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Achieving integrated convoys: Cargo Unmanned Ground Vehicle development and experimentation

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ABSTRACT

The Cargo UGV project was initiated in 2010 with the aim of developing and experimenting with advanced autonomous vehicles capable of being integrated unobtrusively into manned logistics convoys. The intent was to validate two hypotheses in complex, operationally representative environments: first, that unmanned tactical wheeled vehicles provide a force protection advantage by creating standoff distance to warfighters during ambushes or improvised explosive device attacks; and second, that these UGVs serve as force multipliers by enabling a single operator to control multiple unmanned assets.

To assess whether current state-of-the-art autonomous vehicle technology was sufficiently capable to permit resupply missions to be executed with decreased risk and reduced manpower, and to assess the effect of UGVs on customary convoy tactics, the Marine Corps Warfighting Laboratory and the Joint Ground Robotics Enterprise sponsored Oshkosh Defense and the National Robotics Engineering Center to equip two standard Marine Corps cargo trucks for autonomous operation.

This paper details the system architecture, hardware implementation, and software modules developed to meet the vehicle control, perception, and planner requirements compelled by this application. Additionally, the design of a custom human machine interface and an accompanying training program are described, as is the creation of a realistic convoy simulation environment for rapid system development.

Finally, results are conveyed from a warfighter experiment in which the effectiveness of the training program for novice operators was assessed, and the impact of the UGVs on convoy operations was observed in a variety of scenarios via direct comparison to a fully manned convoy.

Keywords: autonomous vehicle, logistics convoy, robotic vehicle, perception software, drive by wire, command and control, machine learning

1. INTRODUCTION

The Cargo UGV project was undertaken with the aim of developing and experimenting with advanced autonomous vehicles capable of being integrated unobtrusively into manned logistics convoys. This paper details the TerraMax™ technology developed to meet the requirements of this application, describes the simulation tools leveraged to expedite development, and provides experimental results from user trials.

1.1 Application Overview

Tactical wheeled vehicles are the delivery trucks of the United States military, used to transport supplies and equipment throughout a theater of operations to sustain deployed combat troops. These vehicles are typically employed within convoys, enabling great quantities of freight to be moved en masse from distribution centers to forward operating bases and combat outposts. Within a convoy, a variety of vehicles will commonly be represented – the lineup may include medium- and heavy-capacity cargo trucks carrying 6 to 15 metric tons each of provisions such as food or ammunition, tanker trucks delivering fuel or water service, wreckers able to tow out any vehicles that get stuck or break down, and armored vehicles providing security for the group as they complete the resupply mission. Furthermore, the routes

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utilized to cross an area of operations often overpass treacherous terrain; hence tactical wheeled vehicles are furnished with features such as all-wheel drive and adjustable tire inflation systems to ensure mobility regardless of the conditions.

In the modern era of enduring conflict, an increase in the execution of counterinsurgency operations against persistent adversaries and irregular warfare against non-state actors has intensified the exposure of troops in logistics roles to lethal attacks. These warfighters have been targeted with ambushes and improvised explosive device (IED) attacks while traversing areas that are fully controlled neither by hostile nor friendly forces. Despite the significant up-armoring of the tactical wheeled vehicle fleet that has occurred to counter these threats, considerable casualties have been sustained producing both tactical and strategic consequences.

In order to counter these tactics and reduce the risk to logistics element forces, the Cargo UGV effort endeavored to develop and test an autonomy system that would enable tactical wheeled vehicles to complete typical convoy missions without personnel onboard. The expected mode of employment consisted of substituting several unmanned cargo vehicles into an otherwise unmodified logistics convoy; significantly, it was anticipated that other manned vehicles would still be nearby performing the more complex activities such as providing security and recovering disabled vehicles. While the autonomous vehicles would be able to rely on occasional input from an operator, they should be relatively indistinguishable from the manned vehicles in both appearance and behavior, capable of occupying any position in the convoy order including leader, and able to traverse the same terrain and operate in the same environmental conditions.

In this project the Cargo UGV vehicles (CUGVs) were endowed with three new functional modes: autonomous, shadow, and tele-operation. In autonomous mode, depicted in Figure 1, mission routes were pre-planned by placing checkpoints along a road network. (Prior to operation in an area, the roads permissible for travel would be designated in a Route Network Definition File, or RNDF[1], that was generated using aerial imagery and geographic information system software). The autonomous mission plan would also include information such as intended convoy order and separation distances, speed limits by region, and exclusion zones. In shadow mode, no predetermined mission plan was required—a manned vehicle such as the Command and Control Vehicle (C2V) would simply be designated as the leader by the operator on-the-fly and the unmanned vehicles would follow anywhere this vehicle went on the RNDF while still performing onboard road-keeping and obstacle detection and avoidance. In tele-operation mode, an operator would assume remote control of a single CUGV in the convoy and directly command vehicle speed and steering via a handheld controller. Notwithstanding the addition of these modes, the ability to manually drive the vehicles as originally intended was preserved to allow the trucks to be used in any scenario.

2. SYSTEM OVERVIEW

The Cargo UGV system consisted of vehicle control components, computing hardware, sensors, and perception and planning software modules that were integrated onto two Oshkosh Medium Tactical Vehicle Replacements (MTVRs) to

Figure 1. Two CUGVs lead the C2V on an autonomous convoy mission in June 2012.

enable fully autonomous operation. The MTVR is considered the workhorse of the United States Marine Corps, with over 9,000 units procured between 2001 and 2011; each has an anticipated service life of 22 years.[2] In order to meet the demanding requirements of tactical resupply, the vehicle is capable of operating in temperatures ranging from -45° to 52°C, fording 1.5 m of water, and traversing a 60 percent gradient and 30 percent side slope while hauling up to 6350 kg.

The Operator Control Unit (OCU) hardware and software were also essential components of the Cargo UGV system, designed to be installed in any other tactical vehicle along with a radio data link which enabled communication with multiple CUGVs from afar. Additionally, diagnostic interfaces and data logging provisions were incorporated to enable testing and validation of the CUGVs.

2.1 System Architecture

Data flow through the Cargo UGV autonomy system can be broken down into transfers between four main blocks, as shown in Figure 2. Incoming sensor data is processed into actionable information by perception software; motion planning software subsequently decides what the vehicle should do in response to its objectives and surroundings; and commanded actions are executed by the vehicle control segment. In the remainder of this section, the hardware provisions of the system are discussed, starting with the implementation of vehicle control interfaces and the selection of sensors and computers. In subsequent sections, more in-depth studies of the perception and planning software are provided as are the interactions at each level with the remote OCU.

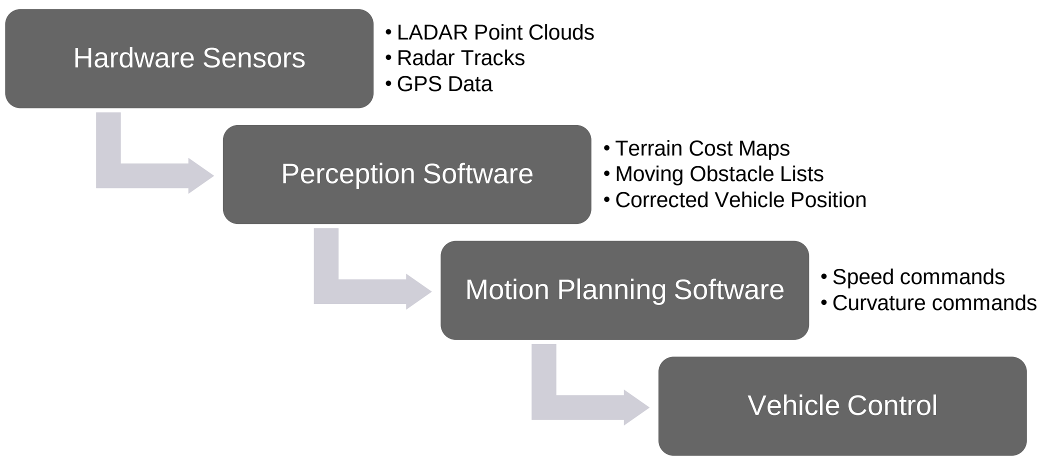

Figure 2. Block diagram of Cargo UGV system architecture.

2.2 Vehicle Control

Physical control of the Cargo UGV was accomplished using existing as well as supplemental embedded electronic subsystems installed on the base MTVR. All low-level subsystems communicated via CAN 2.0b using a combination of custom messaging and, where feasible, SAE J1939 protocol to preserve a high level of commercial automotive standardization. The drive by wire system can be decomposed into four major subsystems: actuation, power control, vehicle diagnostics, and safety monitoring.

The fundamental objective of the actuation subsystem was to control the state of the UGV. Commanded speed was first converted to a desired longitudinal acceleration; engine response was then attained via virtual emulation of the electronic throttle control pedal. An electronically controlled braking system, which included CAN-controlled pneumatic valves at the front and rear axles, was integrated to deliver closed loop control of brake pressure and vehicle deceleration. These valves were paired with yaw and acceleration sensors to enable integrated Electronic Stability Control (ESC) in both human and autonomous control modes. Transmission gear selection was achieved with a custom hardware interface that directly replaced the in-dash electronic shift selector that is standard on the MTVR. This shifter panel permitted the original human control of the transmission to be maintained, while allowing seamless transition to computer control for autonomous operation. To provide precise steering actuation, a previously developed CAN-controlled DC servomotor with appropriate control modes and feedback sensors was integrated into the mechanical steering linkage. In addition to the core mobility functions, computer control of auxiliary features of the truck such as central control of tire inflation, activation of intra-axle and differential driveline locks, and employment of varying levels of engine braking were also supported via interfacing to the underlying electronic subsystems. At any time, full manual control of the vehicle could be immediately regained by an operator by either depressing the brake pedal slightly or activating a dash-mounted toggle switch.

Auxiliary power distribution systems were also added as part of the Cargo UGV retrofit to provide consistent and regulated power to the new autonomy components. Power feeds to computers, radios, sensors, and other elements were individually controllable, and the electrical load for each was continually monitored to ensure proper voltage and current consumption.

One challenge in removing operators from a vehicle is the disconnect encountered when it becomes necessary to detect an error from a remote location. When a human is seated in the vehicle, subtle cues such as an odor from an overheating engine or major events such as a catastrophic loss of tire pressure can be easily detected. In order to fill this detection gap for an unmanned vehicle, each Cargo UGV was fitted with an array of additional sensors that enabled monitoring of attributes such as hydraulic and pneumatic pressures, ambient and local temperatures, fuel and fluid levels, battery charges, and power usage. Communication with the intrinsic vehicle diagnostic system was also incorporated to provide monitoring of the engine, transmission, brakes and drivetrain.

The core of the vehicle diagnostic subsystem was the Vehicle State Service (VSS) software, which continually monitored all hardware sensors and software watchdogs to ensure nominal operation of the entire system. The primary responsibility of the VSS was to adjudicate the current autonomy state of the vehicle and publish it to all software modules. If a state change request from the OCU was issued (for example, an instruction to transition from Manual to Autonomous mode), the VSS would determine whether the change was allowable based on current sensor data. If specific sensors indicated an issue (such as the engine not running when attempting to transition to Autonomous mode), the VSS would disallow the requested state change and notify the OCU operator as to the reason. In addition, if any values exceeded a critical threshold during autonomous operation, an alert would be issued and the vehicle would automatically be immediately halted if the error were severe.

The final component ensuring vehicle safety was an independent radio emergency stop system (E-stop). If at any time during UGV maneuver a safety concern arose, an operator at the OCU or an observer located along the course and equipped with a wireless E-stop transmitter could depress an emergency stop button. This action would instantly initiate application of the vehicle brakes and shut off of the engine, immobilizing the vehicle until a human entered the cab and re-enabled the system. The E-stop receiver also enforced halting of the vehicle if the range of a transmitter was exceeded.

2.3 Hardware selection

A driving requirement when selecting electronic hardware for the Cargo UGV platform was to ensure the system would be fully mission-capable in an operational environment, not simply functional in a research laboratory or for a limited demonstration. The goal was not only to advance the state of the art in autonomous vehicle capability, but also to do so in an implementation that could withstand the environment into which a tactical vehicle is typically deployed—thereby demonstrating a high level of technology readiness for autonomous logistical convoying overall. Core environmental requirements included, but were not limited to: driving rain, deep fording, heavy dust, severe vibration, extreme temperatures and solar loads, and electromagnetically hostile surroundings. A ruggedized embedded computing system was chosen that met these needs and afforded the autonomy software a total of ten 1.86 GHz dual core processors; this was supplemented by two additional ruggedized computers equipped with redundant arrays of solid state disks that were dedicated to comprehensive sensor and video logging.

Sensor selection was premised on the need to provide situational awareness for the vehicle at a range sufficient to support ground speeds of 55 kph. The forward-facing field of view was of principal concern, as the need for reverse driving was limited to tele-operation rather than full autonomy. A 64-laser high definition scanning LADAR was chosen as the primary terrain and obstacle sensor due to the resolution and data richness obtainable. The LADAR modality was supplemented by automotive radars that improved the range and robustness of obstacle detection and tracking, particularly in situations where airborne particulates obscured visibility. The vehicle received positioning data from a

Cargo UGV Sensor Suite

High Definition LADAR	Sense terrain, static obstacles, and moving objects around the vehicle
Wide Dynamic Range Camera	Provide perspective for operator to remotely control vehicle and check for obstacles
Short Wave Infrared Camera	Provide perspective in low-light conditions for operator to remotely control vehicle and check for obstacles
Situational Awareness Cameras	Allow operator to see surroundings on all sides of the vehicle
Short Range Radars	Detect obstacles near the vehicle on all sides
Long Range Radars	Detect large obstacles and moving objects far ahead of the vehicle
Integrated GPS/INS	Provide global positioning, navigation, and timing

Figure 3. Sensors used by the Cargo UGV.

tightly coupled fiber-optic gyro inertial measurement unit (IMU) and anti-jam Global Positioning System (GPS) receiver.

To provide visual situational awareness for an operator at the OCU, nine cameras were oriented around the vehicle. A shortwave infrared (SWIR) camera and a wide dynamic range (WDR) visible spectrum color camera were mounted on the roof to provide the main forward-looking perspective for tele-operation of the vehicle; the operator could toggle between these video sources to obtain visual environmental cues regardless of the ambient light level. The remaining cameras were composed of high dynamic range (HDR) color imagers and forward looking infrared (FLIR) cameras. This combination similarly provided the operator with views to the sides and rear of the UGV in all lighting conditions. The mounting locations of each of the Cargo UGV sensors is shown in Figure 3.

For this effort, another MTVR was established as the command and control vehicle. The OCU was hosted on a 38 cm Widescreen Ultra Extended Graphics Array (WUXGA) rugged touchscreen paired with an embedded computer containing a high-performance graphics processing unit. The C2V was also equipped with a tactical grade GPS/IMU for positioning information, and inter-vehicle communication was provided by multi-band encrypted meshing radios.

3. PERCEPTION

Perception software onboard a Cargo UGV processes incoming sensor data from the LADAR and radar sensors to produce real-time understanding of the nearby environment. Outputs derived from perception software and depicted in Figure 4 include terrain cost maps, lists of moving objects (e.g. vehicles, pedestrians), and perception-based global positioning information to support degraded or GPS-free operations.

3.1 Terrain Detection

The terrain detection module uses ray tracing techniques and LADAR data to derive the supporting ground surface for roadways.[3] In the presence of foliage, it is important for the vehicles to understand the true roadway supporting surface and ignore spurious grass or vegetation. Elevation, slope, and roughness maps with 0.5 m resolution cells were published with radius out to 60 m for use by the motion planner, ensuring detection of hazards at sufficient range to enable safe avoidance. A visibility bitmask was also created to detect larger negative obstacles and decelerate the vehicle during limited visibility situations (created by dust, weather, or when cresting a hill).

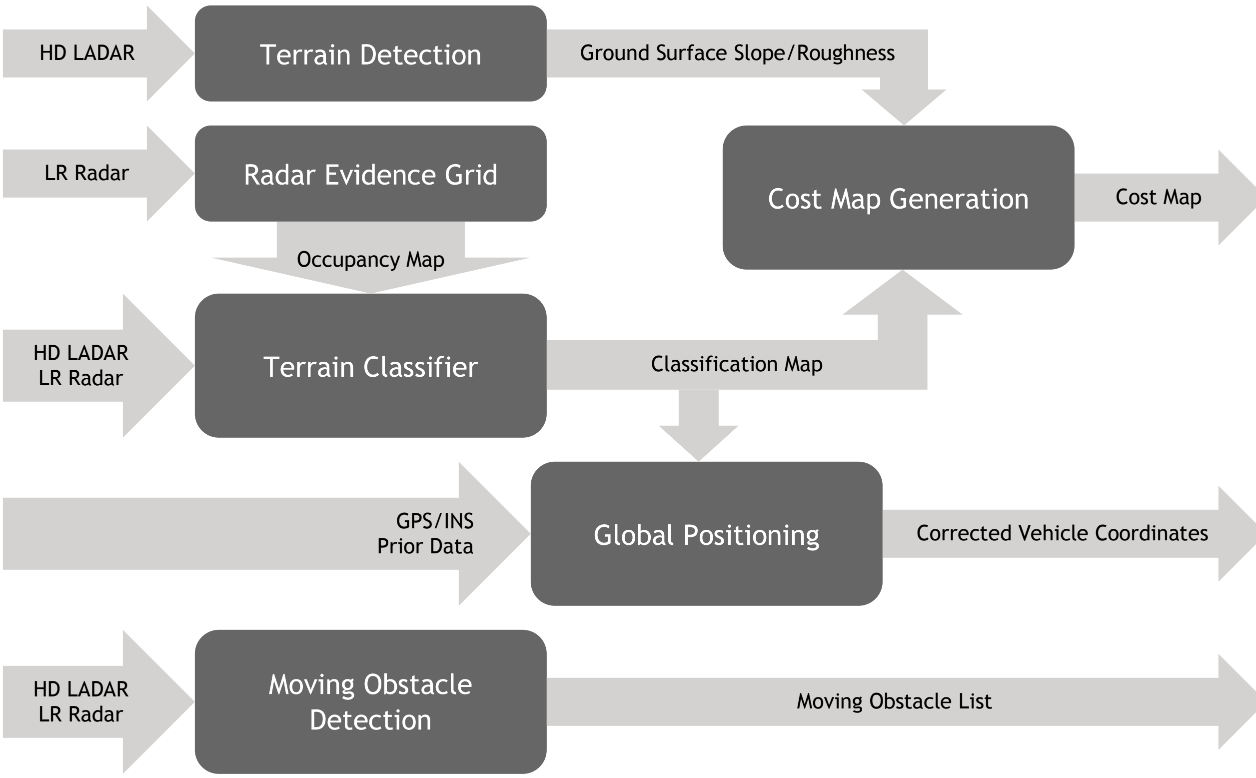

Figure 4. Block diagram of the Cargo UGV perception system data flow.

3.2 Moving Obstacle Detection

Our moving obstacle detection software integrates signals from both radar and LADAR to track and report all positive obstacles exhibiting motion (or previously moving objects that have stopped moving).[4] A sigma point unscented Kalman filter was used to integrate custom observation models for each sensor manufacturer and modality into a single motion hypothesis solution for each object. Objects that were observed with motion for more than 300 ms were classified as vehicle or pedestrian according to size and velocity. Once an object was determined to be a “mover,” it would be tracked and reported even if it stopped moving which would allow the CUGVs to queue smoothly when traffic stopped.

3.3 Radar Evidence Grid

The radar evidence grid module fuses measurements from each of the radar sensors into a single model of occupied and empty terrain. Standard evidence grid approaches[5] are used in order to perform Bayesian fusion of measurements over time. The radar sensor model accounts for actual radar returns as well as implied free space swept by each pulse. The sensor model is derived by collecting actual vehicle data to correlate radar measurements to the presence or absence of geometric objects (as identified by the LADAR). Along with serving as a complement to LADAR-based observations, the evidence grid is valuable in providing obstacle information when the LADAR range is severely limited due to dust or other airborne obscurants.

3.4 Terrain Classification

The terrain classification module fuses LADAR measurements and evidence grid output to produce probabilistic semantic labels for each section of terrain. Based on approaches developed for the DARPA-sponsored Crusher autonomous vehicle program, descriptive features and properties are first extracted at multiple scales for each terrain patch.[6] Features are based on both the geometric properties of the LADAR point cloud, as well as remission and return profiles from individual LADAR pulses. These features are then passed to a classification system trained from a human labeled data set. The output of the module allows for the differentiation between hazardous obstacles and drivable vegetation. It also distinguishes obscurants such as dust, rain or snow from actual geometric objects that should otherwise be avoided.

3.5 Perception Aggregation and Costing

Various perception layers are collected and aggregated into a single module, producing a compact description of the properties of various patches of terrain (e.g. slope, roughness, presence, size and classification of objects, etc.). This information is then converted into a mobility cost that encapsulates the relative hazard of traversing each patch of terrain. Cost information for the entire observable terrain is then sent to the planning subsystem for use in trajectory evaluation. The mapping from multidimensional terrain properties to a scalar cost value is accomplished via a function learned through expert demonstration of desired driving behavior.[7]

3.6 Map Registration and RNDF Alignment

Although GPS provides a consistent and low-uncertainty measure of a vehicle's global position, this position is not necessarily aligned to desired map or road network layers. GPS drift, image orthorectification or georeferencing errors can all combine to create registration errors on the order of several meters. To correct these errors, a map-based positioning approach is used that learns the relationship between various perception layers, and aerial or satellite imagery of the terrain.[8] Comparing GPS position and map-based position provides a registration offset that can be used throughout the system. Additionally, the map-based position is sufficiently accurate and robust to function as the sole source of global position when operating in GPS denied or degraded conditions. A further alignment step is also performed directly on the RNDF, in order to provide a finely tuned and low latency alignment. This step compares perception layers directly to the RNDF, and maximizes the overlap between the RNDF and flat, road-like terrain.

4. MOTION PLANNING

Motion planning software onboard a Cargo UGV processes incoming perception data to produce real-time trajectories as well as vehicle speed and steering commands, as indicated in Figure 5. The motion planning software was developed to emulate human driving capability and good convoying behavior. Other outputs deriving from motion planning software include present vehicle dispersion and reason for slowing or stopping when relevant.

4.1 Local Planner

The local planner is responsible for taking the global path planned by the operator at the OCU and finding a good obstacle-free trajectory within a corridor around that global path. This is accomplished by generating a series of trajectories which are offset from the global path, as shown in Figure 6. This is similar to the planning algorithm used in [9], among others.

Each of these trajectories is then evaluated to determine which cells in the perception-generated cost map will be encountered by the vehicle while executing that trajectory. Additionally, various penalties are computed based on features of the trajectory—features such as how far the trajectory is from the global path and how far it is from the last solution produced by the local planner. These costs and penalties are used to select the best trajectory. The local planner runs at the same rate as the costing module, sending trajectories to the path follower at 5 Hz.

4.2 Speed Planning

Once a trajectory has been produced by the local planner, a speed profile is generated for that trajectory. This is done by taking a set of speed limits (each being speed as a function of distance along the trajectory) and finding an overall profile which has limited accelerations and limited decelerations when possible. These speed limits include lateral acceleration limits, slope, nearby cost, and dispersion control.

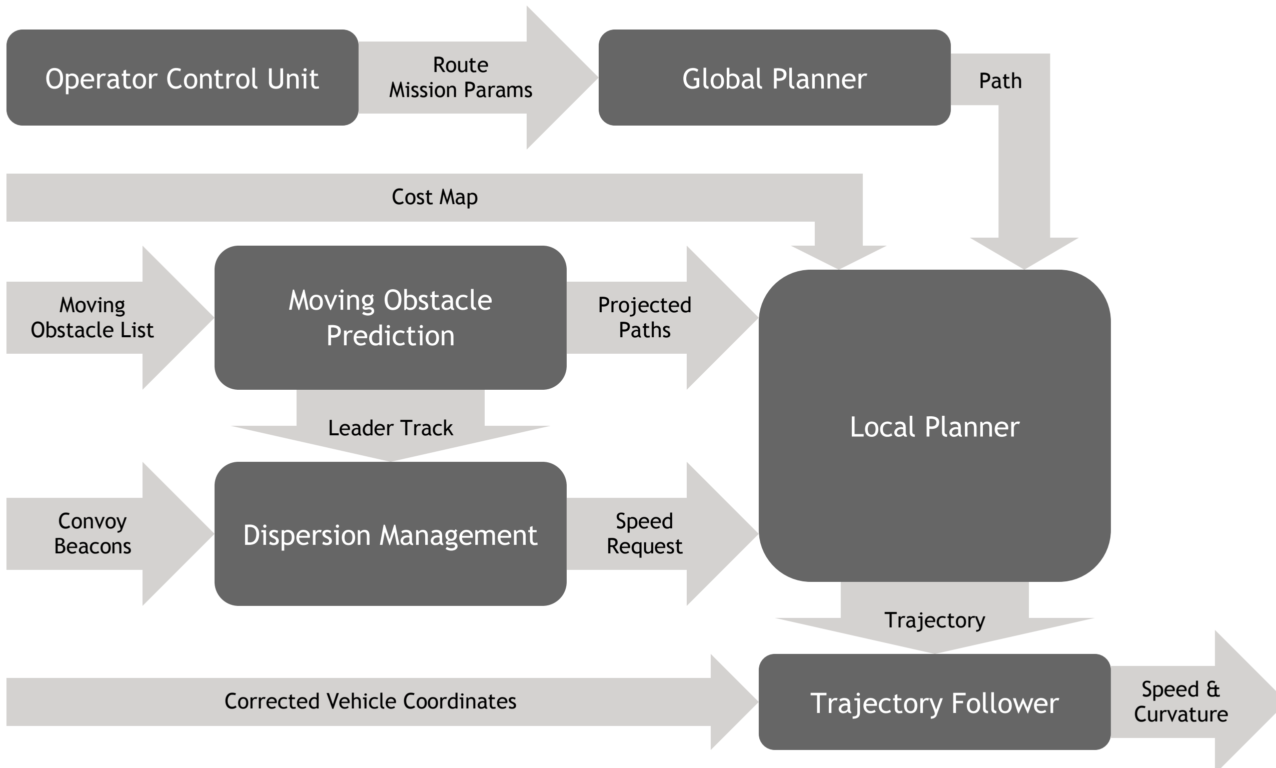

Figure 5. Block diagram of the data flow in the Cargo UGV planning software.

4.3 Path Follower

The local planner trajectory and the accompanying speed profile are passed to a path follower which is responsible for sending commands to the vehicle controller. The path follower runs at 20 Hz and is responsible for correcting tracking errors caused by either errors in the vehicle model or unmodeled terrain interactions. This is a single-step planner which generates a series of trajectories by simulating how the vehicle will respond to a constant curvature command given the current speed profile. These trajectories are then compared with the input trajectory and appropriate vehicle commands are selected.

4.4 Moving Obstacle Behaviors

The moving obstacle detection module provides the planner with a list of objects that are, or have been, moving along with their speed. A predicted path for each moving obstacle is then generated based on the assumption that the objects will either continue to move in a straight line (if they do not appear to be traveling on a known road), or will continue to follow the road if they are on it. Moving obstacles which are heading in the same direction as the vehicle are then treated as a member of the convoy while oncoming and cross traffic are avoided in the local planner.

In order to avoid moving obstacles, information about the obstacles predicted path is encoded into a cost map. This moving obstacle cost map is then added to the perception system cost map allowing the local planner to handle moving obstacles the same way it handles static obstacles. This 3D information (x, y, time) can be encoded into a 2D map because both the moving obstacle and the CUGV are moving along constrained paths. Thus, at any position in the 2D cost map, it is possible to compute both when the CUGV will be at that location (based on its speed profile) as well as where the moving obstacle will be at that time (assuming it maintains predicted path and speed).

4.5 Dispersion Behaviors

When driving in a convoy, the planner is constantly considering how far it is behind its leader as well as how far it is in front of its follower. This separation between vehicles in the convoy is referred to as dispersion. As the CUGV approaches the desired dispersion distance, it will attempt to match the speed of the leader; as the dispersion increases or

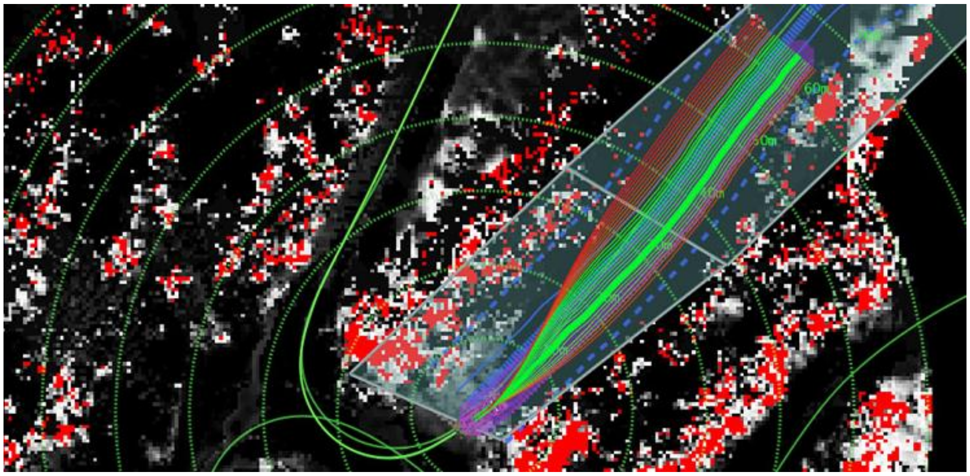

Figure 6. A display showing the Cargo UGV planner in operation. Red cells indicate dangerous terrain, blue dashed lines indicate road boundaries, and green trajectories are evaluated to be safe.

decreases from the desired spacing, the CUGV will try to speed up or slow down as appropriate. However, it is not always possible to increase speed enough to maintain dispersion as there are many other inputs to the speed planner. To avoid problems where some vehicles are left behind, an autonomous vehicle will also reduce its speed if the distance to its follower becomes too large. These dispersion settings can also be defined in terms of time instead of distance (e.g., 4 seconds rather than 50 m) at the OCU to allow following distance to increase smoothly as vehicle speeds increase.

5. OPERATOR CONTROL UNIT & OPERATOR TRAINING

The OCU software, illustrated in Figure 7, allows for mission command and control for mixed convoys comprised of manned and unmanned vehicles. This software can be run in any of the vehicles of the convoy and communicates wirelessly to each vehicle, monitoring their location and status. Route information and convoy behaviors can be preplanned, saved, loaded, and modified as needed during convoy operations. Live position and status of each vehicle, displayed on a zoomable overhead map overlaid with satellite imagery, gives the convoy commander excellent situational awareness about overall convoy spacing, speeds, and upcoming areas of potential threat.

5.1 Planning a Mission

Similar to websites that provide consumer driving directions, the operator is shown an overhead satellite map with roads highlighted. Marines designate mission start and end points with intermediate checkpoints designating which roads to take and which to avoid. The RNDF on which the mission plan is created describes the location of roadways and also contains information about intersections and lane directionality. Paths are calculated automatically to minimize convoy time and are depicted live as they are selected on the display. Overall mission distance and time is shown to the operator for planning purposes. Various overhead map channels are selectable to show satellite, topography, or area-specific prior data.

5.2 Convoy Behaviors and Map Zones

The OCU allows an operator to specify convoy speed limits and desired dispersion behaviors. Custom speed limits, dispersion settings, and other truck settings such as six wheel drive or tire pressure settings are also achievable using the concept of mission zones. These zones are polygons drawn on top of the map which allow the operator to override default convoy settings for specific situations such as heavily populated areas (e.g. slowing the convoy to 15mph) or fording rivers (e.g. slowing and activating 6WD). The OCU operator also has the ability to immediately change convoy speeds, dispersion settings, or pause (or even collapse and park) the convoy at any time for unexpected or intermittent situations.

Figure 7. The operator control unit showing a simulated mission in progress.

5.3 Live Monitoring and Video

Displaying live position, dispersion, and speed information for each convoy vehicle on the overhead map is invaluable to a convoy commander. For situations where visibility is restricted due to dust or weather or night operations, a convoy can continue to run at full speeds with the comfort of knowing exactly where all vehicles are. Video feeds are available from each of the CUGVs and, with good wireless communications, multiple feeds can be displayed on the OCU simultaneously for monitoring purposes.

5.4 Recovering from 'Stop for Obstacle'

When a route is completely blocked by obstacles with no clearly traversable detour, a CUGV will stop and request assistance from the operator via the OCU. At this point, the operator has the choice between tele-operating the vehicle off the road and around the obstacle or specifying a "go-zone" which tells the planner to plot a path of least resistance (potentially running over whatever obstacle was blocking the CUGV). This go-zone behavior is propagated to all unmanned vehicles in the convoy so that subsequent CUGVs will also push through without stopping.

5.5 Wireless Communications Reaction Behaviors

Wireless communications across the entire convoy is a big challenge when separation between vehicles can be up to 200-300 m and line of sight can be intermittently lost. The Cargo UGV system utilizes a meshing radio system that relays data from vehicle to vehicle along the convoy until it reaches the consumer (most likely the OCU). Location data for each vehicle is also utilized to maintain proper dispersion for missions that potentially turn corners or pass through zones with varying speed limit configuration settings. Dealing with wireless dropouts in a sophisticated way was a major system feature for the Cargo UGVs. When a CUGV loses communications to the vehicle in front of it, it will continue to drive to the last known location assuming that communications will re-establish and the convoy smoothly recovers. For a CUGV that loses communications to its direct follower, that CUGV will decelerate and eventually stop just as a human driver would who could no longer contact their follower.

5.6 Operator Training Tools

For live force experiments, training tools were developed to lead U.S. Marines through mission pre-planning. Examples and discussions were included to allow the Marines to analyze various behaviors and settings that work best given different scenarios. The trainees also were able to run their missions in simulation and learn to use the software prior to being part of a full convoy. Live simulation and training software was connected to each Marine's OCU to simulate vehicle stops, errors, and other real-world convoy interruptions that each operator would need to handle.

6. SIMULATION & DEVELOPMENT

The Cargo UGV project integrated hundreds of different technology pieces into a single coordinated system over a brief two year period. Existing technology was improved greatly and parts that were missing were designed and implemented to fill gaps that had not been solved previously for the convoy application. Assimilating all of these components and software modules was a task by itself and the team incorporated many global practices to help reduce integration, debugging, and testing time.

6.1 Live Debug Tools

In addition to the OCU which was used for mission command and control, there were several other monitoring applications that engineers used to investigate detailed system issues that occurred on the CUGVs. A perception graphical user interface (GUI) was created that could display all raw sensor, diagnostic, and processed data. Each perception module produced intermediate maps that could be observed in real time in 3D, enabling a CUGV to be brought to a particular location for engineers to evaluate issues live. A planning GUI was created to oversee the planning and vehicle control modules, enabling developers to also watch terrain costing and trajectory selection in real time. In addition, a VSS GUI was created to allow visibility into the CUGV's safety and low level hardware systems. Each of these tools allowed dynamic changes to occur without rebuilding the software and facilitated more efficient field testing with back-to-back runs utilizing different settings.

6.2 Datalogging and Analysis

All data received by the sensors and produced by each layer of software (including detailed internal instrumentation) was logged continuously during CUGV autonomous driving to create a broad set of autonomous vehicle logs across various terrains, lighting (e.g., day vs. night), and weather conditions. When a failure was observed during testing, often the data necessary to diagnose and fix the issue had already been captured. Playback tools in the perception and planning systems allowed engineers to rework algorithms and replay the same inputs to observe changes in the response. The amount of time needed to resolve a software bug was significantly reduced by leveraging these data logs, as a problem that required multiple people to reproduce in the field could instead be identified immediately and fixed with just one engineer. Automatic analysis and reporting tools were created to post-process missions, evaluating performance of the convoy from many different metrics.

6.3 Simulation

Perception logs were collected and used to construct a simulation environment for offline motion planning development. Having acquired extensive data from a site, a virtual model was created with enough fidelity to evaluate planning software options. Simulated vehicles were implemented that were indistinguishable from real hardware, allowing full planner software to be validated in simulation. Simulation testing was run regularly to verify that new software changes would not break previously proven features and performance.

6.4 Field Testing

In the end, convoy behaviors could only be fully validated by using real vehicles with real drivers in the field. Each week, teams of field testing personnel and engineers would exercise various missions, bringing new challenges to the software and validating new pieces of technology. A 250-acre test site was modified to present varying terrain including slopes, water, vegetation, overhangs, rocks, debris, obstacles, unimproved roads of varying quality, washouts, and high speed open areas. The team tested in all weather (snow, rain, sun, dry dust) and at all times of the day (dawn, daylight, dusk, full darkness). Each year, the CUGVs were taken to other parts of the country for additional testing on military bases with more unique challenges.

6.5 Machine Learning Training Tools

Several components of the system utilized state-of-the-art machine learning techniques to derive complex rules or mappings that would be infeasible to develop by hand. For these systems to function properly, each approach typically required a large set of training data annotated with ground truth (human provided or otherwise). In addition, the proper tool chain is required to not only implement the actual machine learning algorithms, but to repeatedly simulate the component in question to produce the input to the learning system. These tool chains were developed to produce results that could be analyzed and validated prior to installation on the trucks.

7. EXPERIMENTAL RESULTS

The technical goal for Cargo UGV of designing and integrating a system of sensors, actuators, computers, and software enabling driverless tactical vehicles to participate in logistics convoys was accompanied by the strategic goal of evolving concepts of operation (CONOPs) and tactics, techniques, and procedures (TTPs) for the successful employment of large UGVs in future military conflicts. Performance of the project was measured through a series of limited technical assessments (LTAs) and a limited objective experiment (LOE) which involved both technical subject matter experts from government laboratories and United States Marine Corps motor transport operators with combat experience serving in logistics convoy missions.

7.1 Limited Technical Assessments

Four LTAs were conducted, as illustrated in Figure 8. The initial two assessments were conducted and attended by government technical experts and consisted of a single CUGV and the C2V carrying out assigned tests with engineers operating the system. The objectives of LTA 1 were to evaluate the ability of the developing system to satisfactorily operate in both leader and follower modes, avoid static and dynamic obstacles, withstand GPS denial, complete looping missions on primitive roads, and execute water crossings. The follow-on LTA 1.5 assessed the effectiveness of rapid improvements made to the autonomy system to increase consistency of response to dynamic obstacles and reduce sensitivity to vegetation and dust, as well as evaluate changes to the user interface made to streamline operator interactions.

LTA 2 incorporated the perspective of a Motor Transport Operations Chief and four additional motor transport Marines all having prior combat experience in Iraq, Afghanistan, and the Marine Expeditionary Unit (MEU). An operator training course was administered to the Gunnery Sergeant, two Corporals, and two Lance Corporals and their feedback following a sequence of sample missions was used to improve the classroom instruction, scenario simulations, and on-vehicle exercises that were part of the training course. These users also contributed perspectives on desired functionality improvements and CONOPs that were subsequently implemented in the Cargo UGV system.

The final LTA took advantage of both mature CUGVs and focused on assessing performance during convoy operations conducted in concert with the C2V and other interfering vehicles. Test highlights included repeated autonomous missions of over 30 km that traversed deep sand trails, clay roads with encroaching vegetation, and two-track trails overgrown with grass; a GPS denial test in which over 10 km was completed with no noticeable degradation in performance; execution of an extended mission of over 70 km; and demonstrated safe operation at sustained speeds of over 55 kph. Additionally, the single operator largely experienced no problems when supervising the simultaneous operation of two CUGVs, and the CUGVs automatically maintained their speeds and separation distances well without operator interaction even in dusty conditions. Overall, more than 650 km of autonomous driving was accomplished in the one-week test and the average speed for the entire set of missions was over 28 kph.

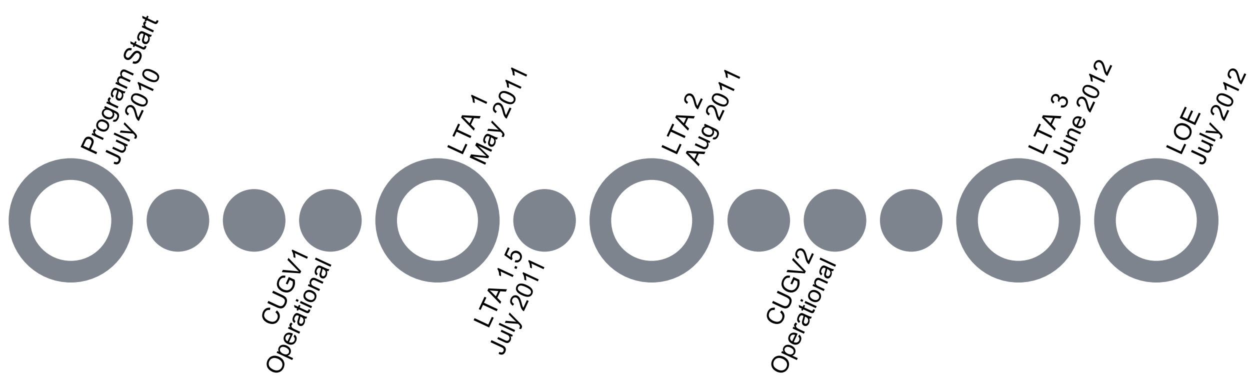

Figure 8. Cargo UGV project timeline.

7.2 Limited Objective Experiment

The concluding exercise of the project was integration into the Marine Corps Warfighting Lab's Enhanced Marine Air-Ground Task Force Operations (EMO) LOE 2.2, established to assess the capabilities of multiple types of unmanned systems and explore TTPs for their utilization supporting expeditionary logistics. This live force experiment began with the training of Marines previously unfamiliar with any UGVs on the use of the OCU through an updated 3-day curriculum of classroom lessons, high-fidelity simulations, and hands-on practice sessions in the area of operations. These operators were then assigned to execute representative logistics resupply missions for the following week, and the performance of a 7-vehicle convoy containing the two unmanned vehicles was compared to a control convoy that was entirely manned.

In the course of these missions, various disruptive conditions were replicated and the impact of the presence of unmanned systems on typical warfighter responses was noted. On multiple occasions the convoy was ambushed or struck by a simulated IED, and the occupied vehicles were forced to adjust their personnel allocations to provide appropriate fire support in the vicinity of the unmanned vehicles. Communications losses and vehicle breakdowns were replicated and challenging scenarios such as river fording were completed in the experiment; in all situations the motor transport Marines made decisions as to when to switch the modes of operation of the CUGVs. In one scenario, an intelligence update was provided to the integrated convoy mid-mission which indicated a road was no longer traversable; the operator was able to effectively re-plan the mission for the unmanned vehicles and use his OCU to redirect the manned convoy vehicles onto the desired route.

7.3 Conclusion

The foremost challenge of this effort was to deliver a vehicle capable of operating autonomously and dependably in the often-uncertain environments relevant to logistics units; in addition to demanding terrain and weather conditions, interactions with live friendly forces and neutral local populace, as well as manned and other unmanned vehicles, had to be anticipated. By the end of the series of experiments, the general consensus of the warfighters surveyed was that the Cargo UGV system far exceeded their original expectations as to its functional capability. Operators believed they could comfortably control three to five CUGVs from a single user interface, and they projected that the integration of unmanned vehicles into their operational environment would occur in the near future.

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