NEAR AUTONOMOUS UNMANNED SYSTEM (NAUS) ARMY TECHNOLOGY OBJECTIVE (ATO) PROGRAM RESULTS

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ABSTRACT

The NAUS ATO (2004-2009) was a follow-on program to the Robotic Follower ATO (2000- 2004) and built on the concept of semi-autonomous leader follower technology to achieve dynamic robotic movement in tactical formations. The NAUS ATO also developed and tested an Unmanned Ground Vehicle (UGV) Self-Security system capable of detecting, tracking, and predicting the intent of human beings in the vicinity of the vehicle. The ATO concluded its Engineering and Evaluation Testing (EET) with a capstone demonstration in October 2008. This paper will detail the technology developed and utilized under the program as well as report on the EET results to the robotic community.

INTRODUCTION

It is understood that the fight for today's soldier has changed from the one experienced by the soldier of the past [1]. It is realistic to expect that tomorrow's fight will also deviate from the one currently experienced by today's soldier. As part of this change it is expected that there will be a continued proliferation of technologies and that save lives; such as robotic systems.

Today, there are approximately 10,000 fielded robotic systems assisting our soldiers in protecting our country and its allies. Many of which are found in Iraq and Afghanistan. Unmanned Ground Vehicles (UGVs) are a subset of these fielded robotic systems. UGVs are currently being heavily utilized in Explosive Ordinance Disposal (EOD) and reconnaissance activities. It is expected that as the technology matures the missions for these systems will increase as will the soldiers expectations.

The ARMY's Research, Development and Engineering Command (RDECOM) has been working with the Assistant Secretary of the Army for Acquisition, Logistics and Technology (ASAALT) on advancing the current capabilities of today's robotic systems. These organizations have overseen and approved robotic ARMY Technology Objectives (ATOs) focused on increasing levels of autonomy. The NAUS ATO is a robotic initiative that focuses on advancing the state of the art for robotic systems in the areas of UGV Formation Control (FC) and Self-Security (SS).

PROGRAM BACKGROUND / ORIGINS

The NAUS ATO was originally termed the Armed Robotic Vehicle (ARV) Robotics Technology (ART) and was designed as a risk reduction effort for the Future Combat System's (FCS's) ARV. This TARDEC ATO was focused on addressing FCS risks associated with local situational awareness, tactical behaviors and self-security for the ARV system. The ART ATO also addressed risks for the FCS Multifunction Utility/Logistics Equipment Vehicle (MULE) and the FCS Autonomous Navigation System (ANS) related to ANS robotic platform integration as well as Unmanned Ground Vehicle safe operations.

In FY 06 the ARMY reorganized its research structure to combine similar efforts under broader categories. As part of this effort, ART was combined with an advanced UGV perception program at the Army Research Laboratory (ARL) and a UGV armament program at the Armaments Research, Development and Engineering Center (ARDEC). This new combined effort was titled the Near Autonomous Unmanned Systems (NAUS) ATO. The NAUS ATO became the single program of record for RDECOM technologies being developed for the FCS UGV community with a primary focus on the ARV.

In FY07 the FCS ARV program was deferred and sent to S&T for further refinement. This new S&T effort was titled the Robotic Vehicle Control Architecture (RVCA) [2] and was staffed through TARDEC. To support this new S&T objective TARDEC refocused its portion of the NAUS ATO toward advancing key enabling technologies in the areas of UGV Formation Control (FC) and Self-Security (SS). FC and SS were both underdeveloped UGV capabilities that were high on the FCS ARV list of technological risks.

The FC portion of the NAUS ATO built upon the concept of UGV leader-follower technology developed under Robotic Follower (RF) ATO. However, while FC is similar in concept to RF (e.g. UGV following a path determined by a manned system) it deviates significantly in approach and level of complexity. Under the RF program it was shown that technology existed at Technology Readiness Level (TRL) 6 [3] to allow a UGV to follow a path previously traversed by a manned system [4]. This was accomplished through sharing of GPS bread crumbs and other locally sensed data. Under the FC effort the concept was altered to now enable UGVs to follow the path of a manned vehicle while maintaining and changing tactical formation [5]. This is a significantly more difficult task to execute as the UGVs no longer benefit from the assumed-safe path traversed by the manned system. The UGVs are now required to operate at a higher level of autonomy [6] to accomplish the mission objective. These systems not only need to react to the non-traversed terrain they encounter (e.g. no longer directly following the path of the manned vehicle) but also arbitrate when it is appropriate to break formation due to local terrain conditions and then reengage in formation.

The SS portion of the ATO effort focused on advancing the state of the art of local UGV self-security/protection. This effort built upon the technology developed under the PM Force Protection program titled Mobile Detection Assessment and Response Systems (MDARS) [7]. However, unlike MDARs concept of using a UGV controlled and monitored by an operator to secure the perimeter of a base/location, NAUS focused on developing automated detection and deterrence algorithms to deter individuals from approaching the UGV. The algorithms developed enabled a level of UGV pedestrian intent inference.

TECHNOLOGY DEVELOPED

ART Effort

The M113 family of vehicles was chosen as the starting point for the ART Chassis because both vehicles and spare parts were readily available. A series of trade studies for mobility performance were completed to select the chassis and drive options. The M113A2 vehicle with a front drive option and the driver in the robotic module was chosen as the ART Autonomous Vehicle Test bed (AVT).

Development of the AVT test bed was undertaken and the development schedule consisted of the following steps.

- GFE Vehicle Assessment, Vehicle Detail design, Vehicle hull modification, automotive integration, Automotive and System Check-Out activities.
- Vehicle architecture development, Vehicle LRU (Line replaceable unit) and Harness Design, Fabrication, Installation and Inspection.
- Robotic Module & Basket Design, Fabrication, Installation and Performance testing.

The system design and integration approach for the M113 based surrogate platform included the following system / sub system integration activities.

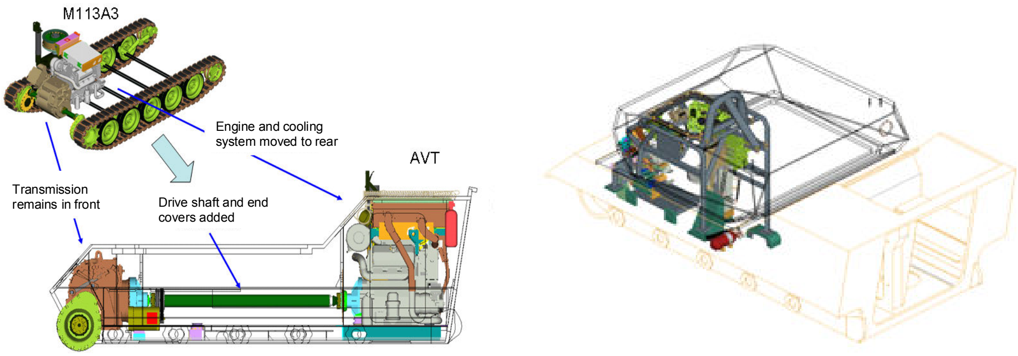
The decision to use tracks on the ART vehicle was made following the conclusion of the track vs. wheels study on the ARV Program, and ARV's subsequent decision that the vehicle will be tracked. A rear engine concept was selected to lower the front two thirds of the chassis structure in order to provide a lower mounting plane for the robotic module, thus resulting in a lower vehicle profile.

A trade study was conducted to determine if the drive sprockets should be located in the front or rear of the vehicle. Three rankings were assigned: 3—easiest; 2—higher cost, and 1—most difficult/costly. The front sprocket design was the preferred option based on the results of the trade study. Mobility performance trade studies were conducted to validate the results of the drive sprocket trade study. The results of the drive sprocket trade study were accepted because there was no anticipated mobility performance that would have overridden them. The front drive concept with driver in the robotic module and a power pack was chosen for the ART Vehicle. Both the ART chassis and the robotic module were provided with their own separate power generation systems.

The M113A3 selected for modification to ART was officially transferred into the contract. The major vehicle modifications included removing the upper forward two thirds of the hull (see Figure 1- top right), relocating the engine to the rear (see Figure 1- bottom left), modification of the suspension for the equal length band track, modification of the air cleaner, modification of the intake/exhaust grill, and relocation of the driver's station (see Figure 1- bottom right) 13 inches to the rear and 8 inches up. The ART Performance Metrics are shown in Figure 2, and the ART vehicle is shown in the top-left of Figure 1.

AVT (ART Autonomous Vehicle Test bed)

Hull Modification



Engine Relocation

Safety Operator / Driver's Station

Figure 1: M1113A3 Modifications for the ART Program

	ARV Requirement	ART Platform Requirement	ART Platform Performance
Hard surface road	50 kph	50 kph	66 kph
Cross country	35 kph	40 kph	40+ kph
Acceleration (0 to 48 kph)	< 10 sec	< 10 Sec	< 10 Sec
Grade @ 5 kph	60%	60%	60%
Side slope	40%	40%	40%
Vertical step	0.5 m	0.5 m	.61 m (Fwd)
Gap	1.0 m	1.0 m	1.68 m
Fording	0.6 m	N/A	> 1M
Minimum turn radius	7.5 m wall-to-wall	N/A	Axis turn

Figure 2: ART Performance Metrics

NAUS Effort - UGV Self Security

UGV-self security poses some challenges not normally encountered in other surveillance systems. As opposed to other surveillance systems, UGVs are mobile, and therefore, the advantages offered by the terrain cannot be easily utilized. For example, in most installations it is easy to have full coverage of entryways utilizing sensors with limited field of view. This is not a luxury available to UGVs since the location of the UGV may not provide this tactical advantage (see Figure 3). The problem is further complicated from the fact that most surveillance systems are manually tuned for the location in which they are placed. This tuning involves, pose selection, sensor adjustment to reduce reflections and shadows, etc. In order to make UGV-self security a successful, much of this manual adjustment needs to be automated to cover a variety of conditions that the system will encounter.

Figure 3: UGV in the field without tactical advantage of environment.

In past programs, autonomous vehicles have been able to approach higher speeds in leader follower modalities (Vetronic Technology Integration, Collaborative Technology Alliance, etc). The reason for this improvement in speed over non leader-follower techniques is as follows:

- Leader-follower systems can utilize the sensors in the first vehicle humanly driven vehicle to “extend” the range of followers by communicating sensed data.

- The leader proves the path followed by the follower, and therefore, we can assume that the particular trajectory is devoid of negative obstacles

- The velocity that the manned leader drives the terrain is a good measure to be used by followers.

Most of these advantages disappear with other formations since the leader is traversing different terrain than the follower. The level of complexity of following non-column formation is closer related to fully autonomy, where each vehicle is responsible for proofing its own terrain. This is further complicated by issues like coordinating the vehicle control, and changing the formations to collaboratively avoid obstacles. Changes in formation also forces the system to coordinate the plan for the motion of the group as opposed to the more common independent planning that happens in most autonomous UGVs.

Technology Overview

The purpose of System Self Security (SSS) is to monitor and respond to local dismounted personnel that might interfere with the Unmanned Ground Vehicle's (UGV) mission or harm the UGV.

SSS actively detects, monitors, and interacts (if necessary) with personnel and vehicles that approach into close proximity of the UGV. The SSS uses appropriate warnings, threats and actions to detect, assess, avoid, and when needed, mitigate hazards.

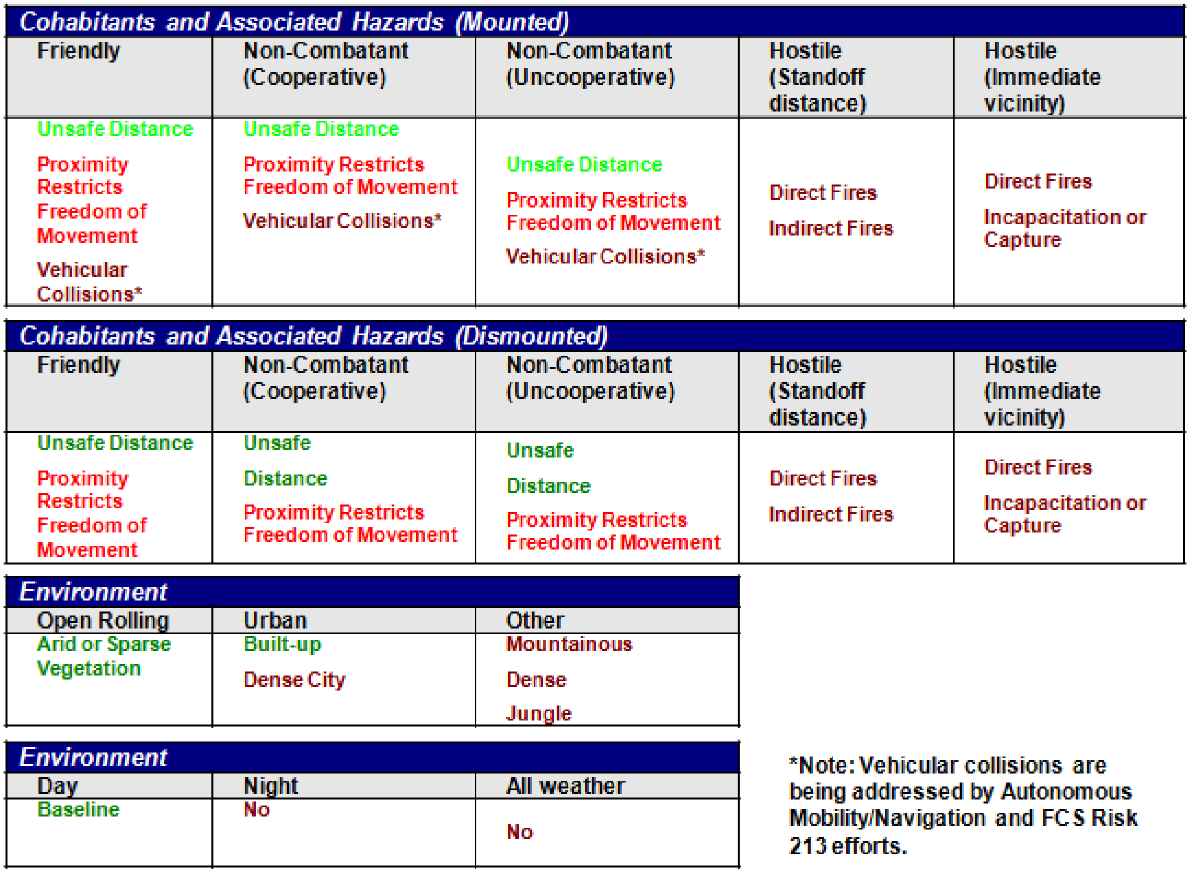
SSS uses the Intruder Detection System Radar (IDSR) to detect persons walking or crawling in proximity to the vehicle and then takes action using the Local Persons Combat Identification (LPCID) algorithm and vehicle subsystem responses, to determine if a track is cooperative or uncooperative. SSS directs "Local Security Responses" (LSR's) to the track such as sounding an aural signal through a mounted speaker, shining a light and/or revving the UGV's engine and then observes the track's reaction based on movement after the issuance of the LSR. The LPCID advises the remotely-located Operator Control Unit (OCU) of changes in the track's apparent intention.

For the NAUS program, SSS utilized a radar based system which functioned only while the vehicle platform was stationary. At present, the radar cannot function from a moving platform, thus hazard detection and mitigation during platform movement was not tested.

The IDS radar is leveraged from the Mobile Detection Assessment Response System (MDARS) program which recently began limited low-rate production (LLRP).

Operational Capability

Figure 4 depicts the operational capabilities targeted by the NAUS SSS effort.



Cohabitants and Associated Hazards (Mounted)				
Friendly	Non-Combatant (Cooperative)	Non-Combatant (Uncooperative)	Hostile (Standoff distance)	Hostile (Immediate vicinity)
Unsafe Distance Proximity Restricts Freedom of Movement Vehicular Collisions*	Unsafe Distance Proximity Restricts Freedom of Movement Vehicular Collisions*	Unsafe Distance Proximity Restricts Freedom of Movement Vehicular Collisions*	Direct Fires Indirect Fires	Direct Fires Incapacitation or Capture

Cohabitants and Associated Hazards (Dismounted)				
Friendly	Non-Combatant (Cooperative)	Non-Combatant (Uncooperative)	Hostile (Standoff distance)	Hostile (Immediate vicinity)
Unsafe Distance Proximity Restricts Freedom of Movement	Unsafe Distance Proximity Restricts Freedom of Movement	Unsafe Distance Proximity Restricts Freedom of Movement	Direct Fires Indirect Fires	Direct Fires Incapacitation or Capture

Environment		
Open Rolling	Urban	Other
Arid or Sparse Vegetation	Built-up Dense City	Mountainous Dense Jungle

Environment		
Day	Night	All weather
Baseline	No	No

*Note: Vehicular collisions are being addressed by Autonomous Mobility/Navigation and FCS Risk 213 efforts.

Figure 4: Operational Capability (Colored text indicates capability either SCHEDULED, SCHEDULED BUT NOT IMPLEMENTED or IS NOT ADDRESSED by current SSS development scope.)

Architecture

Figure 5 is a top level block diagram of the system software and the physical connections between the software components. The LPCID component was developed entirely on NAUS.

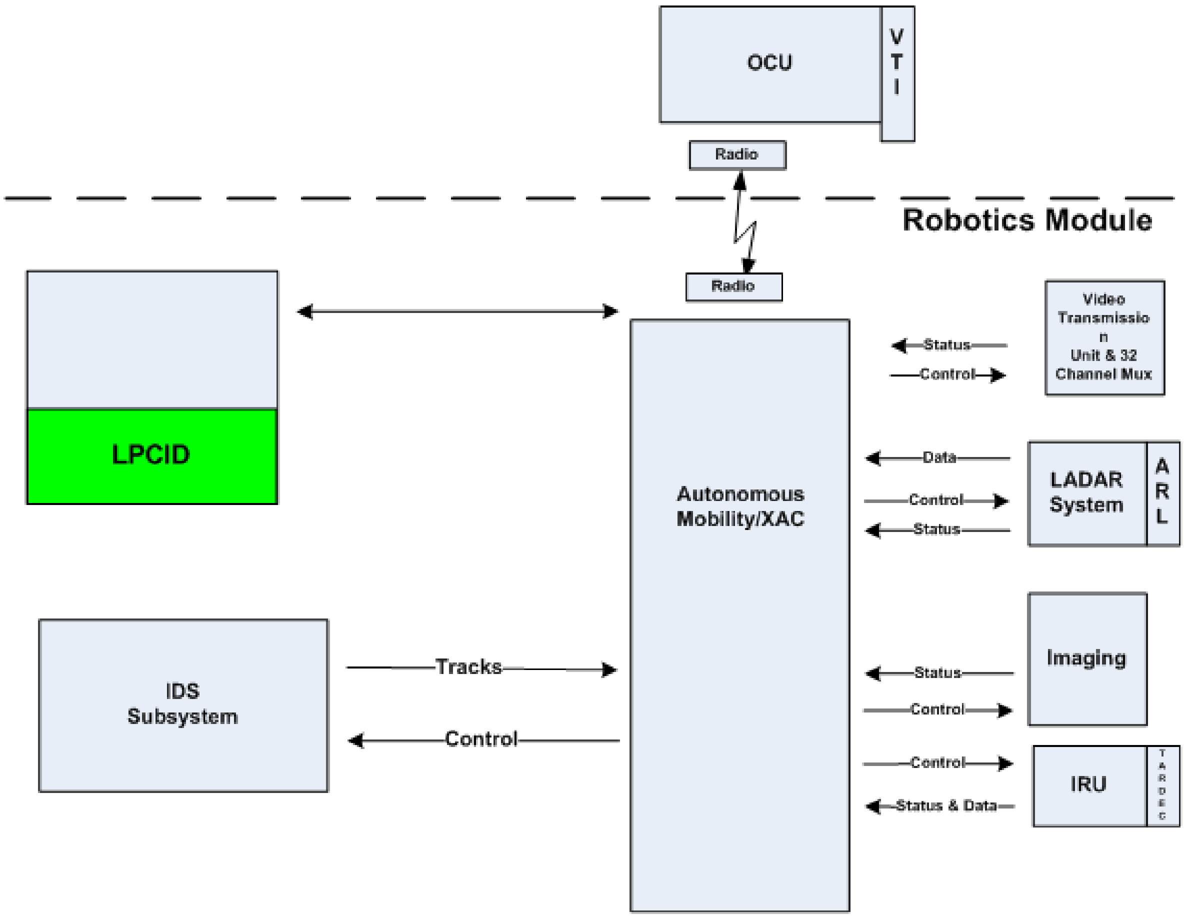


Figure 5: NAUS LPCID System Software and Physical Connections

<u>Subsystems</u>

1) Track detection subsystem.
    - NAUS uses the IDS subsystem to process raw radar returns into a coherent array of relevant tracks.
2) Rules that operate on world state
    - The LPCID applies rules to each track's reactions to LSRs to determine if the track is uncooperative (i.e. generally ignores warnings and threats) or cooperative (i.e. generally heeds warnings and threats).
3) Vehicle subsystems
    - All vehicle subsystems capable of producing LSRs interface through eXternal Autonomous Controller (XAC).
4) OCU
    - The OCU will show to the operator all tracks and their affiliations.

Subsystem Extensibility

The SSS architecture is an extensible framework that allows:

1) Addition of new track detection systems – SSS is architected so that it can replace IDSR and PDS with new track detection systems possessing increased capabilities as they become available.
2) Ability to refine rules operating on track behavior – The SSS is tasked with interpreting track behavior to determine the correct affiliation for each track. The algorithms implemented in these rules will be improved over time to correctly interpret more complex sets of behaviors.
3) Incorporating new LSRs – SSS architecture is architected so that new LSRs using existing vehicle subsystems and new LSRs using new vehicle subsystems can be added.

LPCID Design Overview

LPCID functional block implements the SSS decision making behaviors. As depicted in the block diagram (see Figure 5), the LPCID interfaces with track detection systems to receive track data. The LPCID interfaces with the XAC to send LSR execution commands. The interface to the XAC is also used to collect information on which recommended LSRs were approved, LSRs' execution status, and to pass track information to the OCU.

The inputs to LPCID include track behavior parameters, situational awareness, and track data and attributes. Behavior parameters characterize track initial state and reactions to Local Security Responses. Behavior parameters combined with the track data and attributes are used to determine the track's affiliation. Situational awareness includes information such as the defined level of aggressiveness and risk tolerance.

Test Bed Platform – Experimental Unmanned Vehicle (XUV)

The XUV shown in Figure 6 serves as the test-bed platform for integration and testing of technologies. The XUV has a mobile and a stationary capability. The XUV can be operated by trained operators during day, night and limited adverse weather conditions.

Figure 6: NAUS Test Bed Platform

XUV Platform Mobility

The XUV is 118 inches long and 66 inches wide. It has a 17-inch clearance on the side and a 14-inch clearance in the center. It can traverse slopes with grades of 60% fore and aft and 40% to the side. The XUV can be placed on a trailer for a mode of transport recovery. It has a turning radius of 128 inches.

The XUV utilizes full-time four-wheel drive and four-wheel Ackerman hydraulic steering. It has 78 gallons per minute (GPM) hydrostatic transmission, fail-safe hydraulic emergency brakes and two-speed hydraulic wheel motors.

XUV Operating Speeds

The XUV is powered by a 1.9 liter, 4-cylinder diesel engine that is located in the center of the XUV platform.

Communication

The XUVs communication system is composed of off-the-shelf components and subsystems. Communication data includes vehicle control, sensor and camera imagery, route and map information and terrain classification. The communication system is made up of the following components:

1. Wireless LAN Radio
2. Emergency Stop Radio (ESR)
3. Tele-operation Radio

The safety radio operates independently of any other system to implement an XUV system shutdown. The kill switch is operable at a distance of no less than 1-km when line-of-sight can be maintained to the vehicle. If the safety radio becomes too far from the XUV or the batteries run low the XUV will automatically shutdown.

Safety

The XUV is safely operable in mixed forces (mounted and dismounted, manned and unmanned) in accordance with the basic requirements outlined in MIL-STD-1180 and MIL-STD-882D. These military standards support the basis for this SAR.

XUV Operator Control Unit (OCU)

The XUV OCU utilized a standard laptop computer. It is fully capable when utilizing a standard military Digital Terrain Elevation Database (DTED II) map data. The OCU provides the operator interface to the XUVs, displays, planning, situation and terrain visualization. It is capable of communicating with a XUV to determine the platform's system-self- security status and instructing the XUV to take self-security measures to prevent tampering with the platform.

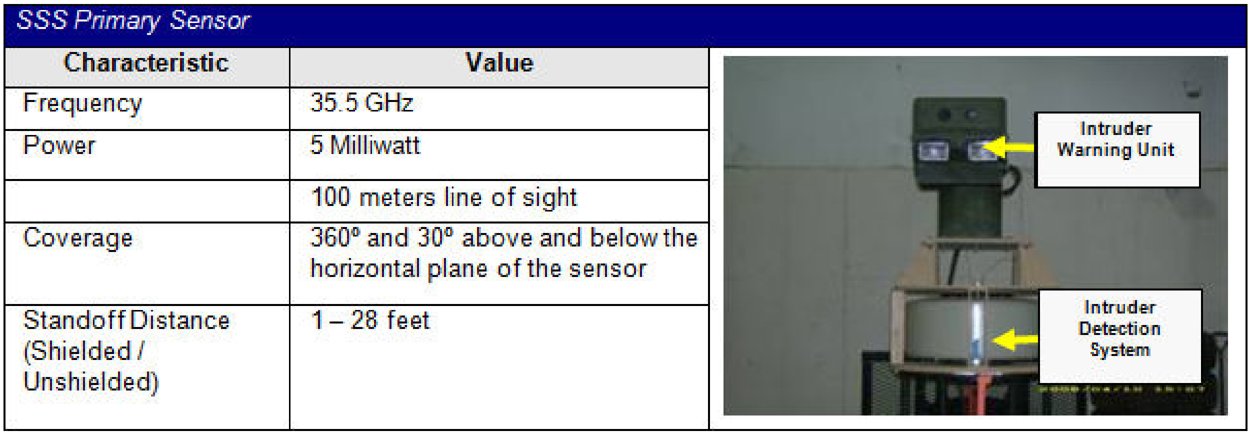
Navigation Components

The XUV navigation system consists of the following hardware which provides the position of the XUV during operations:

- GPS Receiver
- Inertia Reference Unit (IRU)
- Odometer Sensors (Located on each XUV wheel)

Primary Sensor Component – Intruder Detection Sensor (IDS)

The NAUS-ATO XUV is equipped with an intruder detection sensor (IDS). The general characteristics of the IDS are detailed below in Figure 7.



SSS Primary Sensor

Characteristic	Value
Frequency	35.5 GHz
Power	5 Milliwatt
	100 meters line of sight
Coverage	360° and 30° above and below the horizontal plane of the sensor
Standoff Distance (Shielded / Unshielded)	1 – 28 feet

Figure 7: NAUS SSS Primary Sensor

The IDS is leveraged from the Mobile Detection Assessment Response System (MDARS) Program which recently began limited low-rate production (LLRP).

The IDS is used to generate and send human tracking data to the XUV OCU while the XUV is stationary. The IDS is capable of detecting the motion of an upright and moving human intruder to a range of at least 100m line-of-sight (LOS) over 360º and 30º above and below the horizontal plane of the sensor. Detection can occur within ten (10) seconds of the XUV stationary with the engine running. A Battle Space Object (BSO) appears on the OCU corresponding with the target's position as it is detected. This is shown below in Figure 8.

Figure 8: NAUS XUV with mounted IDS radar and LSR pedestal

UGV Formation Control

Formation Control (shown in Figure 9) reduces the cognitive load on the formation leader and allows the leader to rapidly react to terrain and tactical situation with simple verbal battle directives. The XAC Level Planner (XLP) Formation Control (FC) subsystem allows an unmanned ground vehicle (UGV) with an Autonomous Mobility System (AMS) to safely and effectively move in formation, i.e. maintain relative tactical position with respect to a lead vehicle while in the presence of other formation vehicles. Using the OCU, the formation leader can easily form up and modify the formation parameters (spacing, relative bearing, direction) as well as command changes in direction while on the move.

Figure 9: NAUS XUVs in formation following lead HMWVV

Formation Control’s high-level task breakdown is as follows:

- Employ Operational Command Language (OCL) and Automated Command and Control (ACC) near-term route re-planning in combination with existing eXternal Autonomous Control (XAC) /AM Move-on-route (MOR) and Pause/Resume capabilities to key off of the Leader’s navigation state and formation control directives in order to determine the follower’s immediate movement plan.

- Augment digitally communicated position sharing with a 360˚ situational awareness capability that can track formation vehicles while on the move, where the Lead vehicle is initially specified to the system through digitally communicated vehicle identification and location. Vehicle tracking will be accomplished using Global positioning System (GPS) Navigation (NAV) and eventually, testing the value of a Ultra Wide Band (UWB) radio system in the improvement of formation integrity.

- Monitor communications connectivity status and actively determine line of sight outages and use these trigger events within the ACC framework to employ situation dependent “loss of geometric spacing integrity”, “loss of communications” and responses/actions/procedures that consider rules of engagement; local security response assessment and response mechanisms will be extended for these purposes.

Technology Overview

The control system is based on a hierarchical control system loosely following the 4D/RCS architecture. In this architecture, the commands are propagated from the top of the architecture to the bottom. While sensing and perception flows upwards.

Figure 10 shows a general system diagram of the system being utilized. The manned leader is equipped with a navigation system. This system provides location as well as orientation of the lead vehicle. This localization as well as the localization of the followers is fed to the Formation Planner module. This module is in charge of planning the coordination of the group of vehicles. During this program efforts were made to make the leader vehicle hardware independent as to make the results more universal. Two configuration were tested for the leader, one only including a GPS unit for localization, and a second system was also tested which included both a GPS and an IMU and therefore providing a more accurate heading estimation.

Tests performed at Grayling, MI concluded that the more accurate heading estimation provided for a more accurate formation control.

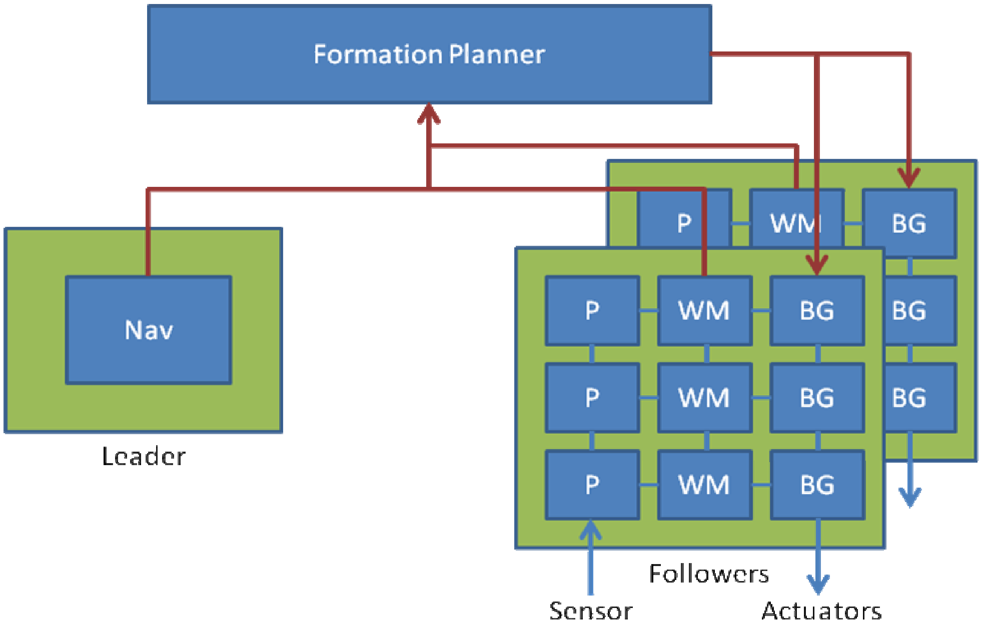


Figure 10: General System diagram for NAUS Formation Control

Architecture

Figure 11 is a top level block diagram of the Formation Control (FC) system software and the physical connections between the software components. The software was developed entirely on NAUS.

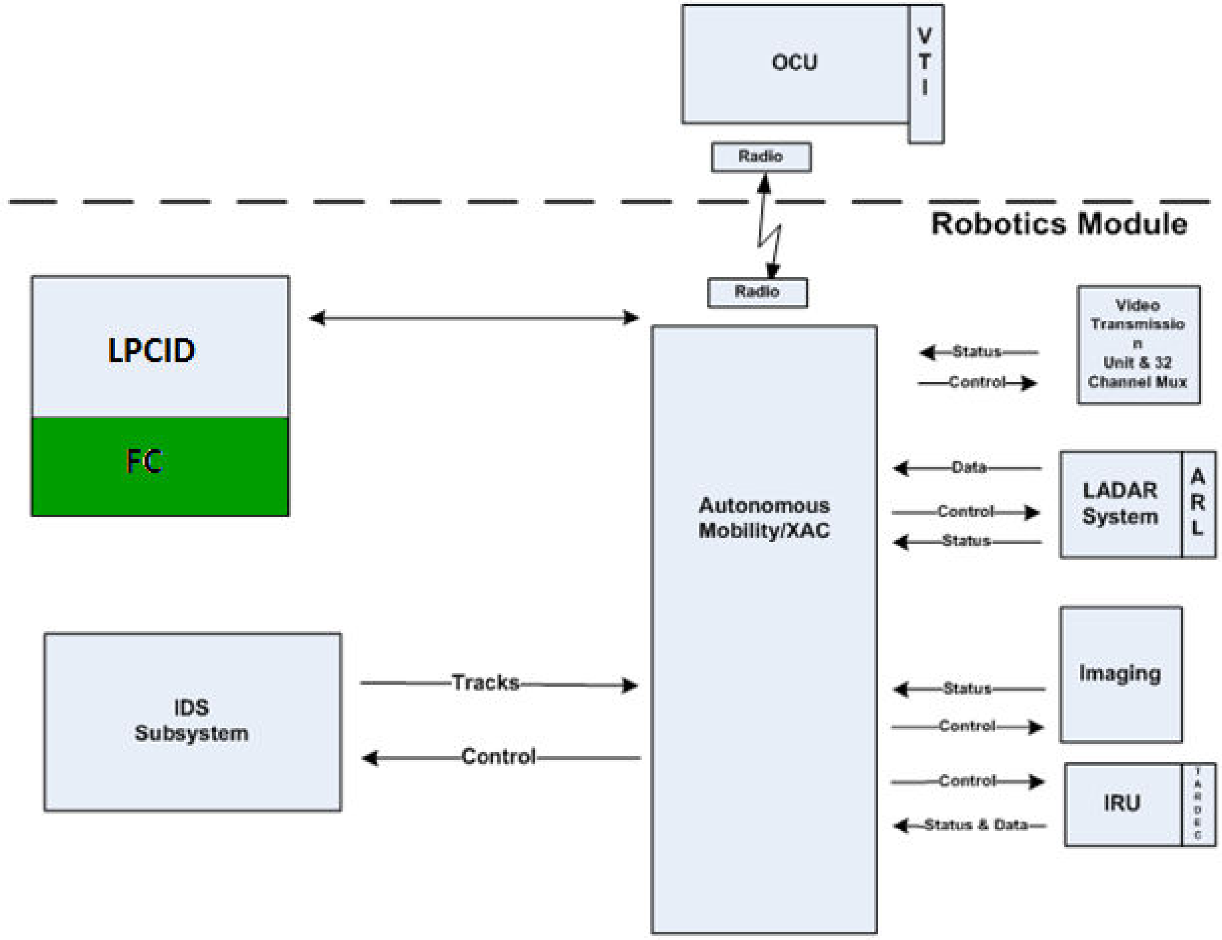


Figure 11: NAUS FC System Software and Physical Connections

Subsystems

- XLP subsystem.
    - ◊ Accepts OCL command language describing the formation
    - ◊ Commands the formation assets to move in formation
    - ◊ Monitors the formation assets to inform of formation deviation
- Rules that operate on world state
    - ◊ Vehicle positions, speed, heading

- Vehicle subsystems
- UWB relative positioning system
  - ◊ NAV supplement to improve formation performance
- OCU
  - ◊ Informs operator of formation assets intended routes

Design Overview

The Formation Control functional block shown in Figure 12 implements the decision making behaviors as follows:

The operator inputs the formation directive by inputting OCL into the OCU interface. As depicted in the block diagram show below, the XAC DDI/DX processes XAC messages and sends OCL messages to the OCL parser. The OCL parser validates the OCL and triggers a rule that directs each formation follower into proper formation position relative to the leader's current position.

Before leader information reaches the route planning module, it goes through a low-pass digital filter. This filter removes noise in the data associated with variations in GPS as well as small route deviations by the leader. Essentially, the leader's route is smoothed to allow for a more accurate follower path.

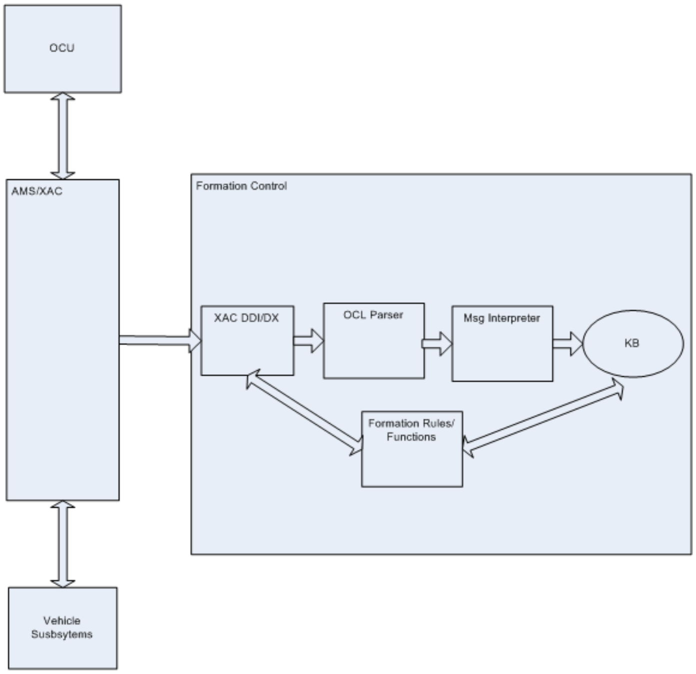


Figure 12: NAUS FC Functional Block

Planning States

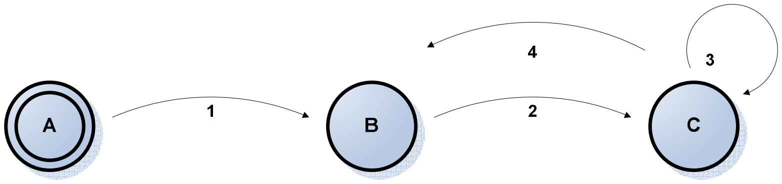


Figure 13: NAUS FC Planning States

States

A. Start state – Represents the system before any formation OCL is received

B. Initialization state – System during its first route plan.

C. Normal operation state – State of the system during most of formation control. Replans for the follower are done at regular intervals

Transitions

1. Formation OCL is received by the XLP.
2. An initial route plan is sent to the follower.
3. Route replan is sent.
4. New formation OCL is received.

Re-planning

During normal operation, re-plans are done every R seconds where R is the re-plan rate from the configuration file. For best performance from a formation perspective, re-planning should be done as often as possible which in this case is 1 second. This is the fastest it is possible for the follower to get new data.

Filtering

When it is time for a re-plan, the most recent leader information is retrieved from the KB and most of it is passed through a low-pass digital filter. This is done in order to remove any noise, such as GPS error, in the leader's information. Essentially, the leader's route is smoothed to allow for a smoother follower path.

Some sort of filter or smoothing is necessary to keep the follower's path from reflecting noise or small variations in the leader's path from doing things such as avoiding a small obstacle. Low-pass digital filters, best-fit line, and best-fit curve were all investigated and in the end a second-order Butterworth filter produced the most desirable behavior.

As mentioned above, not all of the leader's information is passed to the digital filter. The leader's speed is not filtered at all. Initially, this too was filtered however, because this filter introduces a slight lag in the leader data, the follower was not getting accurate enough leader speed in order for it to maintain its relative position to the leader. When speed was being filtered the follower would often overshoot its desired position by a considerable amount causing the follower to stop and then to fall behind its desired position before it could get moving again.

The parameters that are being filtered: position and heading, behave differently and have different effects on the follower's performance so they require different filter tuning parameters. Numerous trials were run to determine the optimal filter parameters for this information and it was discovered that the heading filter had to be much more restrictive than the position parameter.

Projection

Once the leader's information has been filtered it is passed to the projection module. The projection module takes the leader's current information and calculates where the leader will be in P seconds based on this information. P is a configurable number of seconds for the projection module to project into the future. Some projection is necessary so that the follower can be told where it should be in the future so that it has time to react rather than calculating where it should be right now, something that can't be changed. With projection time there are tradeoffs to be considered when choosing a value. A low projection time, 3 sec. for example, can lead to a fairly accurate point because the leader's speed and heading are unlikely to change much in that time. However, if there is a problem, like a communication outage, then the follower only has a route for the next 3 seconds before it will halt. A longer projection time, for instance 10 seconds, gives the follower a longer route but can also lead to a much less accurate point. Any error in the leader data will be compounded for an even longer period of time.

Route design

After projection, the newly derived leader position is passed to the formation route planning module. This module derives the follower's desired position based on the projected leader position and the formation parameters. A route is then planned where the first waypoint is the follower's current position, the second waypoint is the derived desired follower position and then a third point is added out beyond the desired position so that the follower will not slow down as it approaches the desired position. While this is the standard method for generating a plan for the follower there are a couple of special cases.

In the case where the leader vehicle is halted, it is correct for the follower vehicle to halt when it reaches its desired position. To achieve this, the third waypoint is not added to the follower's route. The other special case occurs when the follower is ahead of its desired position in terms of the direction of travel of the formation. Here, it is not desirable for the follower to drive the opposite direction of the formation in order to get in position when it's possible that the formation could just catch up to the follower. When this happens the follower is given a zero point route so that they halt where they are.

In addition to the waypoints, the formation planning module also sets the speed of the route. Separate route segments are used so that a specific speed can be set for the follower from point 1 to point 2 and then a different speed if desired from point 2 to point 3. The speed for the second segment is set to 1 m/s because if the follower reaches this segment before a re-plan happens that means it overshot its desired position and should slow down so as not to get too far out of position. The first speed is calculated by taking the length of the segment and dividing it by the projection time. This way, the follower should reach its desired position at the same time the leader is reaching its projected position.

One problem encountered here is that the speed that's being set for the route is a max speed for the follower vehicle. The AM system on the follower can choose to go slower based on the terrain or other factors and so the speed being set is more of a suggestion. This can make keeping in formation difficult as the XLP has no direct control of the throttle.

When the route planning module completes a plan it is sent out both through xac_ddidx and also through smi_ddidx. The route that goes out through xac_ddidx goes straight to AM and commands the follower to perform a Move-on-route (MOR). The plan that goes through smi_ddidx goes to the operator's OCU so that the operator can see where the follower is planning to drive and can cancel or take control of the vehicle if there appears to be a problem.

Test Bed Platform – Experimental Unmanned Vehicle (XUV)

The XUV detailed in the previous section (see page X) was also used for this effort.

RESULTS

The following section briefly details the results of the NAUS ATO Self Security Systems and Formation Control efforts. The first half of this section is devoted to the accomplishments of the UGV Self Security System and is followed by the projected next steps in the effort. The Second half of the section is devoted to the Formation Control work to date and then the projected next steps in this effort as well.

UGV Self Security

Performance Objectives

System-Self-Security (SSS) EET-08 Capability Performance Goals		
SSS System Capability	**Minimum**	**Goal**
Probability of true positive target detection (% of time)	60%	70%
Probability of false positive target detection (% of time)	30%	20%
Average target classification (ID) time (Seconds)	30 Seconds	25 Seconds
Target range (Meters)	100 Meters	200 Meters

Figure 14: SSS EET-08 Capability Performance Goals

System Self Security Engineering Evaluation Test Objectives/Results (EET-08)

SSS EET-08 Test Series 1.0 Objectives/Results

- Evaluate the capability of the automated SSS System to tailor the LSRs (warnings and threats) it issues to detected local targets based on the speed of the detected local targets toward the established SASO and combat keep out zone boundaries.

- Evaluate the capability of the automated SSS System to issue escalating LSRs (warning and threats) to detected local targets in order to speed up the system's target assessment and classification process.

- Evaluate the capability of the automated SSS System to modify the LSRs (warning and threats) it issues to detected local targets to be more or less aggressive based on the "movement posture" (crawling, walking, or running) of detected local targets in order to provide a faster (more secure) or slower (less threatening) target assessment and classification process.

- Evaluate the capability of the automated SSS System to assess and classify up to 5 detected local targets.

CAPABILITY	AVG DETECTION (M)	AVG CLASSIFICATION (SECS)	% POSITIVE TARGET DETECTION
MINIMUM	100	30	60
GOAL	200	25	70
SASO	73.87	22.06	
COMBAT	83.91	21.97	
ALL	N/A	N/A	100

Figure 15: SSS EET-08 Results

SSS EET-08 Test Series 1.0 Comments

- Detection ranges on average were 73.87 and 83.91 meters respectively for SASO and Combat environments. Classification times on average were approximately 22 seconds for both environments. All targets were positively classified.

SSS EET-08 Test Series 2.0 Objectives/Results

- Evaluate the capability of the automated SSS System to detect and correctly assess and classify local targets as neutral or hostile based solely on the movement posture of the local target (The SSS System will not issue any visual or audible local security responses (LSR) to detected local targets). Neutral targets were not properly assessed.

SSS EET-08 Test Series 2.0 Comments

- LSRs were restricted during this test series and classification was solely based on movement. Neutral targets were not properly assessed since no LSRs were used to monitor behavior.

SSS EET-08 Test Series 3.0 Objectives/Results

- Evaluate the capability of the automated SSS System to constrain its LSRs (warnings and threats) based on pre-determined LSR rules of engagement (ROE).

SSS EET-08 Test Series 3.0 Comments

- Certain LSR classes were constrained in this test series. For example, one test constrained LSRs to no sound, another test constrained LSRs to no light. All targets were properly classified.

SSS EET-08 Test Series 4.0 Objectives/Results

- Evaluate the capability of the automated SSS system to correctly constrain processing of targets (tracks) to those targets within the system's assigned sector to observe.

SSS EET-08 Test Series 4.0 Comments

- The system was successfully able to restrict to contiguous sectors to observe (SOB) (i.e. 90 degree wedge) to classify tracks. Tracks that did not enter the SOB were ignored 100% of the time. Figure 16 shows a graph, from trial 4.2, illustrating a SOB of 270-180. In this trial, there were 4 tracks, however, only 3 tracks are visible as the fourth track was outside of the system's SOB and was ignored by the system.

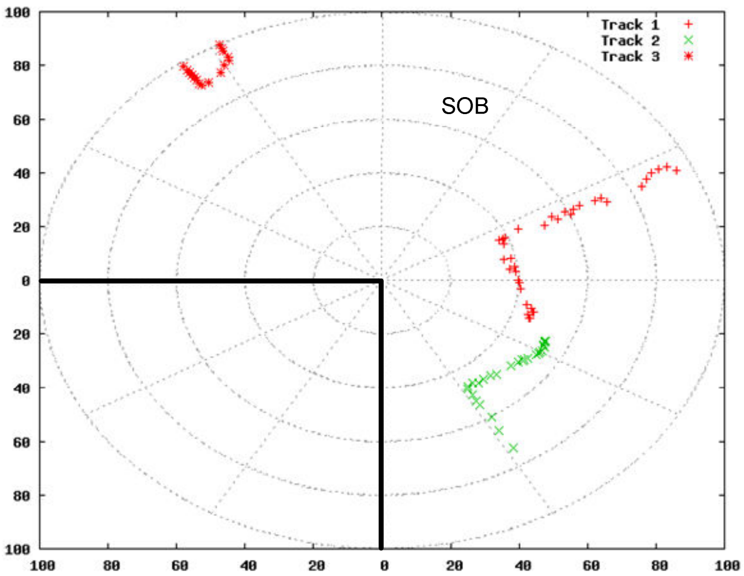


Figure 16: SSS EET-08 Test Series 4.0 Tracks

SSS EET-08 Test Series 5.0 Objectives/Results

- Evaluate the capability of the automated NAUS-ATO System-Self-Security system to maintain a track on a detected local target that is moving but temporarily occluded.

SSS EET-08 Test Series 5.0 Comments

- The system was successfully able to continuously monitor some tracks after being occluded, but other tracks were "lost" and reassigned as a new track. Figure 17 shows trial 5.2 where three of the four tracks were maintained for the whole test and one of the tracks was "lost" and became a new track.

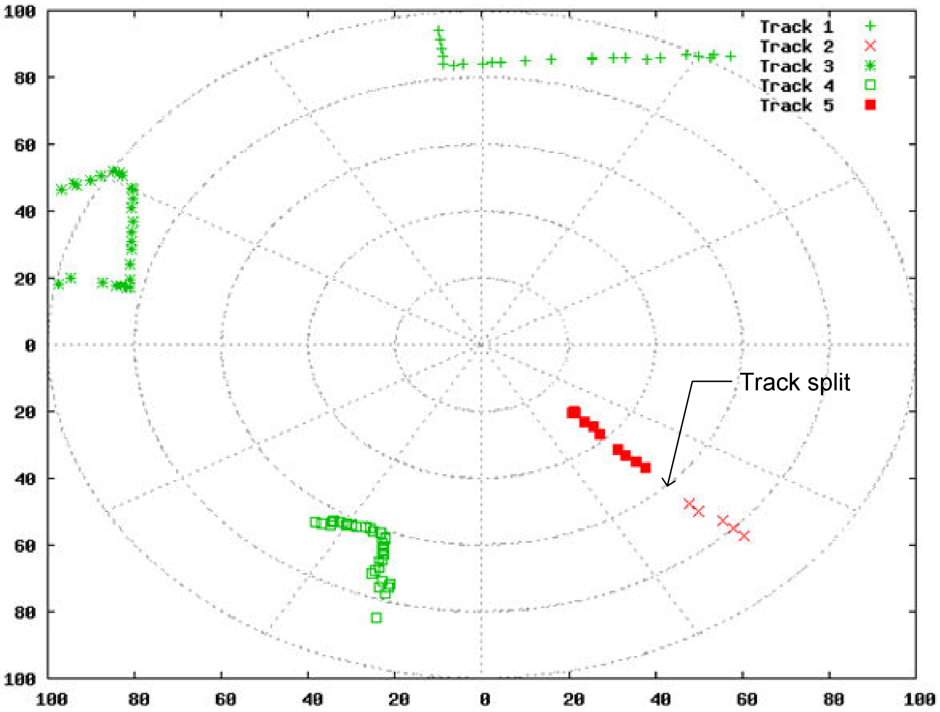


Figure 17: SSS EET-08 Test Series 5.0 Tracks

<u>Next Steps</u>

A portion of the operational capability matrix was implemented under the NAUS Program. Future efforts should tackle the following areas:

- **Proximity Restricts Freedom of Movement**
  - ◊ This requires sensors that operate while moving.
- **Dense City**
  - ◊ This requires a vehicle that can operate in an urban environment and obey traffic laws.
- **Night**
- **All weather**

UGV Formation Control

Performance Objectives

Formation Control (FC) EET-08 Capability Performance Goals		
FC System Capability	**Minimum**	**Goal**
Maximum deviation separation distance (heading rate +/- 3% deg/sec)	10%	5%
Average speed (meters per second)	4	8
Interventions (Qty)/ Kilometer	0 / 1 KM	1 / 3 KM

Figure 18: FC EET-08 Capability Performance Goals

Formation Control Engineering Evaluation Test Objectives/Results (EET-08)

FC EET-08 Test Series 1.0 Objective/Results

Evaluate the capability of the Formation Control (FC) subsystem to accurately project the leader's actual path

- Compare actual versus projected leader position (average)
- Compare actual versus projected leader heading (average)

FC EET-08 Test Series 1.0 Results

CAPABILITY	**PROJECTED LEADER POSITION error (meters)**	**PROJECTED LEADER heading error (radians)**
MINIMUM	N/A	N/A
GOAL	N/A	N/A
RESULTS	5.0349	0.0055

Figure 19: FC SSS EET-08 Test Series 1.0 Results

FC EET-08 Test Series 1.0 Comments

- The 1.0 series of tests represents how accurately the system predicts the leader position in the future

- FC utilizes two navigation solutions to accurately measure the leader's current position and orientation: Relative and Absolute.

- The relative navigation solution provides high bandwidth instantaneous measurements of position and orientation from an Inertial Measurement Unit (IMU) sensor. The sensor incorporates gyroscopes and accelerometer sensors to make a best estimate of the leader's position, orientation, orientation rates, velocities, and acceleration.

- The absolute navigation solution provides lower bandwidth measurement of the absolute location of the leader's position in the world using a Global Positioning System (GPS) WAAS sensor.

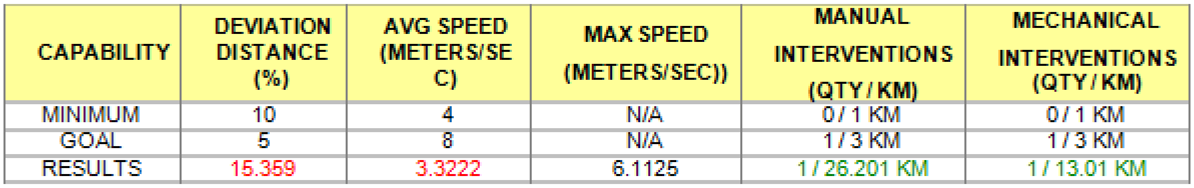
- The leader's current position and orientation is a combination of both relative and absolute solutions. The leader's path is then smoothed using a low-pass filter and a linear projection is computed to derive the future position. The data indicate a 5.0534 meter error in projected versus actual position with a 0.005 radian error in heading.

FC EET-08 Test Series 1.0 Conclusions

- Upgrading the leader vehicle's IMU sensor would improve performance of the relative navigation solution, and may reduce the leader position error.

FC EET-08 Test Series 2.0 Objectives/Results

- Evaluate the capability of the Autonomous Mobility System (AMS) to maintain formation position in restricted and unrestricted terrain.
- Evaluate actual formation position versus desired formation position.
- Evaluate average and maximum speed for the test runs.
- Evaluate number of stoppages due to manual interventions related to safety concerns.
- Evaluate number of stoppages due to mechanical issues.



CAPABILITY	DEVIATION DISTANCE (%)	AVG SPEED (METERS/SEC)	MAX SPEED (METERS/SEC))	MANUAL INTERVENTIONS (QTY / KM)	MECHANICAL INTERVENTIONS (QTY / KM)
MINIMUM	10	4	N/A	0 / 1 KM	0 / 1 KM
GOAL	5	8	N/A	1 / 3 KM	1 / 3 KM
RESULTS	15.359	3.3222	6.1125	1 / 26.201 KM	1 / 13.01 KM

Figure 20: FC SSS EET-08 Test Series 2.0 Results

FC EET-08 Test Series 2.0 Comments

The 2.0 series of tests represents how accurately the robotic vehicles maintain desired formation position.

FC utilizes the leader navigation solution and predicts the leader's future position at time T. FC determines the correct formation position relative to the leader at time T and then calculates the optimal velocity to approach the desired formation position at time T. FC continually recalculates desired position and optimal velocity to maintain formation separation at time T+n. Once the desired separation is obtained, velocity approximates the leader velocity.

The data show an average of 15.359% deviation distance from the commanded route point which is attributed to the following:

- Projected leader position error (refer to EET Series 1.0)

- Projected leader heading error (refer to EET Series 1.0)

- Autonomous Mobility Software (AMS) determining:
  - ◊ actual route point (based on terrain slope and type, obstacles detected)
  - ◊ actual velocity (based on terrain slope and type)

The data show over a cumulative 52.402 KM traveled, only two manual interventions related to dust seen incorrectly as an obstacle and four manual interventions related to equipment related issues (i.e. low battery on the ESR, engine quit)

FC EET-08 Test Series 2.0 Conclusion

Upgrading the XUV test vehicle's IMU sensor would improve performance of the relative navigation solution, and may reduce the deviation distance percentage.

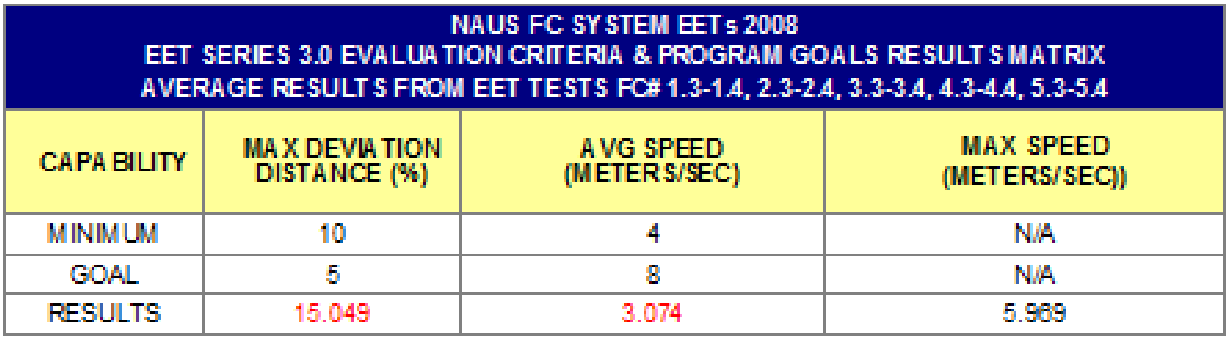
Improving integration between FC and AMS components so the vehicle adheres more closely to the commanded route would also reduce the deviation distance. FC's primary task is to maintain formation integrity and determine where the vehicle should travel, while AMS' primary task is to maintain vehicle stability and determine where the vehicle will travel. These are competing priorities that need to be resolved.

Average speed is directly a result of the test platform's inability to maintain higher speeds due to mechanical issues experienced during the EET.

The small number of manual interventions was a result of the FC and AMS components being well tuned to the XUV test platform.

FC EET-08 Test Series 3.0 Objectives/Results

Evaluate the impact of speed variation on ability to maintain formation position.



NAUS FC SYSTEM EETs 2008
EET SERIES 3.0 EVALUATION CRITERIA & PROGRAM GOALS RESULTS MATRIX
AVERAGE RESULTS FROM EET TESTS FC# 1.3-1.4, 2.3-2.4, 3.3-3.4, 4.3-4.4, 5.3-5.4

CAPABILITY	MAX DEVIATION DISTANCE (%)	AVG SPEED (METERS/SEC)	MAX SPEED (METERS/SEC))
MINIMUM	10	4	N/A
GOAL	5	8	N/A
RESULTS	15.049	3.074	5.969

Figure 21: FC SSS EET-08 Test Series 3.0 Results

FC EET-08 Test Series 3.0 Comments

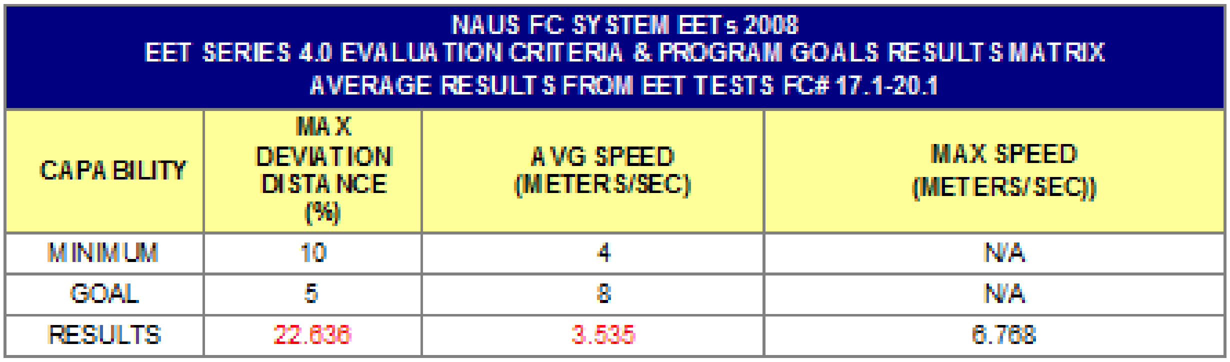
- Evaluate the impact of speed variation on ability to maintain formation position.

- The data shows negligible impact of varying leader speed with deviation distance declining by 2%.

- Varying leader speed had no impact on the results.

FC EET-08 Test Series 4.0 Objectives/Results

- Evaluate the performance impact of the formation when utilizing Ultra Wide-band Radio (UWB) relative positioning to improve leader navigation.



NAUS FC SYSTEM EETs 2008
EET SERIES 4.0 EVALUATION CRITERIA & PROGRAM GOALS RESULTS MATRIX
AVERAGE RESULTS FROM EET TESTS FC# 17.1-20.1

CAPABILITY	MAX DEVIATION DISTANCE (%)	AVG SPEED (METERS/SEC)	MAX SPEED (METERS/SEC))
MINIMUM	10	4	N/A
GOAL	5	8	N/A
RESULTS	22.636	3.535	6.768

Figure 22: FC SSS EET-08 Test Series 4.0 Results

FC EET-08 Test Series 4.0 Comments

- The 4.0 series of tests represents performance impact when enhancing GPS with UWB tracking.

- FC utilizes the leader navigation solution and predicts the leader's future position as described in EET Test Series 2.0. The formation separation is adjusted based on periodic UWB relative position updates to the leader. FC continually recalculates desired position and optimal velocity to maintain formation separation at time T+n.

- The UWB radios and positioning software did not provide the accuracy necessary to easily integrate into the system in support of GPS-denied autonomous operation. The following is a detailed description of the causes of accuracy limitations along with solutions:

Next Steps

- Formation Control needs to be more tightly integrated into AMS so the vehicle adheres more closely to the commanded route. FC's primary task is to maintain formation integrity and determine where the vehicle *should* travel, while AMS' primary task is to maintain vehicle stability and determine where the vehicle *will* travel. These are competing priorities that need to be resolved to improve overall performance.

- Disseminating the leader's entire route to the formation assets would improve scenarios where the robotic assets are in front of the lead vehicle. Knowing when turns will occur in the formation route would allow for higher speeds during turns.

- Implement the UWB enhancements would allow for continued formation control in a GPS denied environment. The UWB enhancements include: increasing measurement accuracy, increasing update rate, reducing dropped packets

SUMMARY

The NAUS ATO developed solutions in the areas of UGV Formation Control and Self-Security. These solutions were tested in relevant environments and shown to be at Technology Readiness Level (TRL) of 6 [8]. However, there still exists a need for further investment, development, refinement and testing in each of these areas as both of these systems represent novel developments.

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REFERENCES

1. http://www.army.mil/aps/98/chapter2.htm
2. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA494554&Location=U2&doc=GetTRDoc.pdf
3. http://peocscss.tacom.army.mil/EMIP/emip_trls.pdf
4. http://ieeexplore.ieee.org/Xplore/login.jsp?url=http%3A%2F%2Fieeexplore.ieee.org%2Fiel5%2F62%2F21777%2F01010117.pdf%3Farnumber%3D1010117&authDecision=-203
5. http://en.wikipedia.org/wiki/Tactical_formation
6. http://www.isd.mel.nist.gov/documents/huang/ALFUS-auvsi-8.pdf

7. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA449408&Location=U2&doc=GetTRDoc.pdf
8. http://en.wikipedia.org/wiki/Technology_readiness_level

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