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DISMOUNTED SOLDIER AUTONOMY TOOLS (DSAT) – FROM CONCEPTION TO DEPLOYMENT

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Abstract

The Dismounted Soldier Autonomy Tools (DSAT) program is the result of the evolution and reuse of work from multiple industry Internal Research & Development (IR&D) programs, as well as work stemming from various multi-service investments made over the past several years. The DSAT program is a direct offshoot of MARTI (Mobile Autonomous Robotics Technology Initiative) - a 5 year IR&D program at Southwest Research Institute (SwRI) from 2006-2011 that created a foundation for autonomy and on road capability. The MARTI work was subsequently leveraged into the Office of Naval Research (ONR) Code 30 SUMET (Small Unit Mobility Enhancement Technologies) program starting in 2009. The DSAT program builds off of these SwRI efforts, as well as previous work by TARDEC and DCS Corp in the areas of vehicle architectures and warrior-machine interfaces to build a consolidated, coordinated program. Working together, the team has made several improvements to the collective code base, resulting in new capabilities and increased modularity for new development. Through this Government/Industry collaboration, the DSAT program is able to maximize multi-service DoD spending by leveraging these previous investments and sharing technologies and capabilities among the ongoing TARDEC and ONR Code 30 multi-team development activities..

1 INTRODUCTION

The DSAT program has developed and integrated unmanned platform capabilities through the fusion of multiple sensors, including visual, multi-spectral, LADAR, and ultra-wideband (UWB) to enable the seamless interaction of an unmanned platform with dismounted Soldiers. This advanced perception system (APS) was leveraged and matured from a $12M Navy ONR-30 program titled Small Unit Mobility Enhancement Technologies (SUMET). Additionally, DSAT utilizes the Autonomous Mobility Appliqué System (AMAS) methodology of A-kits and B-kits (see Autonomy below), with a common A-kit for multiple B-kit enabled platforms. DSAT was designed with various CONOPS in mind for the operator, including day/night surveillance and over-watch, squad offloading of heavy or excess equipment, hasty line breach by utilizing the Anti-Personnel Obstacle Breaching System (APOBS) launching system, and perimeter security. It fulfills these roles by providing a number of capabilities, including multiple Soldier/vehicle following modes (direct, exact, and smart following), teleoperation, driving aids for teleoperation, dynamic waypoint navigation, Soldier/vehicle push (robot lead), point-and-go, and retro-traverse (return upon exact route).

DSAT is a collaborative program between TARDEC Ground Vehicle Robotics, Southwest Research Institute, and DCS Corporation. Each organization is responsible for specific tasks related to hardware and software development, vehicle integration, and testing. The capabilities required to enable the primary DSAT mission set also enable (and serve as risk reduction for) the Squad Mission Equipment Transport (SMET) program of record.

2 TIMELINE

The DSAT program does not exist in a vacuum, but was based on over a decade of autonomy and controller work done at TARDEC in robotics through the various organizations that evolved to become Ground Vehicle Robotics (first Vetronics, then Intelligent Systems, then Intelligent Ground Systems, and finally Ground Vehicle Robotics). Adding to this mix was control experience from DCS Corp gained from over 20 projects and autonomy experience from SwRI gained from over 8 programs, all of which formed a solid foundation for the program. Figure 1 shows pictorially the TARDEC programs that lead up DSAT and the spin-off efforts that follow.

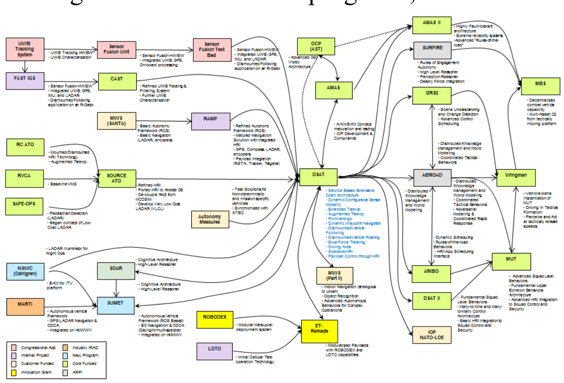


Figure 1. Evolution of DSAT

This precursor work was heavily referenced during program formulation, then leveraged as a baseline for Program Execution, which eventually led to a successful deployment for Combat Assessment.

2.1 Precursor Work

The following is a summary of the autonomy and control work that laid the foundation for DSAT.

2.1.1 Autonomy

From the DSAT perspective, autonomy refers to the software, hardware, and design documents required to build an autonomous system. These are separated into two primary elements: the A-kit, which comprises the sensing and thinking components; and the B-kit, which comprises the vehicle-specific and actuation components. This A-Kit/B-kit concept is described more fully in the architecture section. This autonomy system evolved from several prior efforts by the three contributors to DSAT.

2.1.1.1 MARTI

Southwest Research Institute (SwRI®) initiated a $5 million internal research and development program in late 2006 to investigate and develop sensor/computing/mobile technologies to augment vehicle platforms and provide autonomous vehicle capabilities to improve safety in urban and traffic environments. Through the Mobile Autonomous Robotics Technology Initiative (MARTI®), SwRI is developing technology associated with the autonomous control of cars, trucks, and tractors. SwRI began the MARTI program by conducting an extensive survey of the current state of the art. This included an analysis of existing technology, current relevant research, and the technology gaps that existed in industry. SwRI engineers identified cutting-edge hardware (including some prototype sensors) and developed modular and scalable

Figure 2. MARTI at 2008 ITS World Congress in New York City

software algorithms that resulted in a fully autonomous ground vehicle capable of negotiating a complex urban environment.

Within 12 months, the sensors were integrated; preliminary object identification, classification, and tracking algorithms were developed; and the vehicle was under computer control. The vehicle was capable of operating autonomously around the SwRI test track at various speeds. Within 18 months, MARTI was negotiating intersections in mixed traffic while obeying traffic laws. The system was demonstrated at the ITS World Congress (New York City) in November 2008, alongside Stanford University/VW.

In September of 2009, at the TARDEC Robotics Rodeo at Fort Hood, SwRI demonstrated TRL-6 technology, with an autonomy level of 8+, developed to support the Army's convoy logistics Operational Needs Statement. The technology provides the ability for convoy operations to utilize a UGV in numerous ways. For example, a convoy can instruct a UGV to lead upon command and follow where appropriate in various formations, navigate an urban environment as

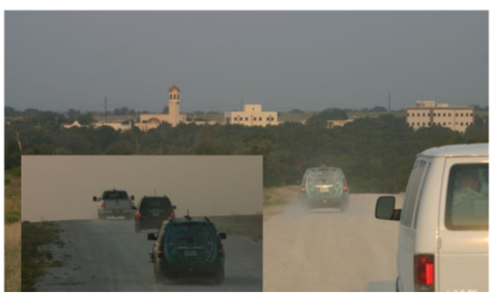


Figure 3. MARTI at 2009 Robotics Rodeo in Ft. Hood, TX

the lead of a convoy and then fall back into formation upon command, and rapidly switch between human operation and full autonomous modes. The Cooperative Convoy System (CCS) technology also enables a UGV to convoy using either GPS and a defined map or active sensors to track a leading vehicle. This technology is available for manned vehicles within the convoy as a SwRI-designed, portable kit, the manned vehicle conversion kit (MVCK). The kit contains relatively low-cost COTS hardware such as redundant communications for Line-of-Sight (LOS) and Beyond Line-of-Sight (BLOS) control, two low-cost Global Positioning System (GPS) units with custom data fusion algorithms enabling greater positional accuracy, and a small computer. The kit can be installed in virtually any manned vehicle in a matter of minutes.

For the October 2010 TARDEC Robotics Rodeo in Ft. Benning, GA, SwRI demonstrated additional MARTI capabilities showing dismounted pedestrian following, supervised autonomy, and teleoperation. SwRI also demonstrated an Operator Control Unit (OCU) to control the MARTI functionality from a separate manned vehicle, as well as transitioning between all of the possible MARTI levels of autonomy seamlessly, without needing to stop the vehicle to transition.

2.1.1.2 SUMET

Figure 4. SUMET EV-1 at 2012 Robotics Rodeo at Ft. Benning, GA

In support of the United States Marine Corps (USMC) Logistics-Connector Distributed Operations Mission and funded by the Office of Naval Research (ONR), Southwest Research Institute (SwRI) developed a low-cost electro-optical (EO) perception,

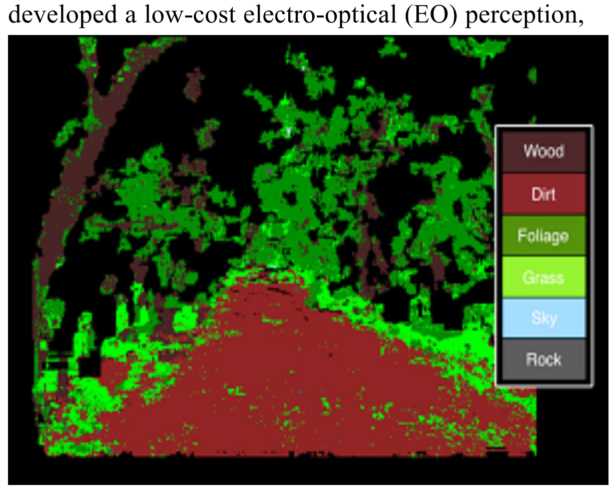


Figure 5. SUMET Material Classification Image

localization, and path planning algorithms for autonomous (driverless) vehicle operation in austere or harsh off-road environments, without dependence on GPS.

The SUMET (Small Unit Mobility Enhancement Technologies) program aimed to increase the platform capability and affordability of unmanned ground vehicle (UGV) enabling technologies by focusing on camera-based perception for full-size tactical vehicles. Major perception advances included material classification based on texture, spectral, and spatial signatures. The SUMET architecture was designed to be open, modular, scalable, and extensible and to allow for rapid realization of additional autonomous behaviors and the use of various sensor modalities.

The SUMET system achieved its goals by developing and employing low-cost EO (camera)-only perception, localization for GPS-denied operation, world model scalability, and near- and far-field path planning.

2.1.1.3 Fast-IGS

The purpose of this project was to integrate, enhance, and demonstrate a 360° Spatial Awareness system using ultra-wideband (UWB) tracking for dismounted following and mounted autonomous tactical behaviors.

This effort resulted in maturing existing UWB tracking technology to enable dismounted following with unmanned platforms, enhancing TARDEC's Robotic Controller to support the developed system, and updating TARDEC's R-Gator to Aware 2.0 and adding control capability for UWB dismount following. The project drastically reduced the amount of Soldier intervention required to take unmanned systems along in dismounted operations and provided 360° Spatial Awareness for all assets in the system (manned and unmanned). This was accomplished by providing the following capabilities:

1. Spatial Awareness—At any given time, any node (Soldier, UGV, manned vehicle, etc.) knows the relative spatial location of any other node within range of the system.

Figure 6. FastIGS System running at Soldier Battle Lab

2. Dismounted Operations—This includes Line-of-Sight (LOS) Blind Following, where the system controls the Dismount Platform in such a way as to maintain a specified distance from the Soldier while both leader and follower maintain LOS. (Here, Line-of-Sight is in the UWB-sense, meaning a robust UWB network connection between the Dismount Platform and the SMI system(s).) The system is also capable of switching leaders between two or more Nodes and the Dismount Platform.
3. Mounted and Dismounted Operations—The system allows safe operation of all Node-Equipped platforms, manned and unmanned. Safe operation is defined as follows: unmanned platforms take into consideration the positions of all the Node-Equipped platforms when planning their paths, and manned platforms are made aware of the spatial positions of all the Node-Equipped platforms through a display.

2.1.1.4 SOURCE

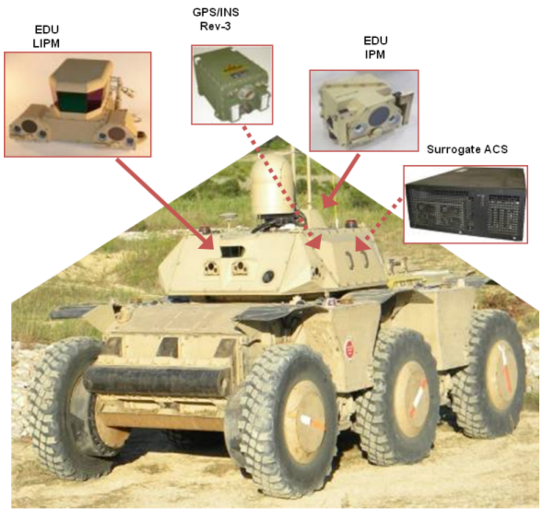


Figure 7. SOURCE APD

The focus of the GVR-led Safe Operations of Unmanned systems for Reconnaissance in Complex Environments (SOURCE) Army Technology Objective (ATO) was improving autonomy in on-road, urban environments. Key capabilities developed under SOURCE included lane following, rules of the road, and safe autonomous operation around pedestrians and manned vehicles. For sensing, the SOURCE system utilized the Autonomous Navigation System (ANS) hardware, which includes high resolution LADAR, as well as monochrome and color cameras. For navigation, the SOURCE team enhanced the baseline ANS planning algorithms to provide improved capability and performance. The SOURCE system was implemented on two distinct vehicle platforms: the Jeep Rubicon-based T2 and the Autonomous Platform Demonstrator (APD). While none of the technology from SOURCE was directly ported to DSAT, the fused sensing approach and platform independence were guiding principles in the design of the DSAT system.

2.1.2 Control

The DSAT Warrior Machine Interface (WMI) was built using a Soldier Machine interface (SMI) library developed by DCS Corp for TARDEC. The current library is the result of more than a decade of TARDEC-supported applied research and development in the area of scalable embedded controls and displays. This work began as an effort to increase automation in traditional manned crew-stations and has evolved to include support highly scalable and portable systems for autonomous vehicles.

2.1.2.1 VTT

The foundation for the current SMI was laid with the Vetronics Technology Testbed (VTT), a research project aimed at demonstrating the capability of a single crewmember to perform both vehicle commander and driver functions while performing a military-significant mission. Meeting this objective required a highly complex and integrated crewstation featuring multi-function displays with touch screens, a three-dimensional audio system, and a speech recognition and generation system.

To assist with development, DCS Corp developed the Adaptable Graphical Interface Library (AGIL) and the Weapon System Mapping Services (WSMS). AGIL abstracted the underlying graphics system such that an AGIL application could quickly and easily be transferred from a host development environment to an embedded target environment independent of the underlying graphical system or graphical hardware. All components of the AGIL were operating system independent and designed for real-time embedded environments. AGIL was modular and extensible providing for standard input, output and input/output devices, in addition to allowing the user to quickly implement new devices. AGIL also provided a simple-to-use transportable and extensible widget library, and a drag and drop screen builder with code generation for both C++ and Ada 95.

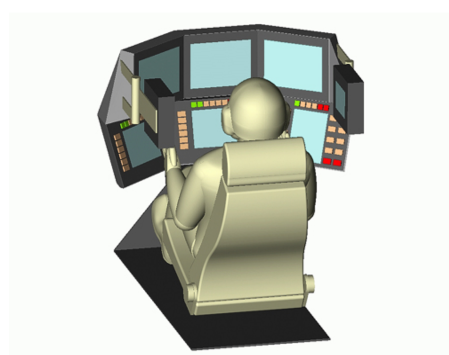


Figure 8. VTT Testbed

The WSMS was the first implementation of a common mapping services API developed by the Weapon System Technical Architecture Working Group (WSTAWG) and mandated by the Joint Technical Architecture to promote commonality and reuse among embedded mapping applications in ground systems. The WSMS has evolved as a separate technology and has been used across several technology demonstrators and fielded systems.

2.1.2.2 SOURCE

A precursor of the current DSAT controller was developed under the Safe Operations of Unmanned systems for Reconnaissance in Complex Environments (SOURCE) program. Under this TARDEC-sponsored effort, DCS Corp developed a dismount user interface to provide the operator with control of an unmanned ground vehicle, allowing the operator to work more closely alongside the vehicle. From the controller, the operator was able to create and execute mission plans, teleoperate the vehicle, and access both fixed and slewable sensors. The controller provided vehicle status and alerted the user in response to fault conditions on the platform. The software for the dismount controller was targeted to the Android operating system to take advantage of the variety of small-form-factor and tablet devices that are commercially available.

SOURCE also developed a set of driving aids for the dismount controller that provided the operator with a better understanding of what the vehicle was sensing and its planned paths. These aids assisted the operator in making better decisions when monitoring the behavior of the vehicle and helped to build trust with the autonomy system. The driving aids were displayed to the user as video and map overlays that fused multiple types of data into a single operational picture.

SOURCE also experimented with a leader-following mode where the vehicle followed an operator's path based on a pedometer device worn on their foot. The pedometer communicated with the dismount controller, which computed its position relative to the vehicle and planned its path accordingly.

2.1.2.3 IMOPAT

As part of the Improved Mobility and Operational Performance through Autonomous Technologies (IMOPAT) program supporting development of a closed-hatch 360˚ SA capability for ground combat vehicles, the TARDEC-led team developed a vehicle electronics architecture that included integrated crewstations for the vehicle driver, commander, gunner, and squad leader. These crewstations consisted of a total of eight (8) state-of-the-art 17-inch WUXGA touch screen displays, each with dedicated general-purpose and video processing capabilities.

Leveraging previous TARDEC ATO efforts which led to the development and maturation of a Service oriented Architecture (SoA) for Soldier Machine Interfaces (SMI), the team also developed an intuitive SMI for 360˚ SA that resides at each crew member station. The 360˚ SA capability integrates a suite of advanced sensor systems that provides the vehicle crew an increased ability to detect potential threats and subsequently slew to cue sensor and weapon systems for further interrogation.

Integrating these advanced sensor systems into a common operator interface while minimizing system proved challenging. To address low latency requirements, the team defined a digital video vehicle electronic architecture, which upgraded existing crewstation processor resources, including video processing resources, while also minimizing the crewstation Size, Weight, and Power (SWaP) footprint. The resultant architecture provided a tightly coupled, integrated sensor, display, network, and processing solution that met low latency requirements. To address challenges of developing an intuitive operator interface, DCS worked with TARDEC and ARL to conduct a 360˚ SA usability study that investigated different options for presenting imagery to the vehicle commander and assessed Soldier-machine interactions. Soldiers participated in the study and the results were carried forward into the 360˚ SA SMI design. The initial study was conducted in a controlled laboratory environment. Subsequent SMI usability studies were conducted in the field, where Soldiers had the ability to interact with the advanced 360˚ SA sensor suite from the crewstation operator interfaces located within the Stryker vehicle. The digital video architecture as well as the lessons learned on presenting video streams to the users directly contributed to the design of the DSAT dismount controller.

2.2 Program Conception

Three distinct elements aligning contributed to the creation of what would become the DSAT program.

2.2.1 GVR's Behavior Sphere

In 2011 a critical mass of GVR engineers came together to find a way to bring in-house expertise back to robotics and start contributing to TARDEC's mission beyond program management and individual research projects. This culminated in the formulation of the "Behavior Sphere" and had as its capstone achievement the creation of the "RAMP Surrogate" – a modified TALON IV with a reconnaissance, surveillance, and target acquisition (RSTA) system and 2-axis turret installed and integrated into an early version of our dismount controller.

The RAMP mission required four key capabilities: autonomous navigation, teleoperation, target acquisition, and weapon targeting. To demonstrate these capabilities, a simple scenario was put together consisting of the following four phases:

1. The robot autonomously navigates down a dirt road given a list of waypoints issued by the operator and positions itself at the base of a hill.
2. The operator takes over manual control of the robot and teleoperates it to the top of the hill.
3. Positioned on top of the hill, the operator uses the robot's RSTA system to search for the target of interest. Once located, the RSTA system passes the target's location to the gun control system.
4. Using the target location from the RSTA system, the gun automatically slews to match the same target. The operator then makes manual adjustments using the gun-mounted camera to ensure the weapon is aimed accurately. When ready, the operator triggers the simulated weapons fire at the target.

Figure 9. RAMP Surrogate

The system developed by TARDEC's GVR successfully demonstrated the tasks as described above for the RAMP mission scenario. While this system was a proof of concept, many of the software components were leveraged when developing the DSAT program. Furthermore, most of the complications encountered with the RAMP Surrogate were issues specific to the model of hardware that were utilized for this system. When ported to the more ruggedized equipment chosen for DSAT program, performance was considerably improved.

2.3 Program Execution

Program Execution was broken down to four phases that started sequentially but quickly became concurrent efforts due to constantly changing requirements and constraints that come along with a short-fused SOF support effort during a time of DoD fiscal uncertainty. These phases were the traditional Design, Development, Testing, and Deployment.

2.3.1 Design

The DSAT program began with the development of a concept of operations modeled after the Small Unit Support IED-Defeat (SUSI) program with adjustments for DSAT's focus on dismount operations. The program then decomposed SUSI's requirements, leading to a requirements document tailored to DSAT's platforms, payloads, and additional autonomous capabilities.

The DSAT team conducted a series of high-level design meetings aimed at understanding the individual technologies being integrated into the DSAT platform. These delibrations led to a high-level system architecture design including communication and power interfaces to the sensors and other components on the vehicle. DSAT later refined the system architecture after completing trade studies, which helped solidify design decisions. After hardware selection, the vehicles and components were modeled in CAD to determine the layout and packaging of components inside the vehicle.

With the system architecture in place, DSAT began developing the software architecture with the definition of individual computer software configuration items (CSCIs) that composed the autonomy system. These CSCIs leveraged the existing SUMET architecture and focused on integrating new autonomous modes, perception sensors, and safety monitoring. DSAT then documented the system states and modes and began developing sequence diagrams to show interactions between components in the autonomy system. Working through the sequence diagrams led to the final high-level software architecture, though low-level component design and interfaces were iterated on throughout the development process.

The DSAT design was captured in a System/Subsystem Design Description (SSDD) document and Systems/Subsystem Specification (SSS). These documents provided traceability back to decisions made on the program and helped to demonstrate a thorough design when DSAT went through the safety release process.

2.3.2 Development

DSAT software development was split into three primary groups: 1) controller, 2) perception, and 3) autonomous behavior, with coordination between the groups handled both at the engineering and management levels. The groups focused their efforts first on transitioning existing baseline technologies to surrogate vehicles for a capabilities demonstration. This provided DSAT with the ability to start developing and maturing technologies while still building the target platforms.

New capabilities were phased in with a series of successive software drops, each including more advanced vehicle behaviors. The software drops were spaced closely together such that integration happened often in the program. During development, DSAT was also continually field-testing vehicles to find and resolve problems, which led to refactoring of primitive capabilities early on in the program when those issues were easier to address. System tests were developed to help verify requirements, but also to test the system in an operational context which was defined in the initial DSAT concept of operations.

The DSAT team also created a vehicle testing environment in the lab by integrating DSAT with the Autonomous Navigation Virtual Environment Laboratory (ANVEL) simulation system developed by the U.S. Army Engineer Research and Development Center (ERDC). This system allowed engineers to develop, test and verify software at facilities without access to the physical hardware or platforms. ANVEL provided DSAT with both a LADAR simulation to simulate the perception system software and a vehicle mobility model to simulate the platform at a low level.

DSAT's approach of using surrogate platforms for development increased the amount of time available for real-world software testing. Once the MRZR platforms were completed, very little configuration and tuning was required to transition the software.

2.3.3 Testing

The DSAT system has and continues to undergo extensive testing to verify both the system functionality and safety requirements across multiple vehicle platforms. This testing has been performed both internally by the project team and externally by the Army Test and Evaluation Center (ATEC). The phases of the internal testing are as shown in Figure 10. As most of the hardware is commercial-off-the-shelf (COTS), developmental testing focuses mostly on software, and begins with the creation and regular execution of unit/component tests. When the component is complete, it is integrated into the vehicle and tested as a complete system. Software issues and defects are informally tracked during these phases; however, hardware issues requiring vendor involvement are entered into the project's defect tracking system and formally managed until resolved.

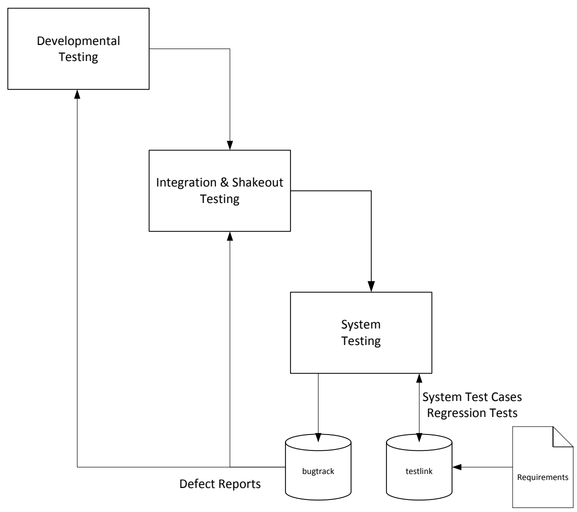


Figure 10. DSAT Testing Phases

System testing occurs prior to a formal release, where a release is defined by a specific set of features and functionality. When all of the required functionality has completed integration and shakeout testing, formal system testing begins. Formal system tests trace back to the requirements and are captured in the project's Testlink database. Testlink also stores regression tests for cases relating back to specific issues and defects found through prior testing. When defects are found, the reports are fed back to the developer and the process repeats until the defect is verified as resolved through formal system testing. To facilitate communication among the team, a DSAT testing working group email list was created and is used to ensure the testing activities are coordinated.

In addition to the formal system testing at the integration facility, the project team also takes every opportunity to field test the vehicle when participating in demonstrations or experiments. These events enable the team to test the vehicle over terrain and under conditions not readily available at the integration site. This has greatly led to improved reliability and stability of the vehicle.

The external testing by ATEC was a requirement for obtaining a safety confirmation for use by Soldiers. The DSAT vehicle was assessed by Special Operations Forces in Afghanistan, and therefore required this safety assessment. This assessment consisted of an extensive array of vehicle system and software tests conducted over several months at the Aberdeen Proving Grounds, as well as Counter Radio Electronic Warfare (CREW) testing conducted at the Yuma Proving Grounds. The result of this testing was a safety confirmation, which describes the modes of operation over which the vehicle is approved for use by Soldiers, and a capabilities and limitations report further detailing the performance limitations of the system experienced and recorded during testing.

2.3.4 Deployment

The DSAT vehicle and TARDEC Field Support Representatives (FSRs) were deployed overseas to support missions for USASOC Soldiers such as forward reconnaissance and mine clearance. This paper will summarize the successes of both deployments, the areas of concern, and the lessons learned from the deployments.

2.3.4.1 Successes

During the first deployment, FSRs brought the vehicle to an operational state after shipping and performed software updates to incorporate improvements made during stateside testing onto the deployed platforms. The ability to perform vehicle updates allowed us to fix software issues and continue development and debugging as potential problems were uncovered.

FSRs performed teleoperation, direct follow, and GPS waypoint following. Soldiers were trained on teleoperation and GPS waypoint following.

The vehicle was pushed forward to a Forward Operating Base (FOB) and was used by Soldiers "outside of the wire" during deployment. Training with the vehicle was performed outside of the wire and feedback was gathered from the Soldiers about potential mission objectives that the vehicle could assist on.

The vehicle received positive feedback and performed well enough to be scheduled for use as a surveillance/reconnaissance platform during a mission. Unfortunately, due to inclement weather conditions, the mission was canceled.

The vehicle drew outside interest from JIEDDO, specifically interest in its potential counter-IED capabilities.

2.3.4.2 *Synopsis of the DSAT Deployment*

The deployment to Afghanistan provided the program with valuable experience and feedback. The team was able to discover and quickly address deployment and operational problems. Unfortunately, due to a change in mission profile, the vehicle capabilities were not able to receive further operational feedback during a second deployment. The project, however, was able to create a capabilities and limitations profile and receive feedback towards potential mission profiles for our vehicle. Additionally, the team gained valuable experience in preparing a vehicle for deployment and how to operate under a deployment environment. These lessons learned will be leveraged to help make the team even more successful in future projects and operations.

2.4 Program Conclusion

The DSAT program reached its epoch with the end of the second deployment. After this point the team began to wind the program down, get the equipment back from theater, finalize the documentation, and work out the details for transitioning the technology into our follow-on efforts.

2.4.1 *Synopsis*

The DSAT effort had six major outcomes:

1. The team developed the first iteration of the Robotic Technology Kernel (RTK). The RTK is the compilation of the processes, designs, and autonomy and controller hardware and software that enables its autonomous capabilities.
2. The team implemented this technology across multiple optionally manned platforms.
3. The project pushed the envelope on autonomy testing in the Army.
4. Two systems were deployed downrange for an in-theater combat assessment.
5. The foundation for all of our in-house autonomy development was established.
6. The team developed a level of expertise in robotics development that prior to this effort did not exist in TARDEC's Ground Vehicle Robotics.

2.4.2 *Next Steps*

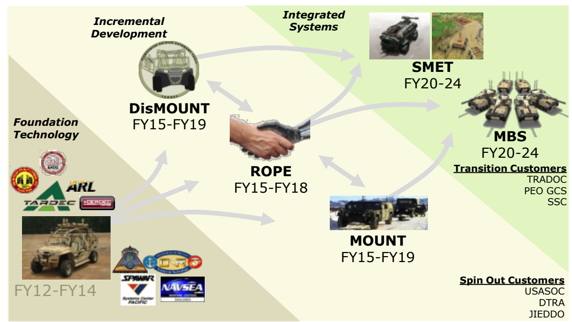


Figure 11. CD5 / Manned-Unmanned Teaming

From an internal development perspective, the group is pursuing three paths: 1) completing the DSAT program; 2) transitioning the technology into the Manned-Unmanned Teaming (MUT) effort; and 3) transitioning the technology into the Multi-UGV Extended Range (MUER) mission.

2.4.2.1 *DSAT Wrap Up*

The group is currently in the process of completing the documentation associated with the DSAT effort, hardening the software modules of the stock capabilities of the Robotic Technology Kernel v1.5 (i.e., addressing intermittent bugs and fixing functionality shortcomings), and improving the configuration management practices to ensure all platforms are running at the same codebase. Finally, the team is performing extensive baseline testing to level-set this stock capability with regards to both MUT and MUER.

2.4.2.2 *CD 5 – Manned-Unmanned Teaming (MUT)*

Currently fielded autonomous ground systems require a high degree of Soldier oversight and often exhibit constrained operational capability. Fielded capabilities tend to be singular to a specific mission and many times are not able to consistently meet warfighter expectations due to limitations in the autonomy and/or robustness of the integrated hardware and software systems. Soldiers are requesting robotic assets that are easy to use, reliable and consistent, adaptable to missions and environments, and proven to be force multipliers. The MUT effort will provide robotic technology advancement and experimentation to increase the autonomous capabilities of mounted and dismounted combat support vehicles and to iteratively define and decrease the gap between autonomous vehicle control and the required level of human interaction. The effort has two primary phases: Iterative Technology Maturation and Integrated System Level Technology Demonstrators. Three primary products will be generated by this effort: 1) an iterative maturation of the Robotic Technology Kernel (RTK) first developed under DSAT; 2) a basic and advanced Soldier Robotic Teaming Capability Kits (S-RTCK); and 3) a basic and advanced Vehicle Robotic Teaming Capability Kits (V-RTCK).

2.4.2.3 Multi-UGV Extended Range (MUER)

The Multi-UGV Extended Range (MUER) demonstrator mission entails a V-22 Osprey loaded with the autonomous MUER vehicle flying to a Landing Zone (LZ). With the assistance of the V22

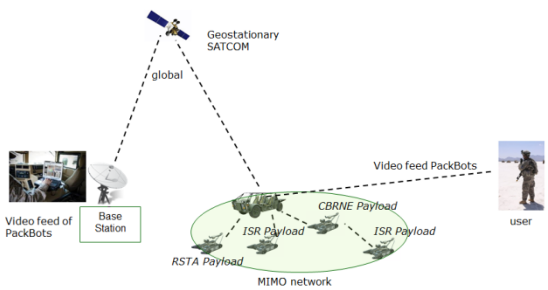


Figure 12. MUER Communications Overview

crew, the MUER will be unloaded and initialized. Upon initialization, the MUER will be given a destination from a base station located a distance of greater than 500 miles from the LZ and then autonomously travel to the objective location.

Once it arrives on site, the MUER will be given an order to release the PackBots from the ROBODEXs. The PackBots will be moved into position autonomously while being supervised from the base station. The PackBots will be configured to conduct either a RSTA 72(O) 36hr (T) mission or CBRNE 24hr mission. Not all of the PackBots will be used at the same time for long-duration missions, but their operation will be staggered and rotated into use as other systems are relieved for recharging. Video feed from the PackBots' on-board cameras will be sent via RF communication to the MUER and then on to the base station through a satellite connection. While the MUER is in motion, video will not be able to be transmitted back to the base station. Once the MUER has completed its mission, it will travel to the LZ where it will be operated into the V22.

3 TECHNOLOGIES DEVELOPED

The DSAT program focused its development efforts around five pillars: 1) open architecture, 2) a platform-agnostic approach, 3) unique sensing and perception techniques, 4) a modular autonomy paradigm, and 5) a scalable control instantiation.

3.1 Architecture

The DSAT system is built on the Robot Operating System (ROS), a collection of open-source software libraries for robotic applications. A ROS system is typically composed of many nodes that run as independent software processes on one or more computers. Nodes communicate via message passing (using a publish/subscribe model) and service calls

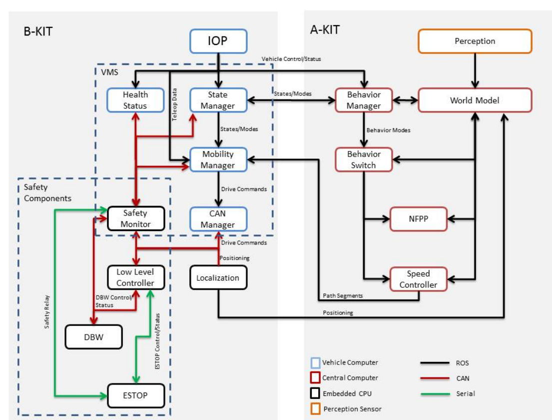


Figure 13. DSAT system architecture

(remote procedure call model). The ROS approach encourages a modular, robust approach to system design that is tolerant of delays and other issues with asynchronous communication.

DSAT leverages the ROS framework to provide a scalable platform that is easy to extend with new capability and facilitates fast development schedules. This is possible because the system is divided into many small nodes that are each focused on a single core responsibility, making them easier to develop and test in isolation. Additionally, ROS provides tools to examine and record the messages that nodes use to communicate, which inherently provides an effective and non-invasive debugging tool.

3.1.1 Safety Monitor

The DSAT architecture includes a safety system that is designed to halt vehicle operations in the case of a critical system failure. At the core of the safety system is the Safety Monitor, an embedded computer directly linked to the vehicle E-stop.

3.1.2 Hardware

The DSAT program focused on using low cost, COTS products, when available, as a common base set of components. If the components were not already environmentally sealed, they were further packaged to operate while exposed to the elements.

Figure 14. DSAT MRZR Component Breakout

To accommodate the low power and small space available on the MRZR, a distributed networking and computing approach was taken with multiple computers and networking boxes distributed within the vehicle. The common set of components generated for this installation were then reused for multiple vehicle types, listed below, such that the vehicles had hardware commonality to make parts swappable between like and disparate vehicles as well as having common spares for the systems.

3.1.2.1 Safety Monitor

The Safety Monitor hardware is the Mototron ECM-5554-112-904, which is the same hardware used for the Low Level Controller. The Safety Monitor is connected to the vehicle CAN bus and has a direct link to a relay in the vehicle E-stop chain. In the case of a critical system failure, the signal to the relay is cut off, which triggers an E-stop.

3.1.3 Software

The DSAT software framework is made up of several components; the World Model, the Near Field Path Planner, the Reactive Speed Controller, the Behavior Switch, the Localization Systems, the Low Level Controller, the Vehicle Management System (VMS), and Safety Monitor.

3.1.3.1 World Model

The World Model (WM) is a central knowledge database for the autonomy system. The world model uses a modular architecture that enables new functionality to be introduced quickly and independently as new needs are identified. One of the most-important roles of the world model is to build a three-dimensional voxel representation of the vehicle's environment from sensor data. The WM is capable of fusing data from arbitrary sensor types into a single voxel representation while taking advantage of each type's unique abilities.

3.1.3.2 Near Field Path Planner

The Near Field Path Planner (NFPP) generates new collision-free local paths for the vehicle at a regular rate. The original SUMET path planner only implemented a route-following behavior. For DSAT, the NFPP was heavily refactored into a modular architecture. Different behaviors are achieved by loading different sets of modules. This reconfiguration is done dynamically while the software is running to change behavior. The modular architecture made it possible to implement a rich set of behaviors while maximizing code reuse for functionalities that are shared among behaviors.

3.1.3.3 Reactive Speed Controller

The Reactive Speed Controller (RSC) determines the vehicle speed in autonomous operation. Like the NFPP, the RSC uses a modular architecture that allows modules to be reconfigured during runtime to achieve different behaviors. During an update, each module provides a speed recommendation based on its unique inputs. The RSC generates a new speed command based on the module input and current vehicle speed to provide safe operation and smooth transitions between speeds.

3.1.3.4 Behavior Switch

The behavior switch provides a single uniform interface for controlling the system's behavior. When a behavior is selected or modified, the behavior switch verifies important pre-conditions and reconfigures other software components to realize the specified behavior.

3.1.3.5 Localization

The DSAT localization package fuses data from many sensor sources to generate both near- and far-field estimates of the vehicle position and velocity. The localization software is robust to sensor failures and temporary GPS drop-outs.

3.1.3.6 Low Level Controller

The Low Level Controller (LLC) is a bridge between the common A-kit and the unique hardware platforms. The LLC has two primary purposes: it provides a common software interface despite differences between the platforms, and it implements speed and steering control laws, effectively generating high-bandwidth hardware commands from relatively lower-bandwidth abstract commands generated by the NFPP and RSC.

3.1.3.7 VMS

The Vehicle Management System (VMS) software tracks the health and status of vehicle subsystems and reports them back to the operator via the controller. The VMS also monitors messages between components to determine if any subsystem failures have occurred and reports any failures to the operator.

3.1.3.8 Safety Monitor

The Safety Monitor software is responsible for monitoring the vehicle CAN bus for regular messages from critical system components—the drive-by-wire system, the Low Level Controller, the controller E-stop, and the Localization Computer. When a specific message is absent from the CAN bus for a specified period of time, the Safety Monitor triggers an e-stop. The Safety Monitor also stores the maximum speed allowed for each mode of operation. An e-stop will also be triggered in the event that the vehicle speed (commanded or actual) exceeds the maximum speed set by the Safety Monitor. In situations where an e-stop would normally occur, but the vehicle is considered to already be in a safe state, the Safety Monitor will not trigger an e-stop. This allows users to perform certain operations, such as restarting various subsystems, without being encumbered by constant e-stops. The vehicle is considered to be in a safe state if it is stationary with the brake fully depressed or when it is not in a robotic mode.

3.2 Platforms

At the heart of the effort were two key-concepts: 1) optional manning, and 2) platform agnosticism. For the missions the DSAT system was intended to support, the platforms would spend a majority of their time driven and used by the operator as a manned platform. The goal was to allow the autonomy to be used as a tool to support dismounted operations at the flip of a switch. Therefore, one of the requirements was that the autonomy-enabling technologies not interfere with manned operations. Also, as mentioned previously, DSAT was an early adopter of the AMAS A-Kit/B-Kit philosophy, and this concept has been proven by running a common Autonomy Kit on four unique platforms to date with a fifth in the works.

Figure 15. DSAT HMMWV

3.2.1 HMMWV

The HMMWV was the first system developed for the DSAT program. It was designed for quick development and prototyping of the software as the other vehicles were in progress. Due to the larger amount of power and space available in the system, the HMMWV utilized a single multi-processor computer and single, configurable multi-port network switch as opposed to the later vehicle variants. This variant also allows for more code debugging on a single computer before having to deal with the complexities of optimizing and distributing the code amongst multiple lower-power computers.

The HMMWV has the common sensor suite and code base used on each vehicle as part of the common A-Kit design, while utilizing a Bolduc AEVIT RPV Drive-By Wire (DBW) kit which was unique to this system amongst the DSAT platforms.

3.2.2 MRZR

The MRZR platform posed much stricter size and power constraints on the system than the HMMWV. For this system, many more distributed and modular components were created so that they could be placed throughout the vehicle wherever space was available. The components for this system were also more exposed to the environment so ensuring they were all properly sealed was a key design factor. Additionally, with the reduced power availability, all of the systems were designed to be low power and passively cooled.

While some of the computing and networking configurations changed from the HMMWV to accommodate the size and power availability of the vehicle, the system maintained the common suite of sensors and code base with only modifications to accommodate the distributed computing nature of this system. This vehicle variant utilized a TORC DBW system with a common interface message set to that of the Bolduc system on the HMMWV and the other systems listed below. In total, three complete MRZR systems were created for the DSAT program.

Figure 16. DSAT MRZR

3.2.3 Rubicon

The modified Jeep Rubicon design was utilized under the DSAT effort to leverage vehicle components created for the SUSI program. While more space and power was available for this system, it was decided to use the components designed for the MRZR to create part commonality between the systems to facilitate the use of interchangeable spares.

Figure 17. DSAT Rubicon Platform

Again for this system, a common suite of perception hardware and software was used as this vehicle’s A-kit in addition to the identical networking and computing hardware from the MRZR. The Rubicon system utilized the common DBW interface message set mentioned under the previous vehicles to control a GDRS-built by-wire system. Overall, two complete Rubicon platforms were created for the DSAT program.

3.2.4 R-Gator

The R-Gator is a by-wire-enabled John Deere 6x6 Gator and is being developed specifically for autonomy testing. Due to its smaller size and limited performance characteristics, it is an ideal candidate for dismounted work and testing in areas where space

Figure 18. DSAT R-Gator Platform

and speed are major concerns. The team removed the existing autonomy hardware and installed a DSAT-to-R-Gator black-box created by DATASPEED Inc. in conjunction with John Deere. This box was designed to accept the same CAN messages used to interface with the other DSAT vehicles. Once again, a common suite of perception hardware and software was used as this vehicle's A-kit, in addition to the identical networking and computing hardware from the MRZR.

3.2.5 CERV

For the previously discussed MUER effort, the team is outfitting a Covert Electric Reconnaissance Vehicle (CERV) with the RTK. The CERV is a series Hybrid with a Ford 1.4 TDCI diesel engine used to power a UQM CD40-400L generator that outputs 350 volts at 475 A peak. The UQM generator is responsible for recharging 2 Johnson Control 96 Cell lithium-ion batteries (JCI battery). Each JCI battery has a nominal voltage of 345 V and a capacity of 41 Ah (14.1 KW).

Figure 20. DSAT CERV Platform

The power bus is 345-400 volts, providing power to the CERV drive motor and vehicle hotel loads. The CERV Hotel loads will connect to the vehicle power buss through a junction box. The junction box will be capable of accepting two wiring harnesses sized to carry ~45A and ~115A. The junction box will provide space for resettable circuit breakers sized to carry the aforementioned current draw. The CERV is currently being modified to accept the same CAN messages used by the other DSAT vehicles. Following that, the common suite of perception hardware and software will compose the vehicle's A-kit and identical networking and computing hardware from the MRZR will be added.

3.3 Sensing and Perception

The sensing and perception systems are currently broken down into the following four areas: Advanced Perception System (APS), LADAR system, UWB system, and Localization system.

3.3.1 APS

The Advanced Perception System (APS) is the Electro Optical (EO), or camera, based component of

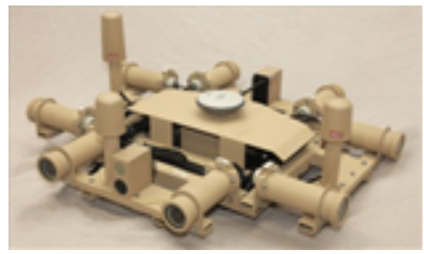


Figure 19. 360° APS from DSAT MRZR

the system. For the DSAT program, the team was able to leverage research and software created under the ONR SUMET program for camera based material classification as well as pedestrian detection. A key design enhancement to the material classification enacted during the DSAT program was the reduction in the number of cameras required from the eight in the forward facing direction for the SUMET program to two for the DSAT program with minimal performance impact.

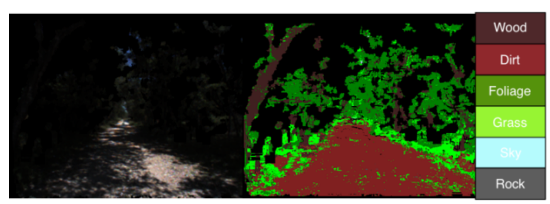


Figure 21. Material Classification

3.3.1.1 Material Classification

Material classification is achieved by two key visual components: multispectral response and image texture. The multispectral information comes from image responses from the environment through a select set of filters. Data collected through these filtered images is collected for a variety of materials, and then a learning algorithm is trained offline using a human based ground truth database to correlate the spectral responses as well as texton-based texture information to actual materials.

3.3.1.2 Object Detection

A state-of-the-art Object Detection algorithm has also been implemented that uses a cascaded classifier based on Haar Features with AdaBoost Decision Trees and HOG Features with an SVM classifier in conjunction with spatial context from stereo data.

3.3.2 LADAR

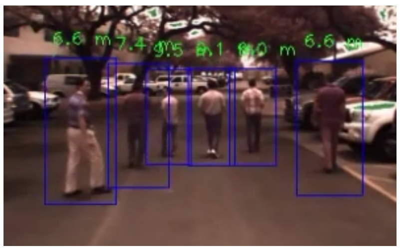


Figure 23. Pedestrian Detection

This section will describe the method used for LADAR-based obstacle detection and object classification used on the TARDEC DSAT vehicles. The system uses two Velodyne HDL-32E LADAR sensors on our vehicles for increased visibility, but the same principles could be used with a single 3D LADAR sensor.

3.3.2.1 Implementation

This implementation is based on the method described in Himmelsbach et. al. [1]; with ground point detection capabilities, clutter/grass detection capabilities, and special cases for overhanging trees added. This implementation also includes object tracking and dynamically adjusting map size/resolution to maintain a constant frame rate. A visual representation of the system is shown in Figure 22.

3.3.2.2 Ground Point Detection

Points which are not “boxed” as objects (shown as red in the figures) are considered for ground point classification. The system examines the contiguous length of these possible ground point contours within each laser scan ring. If the length of the contour and the distance between each of the points meets a certain threshold, these points are classified as

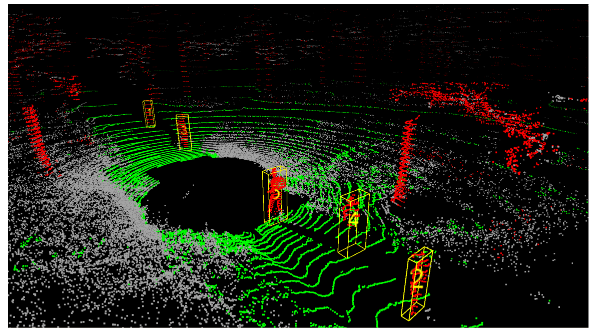


Figure 22. Pedestrian tracking in the woods

ground points (shown as green in the figures). This threshold is distance-based, with the minimum contour length decreasing and the allowed distance between points increasing as the distance from the sensor increases.

3.3.2.3 Clutter/Grass Detection

Clutter and grass detection works similar to ground point detection, except point contours within objects are checked. Thresholds again are distance-based. If an object does not have at least one contour passing the threshold, it is flagged as clutter (shown as gray in the figures). In an off-road environment, this is commonly tall grass or small brush which the vehicle can traverse, so it is not treated as an obstacle by the path planner. This process is illustrated in Figure 24.

3.3.2.4 Overhanging Trees

Overhanging trees are special-cased so that pedestrians or vehicles underneath them are not boxed with the tree. The system looks for a gap between laser scan rings within objects to determine if multiple smaller objects exist within that box. These objects are then extracted and inserted as separate objects.

3.3.2.5 Object Tracking

This system classifies pedestrians and vehicles and is able to track and follow them autonomously. The classification method is described in Himmelsbach et. al. [1]. Some lower-level tracking is done by the LADAR processor, since the classification is not perfect and frequently encounter false positives and false negatives. The LADAR tracking system takes into consideration the object dimensions, velocity, and frequency of positive classification to determine

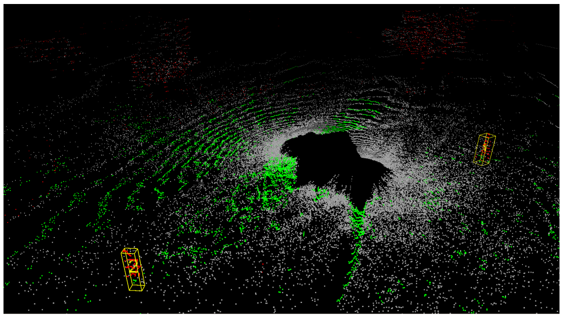


Figure 24. Pedestrian tracking through 2-ft tall grass

when to “lock” on to a pedestrian or vehicle. This object is then tracked regardless of the classification, until the lock is lost. This allows the system to track pedestrians and vehicles at greater distances than the classifier can handle.

3.3.2.6 Dynamic Map Adjustments

The map size and resolution are dynamically adjusted between frames to keep the output frame rate near 10 Hz. In a wooded environment, the number of points returned by the LADAR can vary greatly depending on how many trees are present, as shown in Figure 25. By decreasing the resolution and map size when necessary, autonomous safety can be maintained. The trade-off is that the path planner is not able to plan as far ahead and the path taken may not always be optimal.

3.3.2.7 Synopsis of DSAT LADAR System

The LADAR processor is still in development, but the current implementation works reasonably well for off-road navigation, including areas where there is tall grass or brush.

3.3.3 UWB

One task of autonomous vehicles is to know the locations of nearby pedestrians to avoid hitting one and, in the ideal case, to move strategically in accord with nearby pedestrian operators. Typically, sensors such as LADARs and cameras are used to perform the first task of avoiding collisions, but are limited on the second task where it is beneficial to have location knowledge in non-line-of-sight (NLOS) conditions and consistent identities of tracked pedestrians. Furthermore, the range at which pedestrians can be detected confidently using these light-based sensors

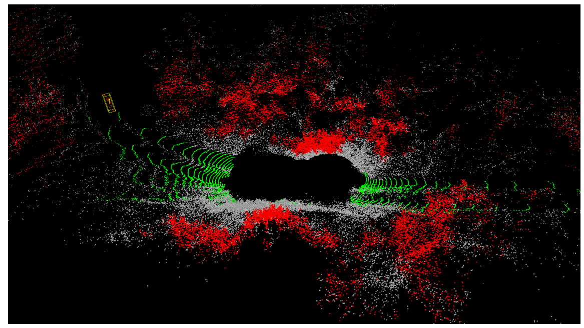


Figure 25. Wooded two-track dirt road

is generally below 50 meters. One solution is to employ ultra-wideband (UWB) radios.

UWB radios have been used before for positioning systems. In particular, they are used on major construction sites to track the locations of heavy equipment [2]. In the DSAT program, we wanted a vehicle to autonomously follow an operator at various distances and in two different driving methods—driving directly towards the operator (direct following) and driving the exact path the operator took (exact following). Using four UWB radios mounted on a vehicle and one remote UWB radio per operator, we were able to accomplish this task.

3.3.3.1 Method

UWB radios use time-of-flight measurement to yield the distance between two radio units. Consider finding the position of a remote (location-unknown, free-roaming) radio in 2D space. With a fixed radio and the distance to a remote radio, there are infinite position solutions along a circle with radius of that distance. With two fixed radios and the distances from each to a remote radio, there are two position solutions. With three fixed non-colinear radios and the distances from each to a remote radio, there is one solution. This is basic trilateration.

To ease mounting design and make the system more robust to failure, we decided on mounting four UWB radios on a vehicle. (Theoretically, four radios could be positioned to find a single solution in 3D space, but the measurements were too noisy in practice to have any precision or accuracy.) They were placed at the corners of the vehicle to maximize the baseline, which minimizes the influence of noise, and so that no three would be in a straight line. With the mounting locations known, the relative location of a single remote radio can be uniquely determined.

3.3.3.1.1 Selection Strategy

Due to the physical characteristics of UWB, there is a trade-off between signal-to-noise ratio (SNR) and measurement time. For the radios used, the measurement time was no less than 20 ms—a non-negligible time when both the fixed and remote radios are moving—for an SNR that produced a maximum range of 125 meters. Even at this SNR level, the accuracy degraded under NLOS and multipath conditions.

Therefore, trilateration is done using two fixed radios as much as possible to shorten the time it takes to update the remote position and to limit the use of fixed radios which may be on the far side of the vehicle and, thus, NLOS. The remaining third and fourth radios are used only when needed to verify that the correct one of two solutions is selected and during initialization.

To determine the best two radios that minimize the influence of noise, we derived the error between the true and estimated x-coordinate of the position:

$$x_{\text{true}} - x_{\text{estimate}} = \frac{\varepsilon_1 r_1 - \varepsilon_0 r_0}{d} + \frac{\varepsilon_0^2 - \varepsilon_1^2}{2d}$$

ε_x: additive error in r_x

r_x: range measurement from fixed radio x to remote radio

d: fixed radio baseline

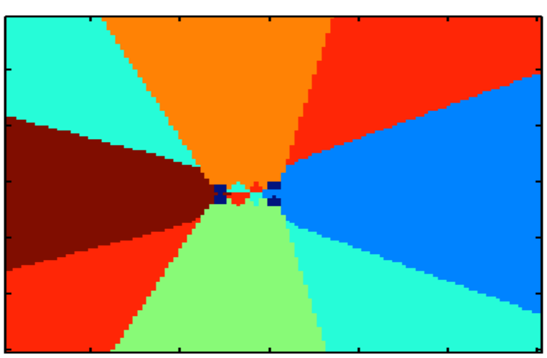


Figure 26. Pair map for selecting two fixed UWB radios. The vehicle front is to the right. The dark blue spots represent the mounted UWBs.

This indicates that the baseline should be maximal and the errors and ranges should similar. While it's not possible to determine if the errors will be similar, if the ranges are similar the multipath and NLOS conditions are more likely to be similar. This leads to the following cost function:

$$C(i,j) = \frac{|r_i^2 - r_j^2| + e_{\text{NLOS}}(i) r_i + e_{\text{NLOS}}(j) r_j}{d}$$

$$e_{\text{NLOS}}(i) = \begin{cases} \varepsilon_{\text{NLOS}}, \text{if radio i is NLOS with remote} \\ 1, \text{else} \end{cases}$$

$\varepsilon_{\text{NLOS}}$: multiplicative NLOS error coefficient

Given this, the pair map shown in Figure 26 for one of our vehicles is produced.

In addition to selecting which pair of radios to range with, we also must determine which remote radios to range if there are more than one. This is done by assigning a desired update rate to each remote radio, with close ones being higher and far ones being lower, and selecting the one whose update rate lags its desired rate the most.

3.3.3.1.2 Trilateration Solution

The system uses three primary methods to solve the trilateration problem: analytic, ordinary least squares (OLS) and non-linear-least-squares (NLLS). Upon initialization, when three or four fixed radios are providing ranges, OLS is used over NLLS because it does not require an initial guess and thus is not subject to converging on the wrong solution. When three or four radios provide ranges in a non-initialization state, NLLS is used over OLS because it is more accurate—NLLS directly minimizes the sum or squares of ranges. The analytic solution is used only when NLLS fails, which happened rarely in practice.

3.3.3.1.3 Filtering

While UWB can be very accurate in ideal conditions, it often degraded from multipath and NLOS conditions due to the dynamic nature of the system. To counteract this, the system employs several filtering techniques.

3.3.3.1.3.1 Reverse Position

If an incoming range is significantly different from the ranges of the predicted position, it is removed. If enough of these ranges are removed in a row, the prediction is considered invalid and the remote position is re-initialized.

3.3.3.1.3.2 Improbable Range

If we have at least three ranges and one of the ranges is greater or less than all other ranges by their respective baselines, it is removed.

3.3.3.1.3.3 Fuzzy Range

A basic fuzzy averaging filter which checks how fast the ranges are changing and either leaves it unmodified, proportionally averages it with the previous range, or saturates at the maximum allowable range change.

3.3.3.1.3.4 Leave-One-Out

When performing NLLS with more than two ranges, this filter finds additional solutions with each range excluded. Of these solutions, it selects the one that is closest to the predicted position.

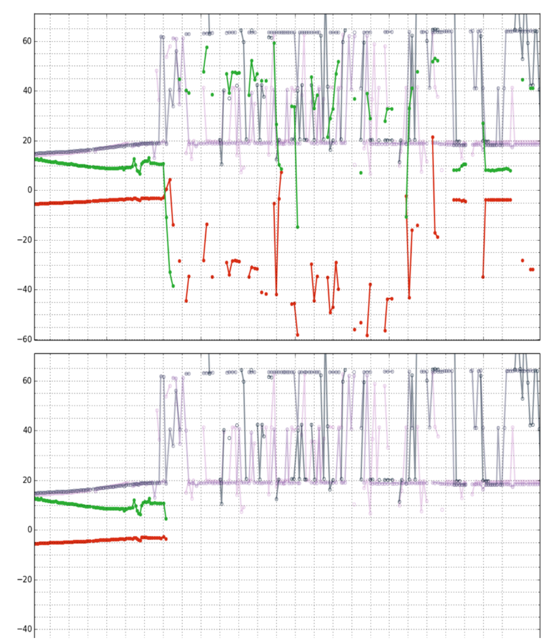


Figure 27. Multipath example with position output continuing (top) and suspended (bottom). The purple and blue lines are range values; the red and green line are *x* and *y* coordinate values of the position, respectively.

3.3.3.1.3.5 Multipath, NLOS

Under multipath or NLOS conditions, the range errors can be insurmountable for extended periods of time. In these cases, it is best to suspend positioning. This condition is detected by looking for a high frequency of spikes in the ranges over a short period of time. (See Figure 27 for an example.)

3.3.3.1.4 Pose Transformation

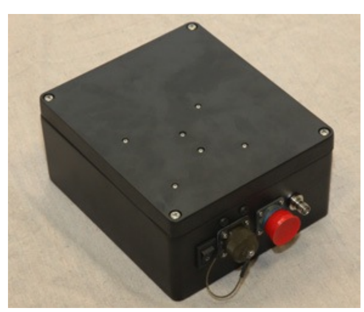
The UWB radios provide relative positioning, but because the vehicle has knowledge of its location, we transform the remote radio positions into a world frame. This eases prediction and filtering since the remote radios can be modeled in absolute terms instead of relative ones. This is especially true when the vehicle is turning since the relative angular speeds of remote radios can get very large.

3.3.3.2 Synopsis of DSAT UWB System

UWB positioning worked satisfactorily for direct following. The position output was very noisy, but because the vehicle moved around the same speed of a human, occasional errors didn't last long enough to significantly alter the vehicle's path. On the average, the vehicle was able to roughly steer in the correct direction and at a proper speed to maintain a loose standoff distance.

However, exact following was very susceptible to noise in the position output since the vehicle tried to follow the noisy path. This was made worse by jumps in the output caused by mirroring when the system would lock on to the wrong two-radio solution. Major improvements need to be made for this to work reliably.

3.3.4 Localization



The localization solution leveraged lessons learned from the ONR SUMET program for sensor selection and viability to create a more compact, self-contained sensor suite utilizing low-cost, COTS components. The localization box is common amongst all DSAT platforms and provides an

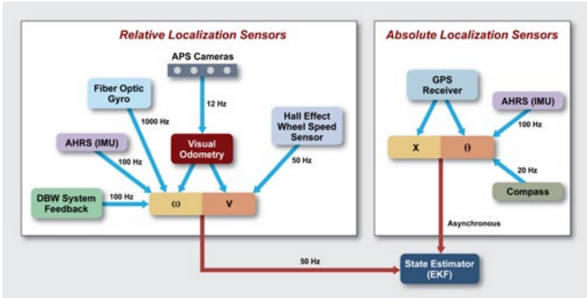


Figure 28. Localization schema

accurate absolute vehicle location as well as extremely low drift in position over time in areas with bad or no GPS coverage for extended periods of time.

3.4 Autonomy

The DSAT autonomy solution implemented in our A-kit consists of a foundational technology that blends together our Obstacle Detection/Obstacle Avoidance, Path Planning, World Model, and Sensor Fusion techniques.

3.4.1 Foundation Technology

The DSAT program was able to leverage multiple years of MARTI and ONR SUMET ROS/C++-based code as a starting framework for the system. This foundational code provided a modular architecture for rapid development as well as the flexibility to interchange and add on software modules to the system to further evolve the system, improving performance and adding capabilities.

3.4.1.1 OD/OA

The DSAT systems are capable of Obstacle Detection/Obstacle Avoidance (OD/OA) maneuvers. While traversing routes autonomously in waypoint, follow or push modes, the fused sensor data is used to detect obstacles in the desired path and classify the material of those obstacles. If the obstacle is large enough and classified as a material that is not traversable then the path planner will either plan around that object or stop if there is no open path. The system also classifies pedestrians differently than other objects, tracking their movement and giving them a wider berth.

3.4.1.2 Navigation

The DSAT navigation system comprises the Near Field Path Planner (NFPP) and Reactive Speed Controller (RSC). The NFPP fills the role of a deliberative planner by generating and updating vehicle routes to achieve the current goal or behavior. The NFPP uses costmaps generated by the world model to evaluate safe and desirable routes for the vehicle. While the NFPP supports arbitrary planners, the current DSAT modes all use an A* path planning algorithm to search the vehicle's trajectory space, but have different strategies for determining a local goal region and for assigning costs to trajectories.

The RSC manages behavior execution by setting the vehicle speed at any given time. This is done by a different process at a faster rate to allow the vehicle to quickly stop when an obstacle is sensed on the current trajectory while the path planner concurrently searches for a new obstacle-free path.

3.4.1.3 World Model

The DSAT world model leverages code originally developed for the ONR SUMET program. The world model provides a modular and extensible means for fusing data from disparate sensing modalities including a ground plane estimate, voxel model and dynamic obstacle information. The world model generates a two-dimensional costmap from the fused sensor data which represents the traversability of the area around the vehicle. Regions identified as pavement or dirt roads are considered more traversable than areas classified as tall vegetation. A single reserved value is used for regions not traversable that are occupied by obstacles. Costmaps

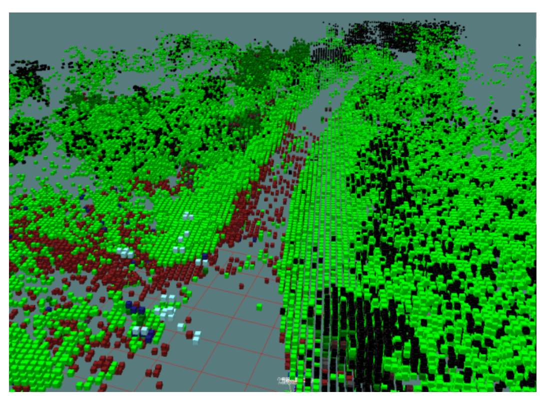


Figure 29. World Model Representation

allow the navigation system to intelligently avoid obstacle and preferentially drive on safe, paved roads without being overwhelmed by a detailed three-dimensional world model.

3.4.1.4 Sensor Fusion

The DSAT program was able to build off of the ONR SUMET world model that was originally programmatically constrained to incorporate only stereo-based depth data and material classification information and modify and extend it to incorporate the new DSAT sensing modalities of LADAR and UWB information. The system was also modified to receive and fuse dynamic obstacle data from the various input sources in addition to fusing ground plane and voxel information.

3.4.2 Capabilities

As part of the DSAT program, a behavior framework was created to facilitate the creation and incorporation of new behaviors and capabilities as well as the switching between these modes as they are created. At the end of the DSAT program, the capabilities that are present across all the DSAT-enabled platforms are Tele-Operation, Waypoint Following, Dismounted Following, and Dismounted Pushing.

3.4.2.1 Tele-op

Remote control (R/C) and teleoperation capabilities were added to the DSAT system. The system can either be controlled through a set of physical joysticks on the large tablet or through soft joysticks on the screen of the small or large tablet. Cameras dedicated to tele-operation are provided on each vehicle facing forward and rear including a color camera for daytime operation and an IR camera for night operations.

3.4.2.2 Waypoint

The DSAT system is capable of following predefined waypoint routes autonomously. These routes can be created in a variety of ways, including loading existing waypoint routes, recording a route while driving the vehicle manually or in teleoperation, and drawing the route by hand on the tablet on top of aerial imagery. The path planning in waypoint mode for the system allows for adjustably large path deviations to accommodate errors in GPS data from recorded routes or poorly geo-registered aerial imagery as well as vehicle GPS error due to outages and bad data. The system is also capable of following routes defined by relatively sparse waypoints and finding its own path between those points.

3.4.2.3 Follow

The DSAT system has a dismounted Soldier following capability. This capability allows the autonomous vehicle to follow a selected pedestrian as he/she is walking in front of the vehicle at a specified distance. This following can be performed in either an exact or direct manner. The exact following keeps track of and mimics the exact path that the pedestrian is following. In contrast, the direct following mode has the vehicle take the shortest path between the vehicle's current position and the current position of the pedestrian that is being followed, while still avoiding obstacles. This behavior is currently facilitated through using the UWB or LADAR sensors returns independently or the fusion of data from both sensing modalities.

3.4.2.4 Push

Similar to the follow behavior, the DSAT system has a push capability in which, using the same sensing modalities, the autonomous vehicle proceeds in front of the dismounted Soldier at a set distance. Steering control is accomplished by the pedestrian moving to the opposite side of the vehicle to which they want the vehicle to turn, i.e., moving to the left while pushing the vehicle will cause it to turn right, and vice-versa. A push behavior that maintains a distance from the user while allowing the user to control steering via the tele-op controls is also currently in development.

3.5 Control

Several different control-related technologies were developed for the DSAT program, including the use of newer, scalable handheld devices; innovative modalities for interacting with system to command various tasks; and improved diagnostics for improved vehicle maintainability.

3.5.1 Hardware/HFE

The DSAT developers selected two different control devices to provide the operator with flexibility to interact with the autonomous system using a controller optimal for their mission. The first device was a 7” ruggedized Harris tablet, which provided a large screen for monitoring video feeds and creating mission plans while remaining easily carried by a dismounted operator. The Harris tablet meets MIL-STD-810G requirements, has a resistive multi-touch screen, and supports gloved operation.

The second device was a 4.3” Scorpion H2 handheld, which was small enough to be stored in a pocket or worn on a uniform. Though the device has an IP65 rating, it has a capacitive touchscreen, rendering it unusable with standard gloves. Though this device supports the same functionality as the tablet, it does not have hardware controls for tele-operating the vehicle and slewing sensors. It is intended to be used for leader-follower and waypoint following behaviors.

The dismounted controller can be either tethered to the vehicle or the dismounted backpack so that it can communicate with the autonomous vehicle. The dismounted backpack provides the controller with power and a connection to the vehicle through an 802.11 Rajant radio with a line of sight range of about 1.5 km. The dismounted backpack also contains an ultra-wideband radio that allows the vehicle to determine the operator’s location for leader-following.

3.5.2 Modalities

Using the dismounted controller, there are multiple ways for the operator to interact with the autonomous vehicle. In the waypoint following mode, waypoint plans were either generated on the controller, loaded from an external source, or the path recorded as the vehicle is driven. The plans contain information on vehicle’s path and contains meta-data specifying how to follow the path. Once the operator executes the plan, they stay in autonomous over-watch where they can intervene if necessary, either by stopping the plan or tele-operating.

The controller in leader-follower mode displays the entities that the vehicle can track, either UWB or LADAR entities. Once the operator selects a leader, the system will generate paths that take it directly to the leader’s position. When the leader moves, the vehicle will sense their new position and start re-planning accordingly. The only time the leader needs to interact with the vehicle is to stop the leader-follower behavior.

The operator is also able to tele-operate the vehicle either as the primary method of control or when taking over from an autonomous behavior. On the tablet, hardware joysticks provide both steering and speed control, but in the event of a hardware failure or by user selection, onscreen controls are available. The onscreen controls are the main method of teleoperating using the handheld device, but the operator also has the ability to plug in an external gamepad.

3.5.3 Diagnostics

DSAT utilizes the vehicle management system (VMS) to report the vehicle’s system diagnostics to the controller. Among these diagnostics are sensor information, CPU temperatures, drive-by-wire information, and the current autonomy mode. The VMS keeps track of the status of various vehicle components and reports them to the controller in two ways: 1) via a list of the components’ statuses on the WMI’s Health screen, and 2) through warning, caution, alert, and notification (WCAN) messages. The components of the system publish their data periodically such that other components can use them. Since any node in the system can subscribe to another node’s published data, the VMS is able to “snoop” on certain data that it deems necessary for diagnostics. The VMS extracts this data and sends it to the controller at 1 Hz; the data is displayed on the Health screen, organized by subsystem and displayed as raw data, such that the operator can check on the status of the vehicle’s components at any time.

In addition to reporting the vehicle’s diagnostics to the Health screen, the VMS also analyzes the diagnostics data to determine whether something is at fault. If something is deemed at fault or is deemed recovering from a fault, the VMS publishes a WCAN message to the controller, which appears on the system bar of the WMI despite which screen is currently active, and thus ensuring that the operator takes notice. Each message contains text explaining the fault and has a symbol denoting the severity level: Warning for most severe, Caution for less severe, Alert for least severe, and Notification for either recovering from a fault or an otherwise useful piece of information that is not serious but the operator should know about immediately. The WCAN messages also show up chronologically on the WMI's Alert screen, on which messages can be deleted by the operator.

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