The Marine Corps Warfighting Laboratory and the Joint Ground Robotics Enterprise Robotics Technology Consortium have sponsored a program which began in July 2010 to demonstrate the ability to integrate an Oshkosh Corporation autonomous system into a tactical vehicle capable of hauling a 7-ton payload cross-country. This initiative is intended to determine the feasibility of reducing the exposure of Marines to lethal attacks by replacing some of the manned vehicles in logistics convoys with unmanned vehicles, as well as to assess the feasibility of having autonomous vehicles act as a resupply multiplier through one-to-many operator control. This concept demonstrator will participate in a live-force experiment to assess the ability to assimilate a UGV into a supply distribution mission in a tactical environment. The government expects to spur advances in the development of unmanned ground system technologies, standardize the maturation and evolution of these systems as appropriate, and improve the integration of mission equipment packages. Additionally, the Concept of Operations and Tactics, Techniques and Procedures developed during this initiative for employing autonomous vehicles in logistics convoy operations will feed future combat development. There is also the potential for delivering the concept demonstrators directly to operating forces for an Extended User Evaluation. This paper details the specific challenges the tactical cargo application presents for UGVs, including leading and following other manned vehicles in a convoy, interacting with non-cooperative vehicles and pedestrians, operating safely in urban, rural, and rugged off-road environments, and facilitating operator interaction from beyond line-of-sight. The impact these requirements have on system design is presented, as are preliminary results obtained at a limited technical assessment. Lessons learned and the path forward for the program through 2012 are discussed.

INTRODUCTION

The increasing level of technical functionality demonstrated by progressive unmanned ground vehicles (UGVs) has liberated them from the highly constrained environments of research laboratories and rigidly structured scenarios, and has transformed consideration of their use in military operational environments from hypothetical to imperative. In less than ten years, prototype full size UGVs have advanced from faltering expeditions across only a few miles of static terrain to high speed trips in complex freeway traffic; in the same time frame, small unmanned ground ve-
Vehicles have proven their combat effectiveness in explosive ordnance disposal (EOD) missions and been deployed by the thousands, and unmanned aerial assets have become indispensable tools for the U. S. Department of Defense (DoD) in combat and non-combat missions. The confluence of budding cultural acceptance and growing practical capabilities of unmanned systems in all domains has resulted in a thrust within the DoD to promote the accelerated fielding of ground robotics for focused, practical missions with compelling returns on investment and a high probability of successful execution.¹

Simultaneously, the United States Marine Corps (USMC) has dedicated itself to excelling as the “expeditionary force in readiness” and is evolving to contend with the highly dynamic nature of today’s battlefields. In the Marine Corps Vision and Strategy 2025 document, the impact of greater force protection requirements on the traditional equation balancing high combat effectiveness with successful force projection is detailed.² Escalating threats in complex environments such as urbanized littorals and mountainous terrain are acknowledged as prime areas of operation for Marines in the future, and the subsequent effect on the Logistics Combat Element (LCE) is noted to be substantial. At the same time, a reduced dependence on combat units for protection of logistics support activity is promoted. These factors result in the increased valuation of unmanned systems if they can be demonstrated to be robust and efficient solutions to logistics challenges in the demanding operational environments in which Marines must serve.

“We will pursue means to deliver personnel and logistics in complex terrain with precision. The application of unmanned systems has to be more aggressively explored…” – Marine Corps Vision and Strategy 2025

The Office of the Secretary of Defense Joint Ground Robotics Enterprise (OSD/JGRE) has sponsored the creation of a Robotics Technology Consortium (RTC) to facilitate rapid response to circumstances such as this – by granting an Other Transaction Authority award to the Consortium, the DoD enabled its individual organizations to quickly compete and execute prototype development efforts with companies without the burden of extensive contracting for each activity. This arrangement has permitted the Marine Corps Warfighting Laboratory (MCWL) to engage Oshkosh Corporation in developing a robotic vehicle system to evaluate the utility of unmanned assets in a supply distribution role; this program is known as Cargo UGV. The Oshkosh team also includes the Carnegie Mellon University Robotics Institute’s National Robotics Engineering Center (NREC) and Teledyne Scientific and Imaging. Begun in July of 2010, the intent of the program is to test the performance of a system equipped with advanced perception and localization technology in Limited Technical Assessments (LTAs) and live force Limited Objective Experiments (LOEs) and to explore Concepts of Operations (CONOPS) and Tactics, Techniques, and Procedures (TTPs) to assist future combat development.

CARGO UGV REQUIREMENTS

The USMC tactical supply distribution application drives very specific requirements for an intelligent ground vehicle due to inherent technical and logistical characteristics. The system must adapt existing fleet vehicles for unmanned operation; it must not detrimentally impact the utility of the existing platform; it must be capable of operating successfully wherever Marine convoys go, whenever they go there; and finally, it must be capable of interacting safely with other intelligent agents in its environment.

Adaptation of Existing Vehicles

The advantages of an add-on unmanned vehicle system over a purpose-built unmanned platform are myriad. At present, the equipment readiness posture of the USMC has been challenged by the operational tempo, austere environment, and distributed nature of combat in Iraq and Afghanistan; this has been exacerbated by the added strain of vehicle up-armoring.³ As a result,
materiel expenditures are focused on reset and recapitalization of assets rather than the more costly development and procurement of entirely new platforms. Vehicles which can be optionally manned are also more adaptable for an operational environment – a warfighter can simply jump in and drive when the mission at hand demands a human in the cab, allowing for the incremental introduction of intelligent vehicles into tactical roles as system capabilities and trustworthiness improve. Additionally, having unmanned assets that at range are indistinguishable from manned vehicles enhances the survivability gains the UGVs present; if an adversary is unable to detect which vehicles in a convoy carry personnel, the risk of a casualty due to an ambush or remote control improvised explosive device detonation can be reduced.

In order to be palatable to the warfighter, however, the addition of an unmanned-operation capability must not interfere with the existing performance of the host platform upon which he or she relies. The swift traversal of severe terrain is a critical capability for an expeditionary force and is the hallmark of USMC tactical wheeled vehicles; any components added to the vehicles as part of the autonomy system must not only avoid interfering with mobility, but must also survive the stress that this mission profile dictates. Payload capacity must also not be unduly impacted by the autonomous system. By definition, a supply distribution application requires vehicles to transport significant quantities of goods, and the logistics chain is already optimized to utilize the standardized capacities of the current fleet. Finally, no tradeoffs with core vehicle survivability or reliability will be tolerated – an unmanned system which increases risk to a warfighter is defeating its primary purpose.

Complex Operational Environment

In addition to utilizing existing platforms effectively, the autonomous systems must also be able to perform in all operationally relevant conditions. A combatant commander will not be sympathetic to systems that only operate in daylight or in fair weather, as his or her missions must be unrestricted by these variables. Similarly, a supply convoy may traverse surroundings ranging from primitive to rural to urban, and viable Cargo UGVs must be functional throughout these environs. The UGVs must also be capable of significant endurance to facilitate support of widespread combat outposts and forward operating bases, and must not decrease the stamina of other convoy participants due to additional demands on their attention.

The dynamic combat environment poses a final challenge to intelligent ground vehicles integrated in a logistics convoy. The UGVs must have the ability to interact with “friendly” vehicles in the same convoy, leading or following similar vehicles and tolerating physical occlusion and dust. They must also be enabled to react appropriately to non-cooperative vehicles, i.e. non-convoy vehicles and local traffic, and must withstand naturally occurring outages of GPS signals as well as potential active denial. Above all, the Cargo UGVs must have the ability to quickly adapt to unexpected conditions on the ground; an operator must be able to quickly direct a vehicle to an alternate route or adjust a vehicle characteristic such as speed dynamically just as a convoy commander redirects conventional drivers on-the-fly.

CARGO UGV SOLUTION

The Oshkosh team’s approach is an add-on system which offers an advanced level of perception and localization, enabling a high level of autonomy and reducing reliance on operator interaction. Each unmanned vehicle is independently able to navigate to the objective, enabling the composition of the convoy to change as demanded by traffic conditions, road blockages, or other anomalous situations. This approach is implemented using highly capable and reliable hardware and is integrated onto the vehicle to minimize system vulnerability, as depicted in Figure 1. A
unique user interface has also been developed which addresses the usability and functionality needs of the warfighter in the field.

Figure 1. The initial Oshkosh Cargo UGV undergoing field testing in May 2011.

Established Vehicle Platform

The Cargo UGV is based on the Medium Tactical Vehicle Replacement (MTVR), a 7-ton pay-load off-road logistics vehicle of which over 8,800 are in service with the Marine Corps. Developed and built by Oshkosh Corporation, the truck exploits an independent suspension for increased vehicle mobility, ride quality, off-road speeds, and load-carrying capacity and also features an integrated electronic control and diagnostics system. The Cargo UGV autonomous system interfaces directly with existing communication networks on the MTVR, facilitating tight control over core systems such as the engine and transmission and auxiliary systems such as central tire inflation, driveline locks, engine braking, and anti-lock braking. This high level of integration ensures that the fundamental mobility of the vehicle is not reduced by the addition of the autonomous system and permits nearly instantaneous transition from autonomous to manned modes of operation; additionally by leveraging the MTVR technical data package, the installation of hardware was achieved with minimal impact to the truck’s visual signature.

Advanced Perception and Control

The Cargo UGV leverages a multi-sensor system employing intelligently fused radar, LIDAR, and camera systems which compensate for the weaknesses in one sensing modality with the strengths of another. These sensors facilitate estimation of the true supporting ground surface around the vehicle; detection and avoidance of negative and positive static obstacles; detection, tracking, and avoidance of collisions with moving objects; and classification of terrain traversability based on categorization of vegetation, dust, obstacle, or ground. This is combined with registration techniques that couple the vehicle’s perception of its surroundings with ground truth geospatial mapping data to correct for errors in the position estimate, allowing the system to be enhanced by (rather than dependent on) GPS and vehicle-to-vehicle data when available. The UGV relies upon the output of these modules to navigate on paved, gravel, and dirt roads at speeds of up to 35 mph.
The Operator Control Unit (OCU) facilitates the semi-autonomous commands that may be necessary in urban or primitive rural conditions, and allows the configuration of UGV order and the establishment of following distances in convoy operations. The operator has the ability through the OCU to adjust waypoints, plan or re-plan specific missions by selecting checkpoints, alter the mission while in progress, monitor the status and performance of the unmanned assets, and remotely control the UGV if necessary. The OCU selectively displays overhead map data and video feeds, and can be used to designate keep-out or obstacle-override areas for the UGVs.

PRELIMINARY RESULTS

The initial Limited Technical Assessment for the Cargo UGV program was held in May 2011 at Ft. Pickett Army National Guard Maneuver Training Center. A battery of tests was performed over the course of a week with a single Cargo UGV (CUGV1) and a Command and Control Vehicle (C2V) to evaluate the current capabilities of the system and identify focus areas for further development. Static and dynamic obstacle avoidance behavior, looping mission completion, leader/follower behavior, GPS-denied operation, and primitive road traversal including water crossings were tested and vehicle performance was assessed by external observers. As a result, the following areas were targeted for further development:

- maintaining lane,
- reducing false obstacle detections,
- enhancing dust performance,
- streamlining operator recovery actions, and
- increasing consistency of dynamic obstacle response behavior.

Maintaining Lane

On a coarse scale, CUGV1 was largely successful in maintaining global positioning despite degraded or entirely denied GPS signal – in one test, the vehicle completed over six miles of autonomous driving without GPS input, and required only one operator intervention due to course divergence. However, on a finer scale, the vehicle at times struggled to maintain precise alignment with the road and often deviated one to two meters from the path that a human driver would likely restrict operation to. Root causes for this included difficulty in differentiating road surface from surroundings, deficient incentivization of road-following behaviors, and inaccurate map data. The current Cargo UGV system exclusively utilizes LIDAR data for terrain classification, and the operational environment at Ft. Pickett of freshly mowed grass alongside an unimproved roadway posed a challenge for differentiation due to similarity in texture of these surfaces.

Improvements have now been made to capitalize upon weak signals in the LIDAR data, resulting in more consistent performance of map registration even in such an environment. Future work will incorporate visible and near-infrared cameras to the terrain classifier, resulting in an enhanced ability to differentiate vegetation from road based on more observable characteristics. To improve road following behavior, additional logic has been added to the motion planner to recognize and react appropriately when the prescribed route does not align with a clean road surface – in addition to improving driving performance in such circumstances, this will also lead to more conservative behavior in the inevitable case of moderate map data inaccuracies.

False Obstacles

There is a relatively unavoidable tradeoff between obtaining high probabilities of obstacle detection and achieving low false alarm rates; while CUGV1 successfully avoided all true obstacles
during the Ft. Pickett LTA, it did yield unnecessarily to vegetation on several occasions. This is expected at this stage of development; a conscious decision to prefer conservative behavior over aggressive performance was made. As development progresses, additional camera and radar data will be incorporated in assessing the likelihood that an anomaly is truly an obstacle to be avoided. Additionally, system improvements in latency and path planning are being pursued to minimize the circumstances in which a late detection results in halting the vehicle due to lack of avoidance options.

**Dust Performance**

The unfavorable effect of a dusty environment most expected by a human observer is the appearance of an opaque dust cloud as an obstacle; however, this turns out to only be a minor contributor to the irregular behavior exhibited by CUGV1 in dust and it will continue to decrease in significance as more training data with radar is incorporated into the machine learning system. The more dominant effect is the obscuring of nearby areas to the laser sensor, as the vehicle attempts to avoid large areas where it cannot see the ground since these could be negative obstacles or obscured hazards. This issue is being addressed by incorporating the knowledge of why these areas are unobserved into the path planner; by recognizing that dust is obscuring the ground, an intelligent decision can be made to simply increase following distance to the preceding vehicle to allow more time to perceive the upcoming road surface.

**Streamlined Recovery**

It is expected that even with increasing maturity, the Cargo UGV system will still not be able to handle all possible contingencies that may arise in an operational environment. In these circumstances, it is critical for an operator to be able to swiftly direct the vehicle as to how to achieve the desired resolution. The LTA offered a unique environment to gain insight from warfighters about the critical features of the operator interface, and subsequently enhancements have been made to the OCU – particularly in the realm of expediting repetitive actions to handle recurring mission interruptions. Future development will enhance the ability of a single operator to supervise the maneuver of multiple UGVs and quickly interact with different vehicles as needed, allowing for assessment of the potential for autonomous vehicles to serve as a resupply multiplier.

**Dynamic Obstacle Response**

By far one of the most challenging aspects of the intended operating environment for the Cargo UGV program is the prevalence of dynamic obstacles such as people and other vehicles in complex surroundings. At the LTA, CUGV1 demonstrated quite successful tracking of a variety of cooperative and non-cooperative lead vehicles using long-range radar. The addition of short-range radars to the system will allow for 360 degree close-proximity obstacle detection and avoidance, enhancing the ability of the vehicle to safely operate around pedestrians and in dynamic traffic situations. However, challenges currently persist in distinguishing true versus false obstacle detections in a cluttered off-road environment, as well as accurately predicting and reacting to obstacle motion with limited sensor information. In the future, tighter fusion of LIDAR and radar data will be implemented to improve detection performance, and leveraging of environmental structure will be pursued to enhance tracking and augment avoidance behavior.

**CONCLUSION**

The Cargo Unmanned Ground Vehicle program has completed its first Limited Technical Assessment; in so doing, initial assessments of the viability of current intelligent vehicle technology for logistics resupply in an operational environment were performed, and areas of
focus for further development were identified. As the system matures, it is anticipated that the
CUGV1 will continue to exhibit more intelligent, reliable behavior as enhancements are made to
the underlying software. Additionally, Phase II of the program will involve fabrication of an
identical CUGV2 to allow for multiple-UGV missions with a single operator, and the systems
will be operated and evaluated by combat veteran Marines at a Limited Objective Experiment in
2012.

This experimentation will assist the Marine Corps in steering modernization of its Logistics
Combat Element, and will help the Department of Defense drive towards its vision for ground
robotics as an integrated manned/unmanned force.

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