. During this exercise, the MAGV core capabilities formed the foundation for autonomous maneuver driving and coordinated mission planning for all the vehicle platforms. In addition to two HMMWVs, the MAGV core capabilities were installed and demonstrated on the Small Reconnaissance and Detection Expendable Rover (RaDER), created jointly by SSC Pacific and Naval Surface Warfare Center Panama City Division (NSWC PCD). The technical achievements highlighted at the Camp Pendleton demonstration in May 2016 played more of a supporting role during this demonstration by providing the autonomy needed for performers under the MEHDS program to highlight their detection payload capabilities. The line-haul and formation reconfiguration coordinated behaviors discussed above were featured during this demonstration. Figure 9 shows the formation reconfiguration demonstration.

Figure 9. Technical demonstration of autonomous capabilities at Fort A.P. Hill, VA.

3.9 Transitions

Under the ONR Code 30 MAGV program a substantial autonomous ground vehicle technological base has been established. The technology has already begun to transition to other organizations for both further S&T development as well as for experimentation and military utility assessments. The U.S. Army's Tank and Automotive Research and Development Command (TARDEC) has leveraged the initial ONR Code 30 autonomy baseline software package for a number of programs including the Distributed Soldier Autonomy Toolkit (DSAT) and Robotic Toolkit (RTK) efforts. The technology is also leveraged via the individual performers on the program such as Neya Systems applying the maneuver-level path planner to the DARPA Squad-X and Fuel and Water Transport programs. SSC Pacific is applying the test and experimentation methodologies established under the MAGV program to the DARPA Cross Domain Maritime Surveillance and Targeting (CDMaST) program.

4. FUTURE DIRECTION AND CONCLUSION

The key technical achievements described above can be leveraged for future DoD S&T work. SSC Pacific is applying technologies and methods developed under the MAGV program to a new ONR Code 30 autonomy program, as well as building on the perception, behavior generation and mission-level autonomy planning technologies in future S&T research.

4.1 Unmanned Swarming Autonomous Amphibious Craft (USAAC)

The FY17 new-start ONR Code 30 Unmanned Swarming Autonomous Amphibious Craft (USAAC) program seeks to develop low-cost, small, autonomous amphibious vehicles capable of performing missions in the surf zone as well as on land. The Government is outfitting small commercial amphibious vehicles (Gibbs Quadskis) with drive-by-wire kits that will be furnished to selected performers, who will use the platforms as testbed prototypes for autonomy capabilities they develop. Components of the MAGV autonomy program will be used as a baseline system for the USAAC program. The Government will also employ the UxSITE methods and process for the testing and experimentation efforts under the program.

4.2 Future S&T investments

4.2.1 Semantic Perception

Under the MAGV program efforts were made to use multi-spectral analysis of fused image data to detect, segment, and classify materials and semantic features under varying environmental conditions. It proved successful to a degree but the system was brittle when exposed to significantly different environments and was susceptible to over training. Beginning in FY17 a new effort will be kicked off to explore the use of deep learning to detect and classify features in the environment and to specifically research methods of applying deep learning systems training in one sensor modality to other modalities where large training data sets are not available.

4.2.2 Advances in behavior generation

Future work in behavior generation and complex maneuvers includes further refinements to vehicle path generation with explicit wheel placement, as well as planning that includes 3D terrain information. Future work in explicit wheel placement includes refinement of wheel tire models, and improvements of computation efficiency so that the vehicles can navigate through complex rough terrain at full speed. A key addition to maneuver planning using 3D terrain information includes development of appropriate behaviors for soft soil mobility.

4.2.3 Mission-level autonomy

Current limitations to the M2PEM framework include its centralized design, added latency, and brittleness to error. Currently, M2PEM requires full communication to all vehicles for the mission to advance. Additionally, errors such as false detection and noise propagate and adversely affect precision, navigation and timing. Future work in this area will develop distributed execution of missions, permitting mission advancement robust to poor communications. This will require synchronization of missions or parts thereof between platforms. Improvements to mission verification will include checking for deadlocks and invalid tasks, and will include verification with a model checker. Further expansion will include a resource allocation algorithm that will assign tasks to the appropriate platforms.

4.3 Conclusion

The ONR Code 30 Ground Autonomy program (MAGV) has made many significant advances in off-road autonomy in the areas of perception, world modeling, behavior generation, multi-vehicle coordinated behaviors, mission autonomy, and in the integration, testing, and experimentation system-of-systems systems engineering domains. All of these capabilities and advances have been integrated and demonstrated on a fleet of militarily relevant vehicle testbeds and established a technological base for future Government S&T programs to build upon. Key to the success of this effort was the development and application of the UxSITE strategy, which enabled rapid, agile development facilitated by a single lead systems integrator. ONR Code 30 plans to continue a robust investment in the research and development of autonomous capabilities for the USMC and Naval expeditionary forces.

REFERENCES

[1] "When Cars Drive Themselves," The New York Times. 14 December 2017. https://www.nytimes.com/interactive/2016/12/14/technology/how-self-driving-cars-work.html (13 March 2017).

[2] McFarland, M., "2016: A tipping point for excitement in self-driving cars," CNN, 21 December 2016, http://money.cnn.com/2016/12/21/technology/2016-year-of-autonomous-car/ (13 March 2017).

[3] Barr, A., and Bergen, M., "One Reason Staffers Quit Google's Car Project? The Company Paid Them So Much," Bloomberg, 13 February 2017. https://www.bloomberg.com/news/articles/2017-02-13/one-reason-staffers-quit-google-s-car-project-the-company-paid-them-so-much (13 March 2017).

[4] Thrun, S., Montemerlo, M., Dahlkamp, H., Stavens, D., Aron, A., Diebel, J., Fong, P., Gale, J., Halpenny, M., Homann, G., et al., "Stanley: The robot that won the darpa grand challenge," Journal of Field Robotics 23(9), 661-692 (2006).

[5] Leonard, J., How, J., Teller, S., Berger, M., Campbell, S., Fiore, G., Fletcher, L., Frazzoli, E., Huang, A., Karaman, S., et al., "A perception-driven autonomous urban vehicle," *Journal of Field Robotics* 25(10), 727-774 (2008).

[6] Urmson, C., Baker, C., Dolan, J., Rybski, P., Salesky, B., Whittaker, W., Ferguson, D., and Darms, M., "Autonomous driving in traffic: Boss and the urban challenge," *AI magazine* 30(2), 17 (2009).

[7] Zhang, Z., "A flexible new technique for camera calibration," *IEEE Transactions on pattern analysis and machine intelligence* 22 (11), 1330-1334 (2000).

[8] Zapf, J., Ahuja, G., Papon, J., Lee, D., Nash, J., and Rankin, A. "A Perception Pipeline for Expeditionary Autonomous Ground Vehicles," in *Proceedings of SPIE*, Paper 10195-14 (2017)

[9] Teichmann, M., Weber, M., Zoellner, M., Cipolla, R., and Urtasun, R., "Multinet: Real-time joint semantic reasoning for autonomous driving," *arXiv preprint arXiv:1612.07695* (2016).

[10] Haklay, M., and Weber, P., "OpenStreetMap: User-Generated Street Maps," *IEEE Pervasive Computing* 7 (4), 12-18 (2008).

[11] Johnson, E., Alban, M., Garcia, R. D., and Kozak, K., "Augmenting autonomous vehicle sensor processing with prior data," *Proceedings of SPIE*, Paper 10195-18 (2017).

[12] Pivtoraiko, M., Knepper, R. A., and Kelly, A., "Differentially Constrained Mobile Robot Motion Planning in State Lattices," *Journal of Field Robotics* 26 (3), 308–333 (2009)

[13] Likhachev, M., and Ferguson, D., "Planning long dynamically feasible maneuvers for autonomous vehicles." *The International Journal of Robotics Research* 28(8), 933-945 (2009).

[14] Howard, T. M., Green, C. J., and Kelly, A. "Receding horizon model-predictive control for mobile robot navigation of intricate paths." *Field and Service Robotics*. Springer Berlin Heidelberg, 2010.

[15] Likhachev, M., Ferguson, D., Gordon, G., Stentz, A., and Thrun, S. "Anytime search in dynamic graphs." *Artificial Intelligence* 172 (14), 1613-1643 (2008)

[16] S. Gill, J. S., Capodieci, A., and Ollis, M. D., "Wheel placement reasoning in complex terrain," *Proceedings of SPIE*, Paper 10195-17 (2017).

[17] Allmen, M., and Hassman, M., "Adaptive terrain traversability estimation using passive sensing," in *Proceedings of SPIE*, Paper 10195-16 (2017).

[18] De la Croix, J. P., Lim, G., Hook, J.V., Rahmani, R., Droge, G.N., L. Xydes, A. L., and Scrapper, C. J., "Mission planning, execution and modeling for teams of unmanned vehicles," *Proceedings of SPIE*, Paper 10195-19 (2017).

[19] Droge, G. N., Xydes, A. L., Scrapper, C. J., and Rahmani, A., "Adaptive formation control for route-following ground vehicles," *Proceedings of SPIE*, Paper 10195-20 (2017).

[20] Denewiler, T., "Best practices for autonomous vehicle configuration management," *Proceedings of SPIE*, Paper 10195-23 (2017).

[21] Halterman, R., and Scrapper, C. J., "A systematic approach to autonomous unmanned system experimentation," *Proceedings of SPIE*, Paper 10195-22 (2017).