Robotic Follower Experimentation Results

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ABSTRACT

Robotics is a fundamental enabling technology required to meet the U.S. Army's vision to be a strategically responsive force capable of domination across the entire spectrum of conflict. The U. S. Army Research, Development and Engineering Command (RDECOM) Tank Automotive Research, Development & Engineering Center (TARDEC), in partnership with the U.S. Army Research Laboratory, is developing a leader-follower capability for Future Combat Systems. The Robotic Follower Advanced Technology Demonstration (ATD) utilizes a manned leader to provide a high-level proofing of the follower's path, which operates with minimal user intervention. This paper will give a programmatic overview and discuss both the technical approach and operational experimentation results obtained during testing conducted at Ft. Bliss, New Mexico in February-March 2003.

INTRODUCTION

The U.S. Army recently evaluated its future operational requirements and developed a vision to transform its forces to meet those requirements. The Army Vision states that its "spectrum of likely operations describes a need for land forces in joint, combined, and multinational formations for a variety of missions extending from humanitarian assistance and disaster relief to peacekeeping and peacemaking to major theater wars, including conflicts involving the potential use of weapons of mass destruction. The Army will be responsive and dominant at every point on that spectrum. We will provide to the Nation an array of deployable, agile, versatile, lethal, survivable, and sustainable formations, which are affordable and capable of reversing the conditions of human suffering rapidly and resolving conflicts decisively."[i]

The Army has partnered with the Defense Advanced Projects Agency (DARPA) to meet this requirement in the Future Combat Systems (FCS) program. The program's goals are to improve land force lethality, protection, mobility, deployability, sustainability, and command and control capabilities. "The Future Combat Systems (FCS) program will develop network centric concepts for a multi-mission combat system that will be overwhelmingly lethal, strategically deployable, self-sustaining and highly survivable in combat through the use of an ensemble of manned and unmanned ground and air platforms. An FCS-equipped force will be capable of providing mobile -networked command, control, communication and computer (C4) functionalities; autonomous robotic systems; precision direct and indirect fires; airborne and ground organic sensor platforms; and precision, three-dimensional, air defense; non-lethal; adverse-weather reconnaissance, surveillance, targeting and acquisition (RSTA). The funds provided under this project will be used to accelerate the development of enabling technologies for unmanned systems within the FCS program."[ii] (Fig 1).

To support this effort, the Army has focused a significant portion of its science and technology funds toward developing robotics technology and providing the baseline capabilities required to introduce unmanned elements into FCS. The Army program leverages technology developments achieved under the Army/Office of the Secretary of Defense (OSD) Demo III program in two key thrusts; the Robotic Follower Advanced Technology Demonstration (ATD) and the Semi-autonomous Robotics for FCS Science and Technology Objective (STO). The Robotic Follower program is directed at rapidly developing and demonstrating baseline capabilities that can be inserted into the initial FCS development program. To achieve this early technology insertion, the concept relies upon the coupling of unmanned followers with either a manned lead vehicle or a dismounted solider maneuvering over the same terrain. The Semi-autonomous Robotics for FCS program targets more advanced, longer-term capabilities that will allow the unmanned systems to precede their manned counterparts. This paper describes the Robotic Follower ATD program, its technology approach and operational

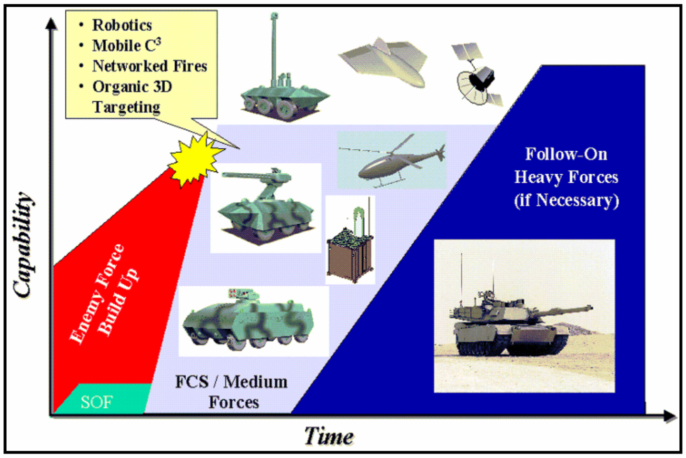

Figure 1. Future Combat Systems Concept.

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ROBOTIC FOLLOWER ATD PROGRAM

The Robotic Follower Advanced Technology Demonstration (ATD) is a joint U. S. Army Tank Automotive Research, Development & Engineering Center (TARDEC)/U.S. Army Research Laboratory (ARL) program designed to speed the incorporation of robotics into the next generation of land systems through the coupling of advanced perception technology with human sensing and reasoning. The lead soldier's innate perceptual abilities and tactical training are used to reduce the intelligence and perceptual capabilities required by the follower vehicles and allow them to operate at improved speeds and robustness, compared with robots that precede manned systems.

During operations, the soldier operating the lead vehicle (or acting as a dismounted leader) chooses paths that avoid serious obstacles to forward mobility, use terrain to provide cover and concealment and avoid paths that would compromise RF communications capabilities. The soldier's path is then automatically transmitted to the unmanned follower vehicles over tactical command and control data networks. The path consists of a series of waypoints that the lead soldier passed through, augmented by terrain features or data captured by the leader. The followers, utilizing their perceptual capabilities to detect any new obstacles, e.g., vehicles, civilians, or bomb craters, that have appeared since the passage of the leader, then follow the path defined by these "breadcrumbs," potentially with significant physical or temporal separation. This separation could extend to as much as a day later. Increasing the separation between leader and follower vehicles will, of course, place increasing perceptual and intelligence requirements upon the followers.

The Robotic Follower ATD has been structured to develop, integrate and demonstrate the technology required to rapidly incorporate this technology into future military systems for both mounted and dismounted warfare. Its aim is to conduct applied research and field experimentation to successively demonstrate a maturing autonomous mobility capability, placing primary emphasis upon the development and implementation of advanced perception algorithms required to rapidly detect and classify mobility obstacles. It focuses upon fusing information from multiple sensors to provide capabilities for operation during day, night, and limited visibility. It will address operation in traffic and operating on roads in accordance with traffic regulations. An emphasis is also placed on the interface requirements needed to embed the control of the follower vehicle in the manned lead vehicle and the interaction between the lead and follower vehicles. It has integrated the technology on surrogate platforms to examine the relative maturity levels of component technologies. It will also focus upon increasing the robustness of the technology to insure its readiness for rapid transition into System Development and Demonstration (SDD) programs.

During the program formulation process, technical goals were developed in conjunction with the Army Training and Doctrine Command (TRADOC) focusing upon four representative mission classes for the unmanned follower deemed applicable to future military operations: beyond/non line-of-sight weapons platforms, rear security vehicles, supply operations, and as a "mule" for dismounted troops. (Fig 2.) Each of these proposed missions places differing demands upon the system, in terms of vehicle speed, mobility and inherent intelligence. In support of dismounted troops, vehicles will typically maneuver at relatively low speeds, but require the ability to maneuver through highly complex terrain. During logistics operations, the vehicles may operate primarily on-road at high speed, but might initiate missions as much as 24 hours after the passage of the manned lead vehicle, placing significant demands upon perception and intelligence capabilities. These requirements were aggregated to produce the overall technical criteria for the program, shown in the Table 1.

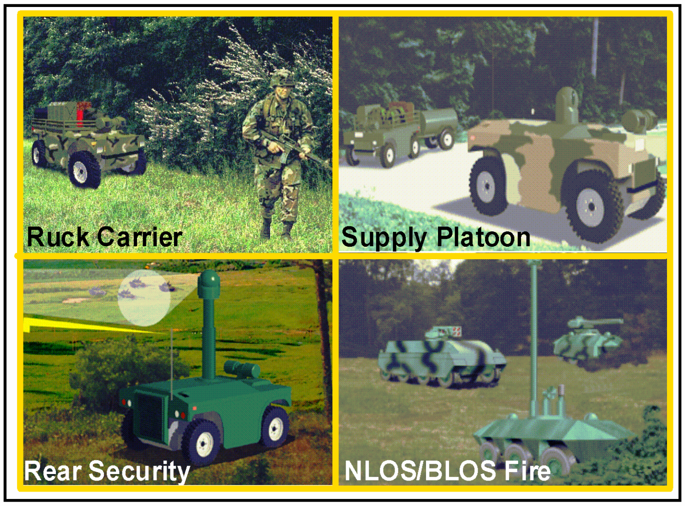

Figure 2. Robotic Follower Mission Classes.

Metric	Speed on Primary Road	Speed X-Country	Range	Max Time Delay	Separation
Minimum	65 kph	30 kph	160 km	24 hrs	Min: 10m Max: 5 km
Goal	100 kph	65 kph	750 km	24 hrs	Min: 1m Max: 200 km

Table 1. Robotic Follower Exit Criteria.

ROBOTIC FOLLOWER APPROACH

The Robotic Follower ATD leverages breakthroughs in perception and autonomous navigation from ARL's Semi-Autonomous Robotics for FCS Science and Technology Objective (STO). The primary technical objectives of the Robotic Follower ATD are to significantly increase the separation time/distance, increase follower speeds, integrate road lane detection and oncoming traffic detection capabilities for operation on road lanes, and augment the GPS waypoint approach taken in earlier efforts to improve robustness of the system.

In September 2001, an initial demonstration of robotic following was conducted under the Demo III program to demonstrate the potential capability of a robotic follower. It utilized a simple approach of transmitting the GPS-based position of the lead vehicle over a radio frequency link at predefined time or distance intervals. The follower would then go to each of these locations in sequential order, employing its obstacle detection and avoidance capabilities.

This approach was adequate to demonstrate the concept, however, it was not sufficient to meet the Robotic Follower ATD exit criteria. GPS fallout and/or GPS position accuracy drift means that the variation in actual to GPS measured absolute position can be as much as 100 meters at any given moment. Because both the lead and follower vehicles are subject to the same variations, the follower vehicle could be as much as 200 meters from the actual path of the leader vehicle. This error effectively negates the benefits derived from the soldier generated lead path.

To improve on the proof-of-concept approach and to demonstrate a robust robotic follower capability for early insertion into FCS, our technology development approach is concentrated in four areas; core leader-follower technology, improved obstacle detection and autonomous navigation, on-road convoying technology, and Soldier-Robot Interface. These technologies were integrated into a Stryker Infantry Carrier (IC) platform for field experiments and demonstration (Fig 3).

Figure 3. Robotic Follower based on Stryker Infantry Carrier Platform.

CORE LEADER-FOLLOWER TECHNOLOGY

Core leader-follower technology involves capturing the path of the leader and providing enough information to the follower to minimize any lateral deviation from the intended path. The approach for the Robotic Follower ATD is to augment GPS position with inertial navigation data and information from sensors on the lead vehicle.

Using an identical sensor suite as the follower vehicle, the lead vehicle generates a high resolution, local terrain map. Advanced map registration techniques register this map with a priori Digital Terrain Elevation Data (DTED) to provide an accurate estimate of the lead vehicle's position. This position and, when communication bandwidth allows, a compressed version of the local terrain map is sent to the follower. The follower utilizes the same registration techniques to estimate its position, allowing it to accurately follow the lead vehicle's path.

OBSTACLE DETECTION AND AUTONOMOUS NAVIGATION

The second focus area, heavily leverages ARL's Demo III Program and Semi-autonomous Robotics for FCS STO and improves the ability to perceive and react to new or unexpected obstacles that may present themselves during the temporal and/or spatial separation between the lead and follower vehicles. At the heart of the autonomous navigation system is the autonomous mobility (AM) sensor suite, which is integrated on both the leader and the follower platforms. The AM suite is a combination of the Demo III Experimental Unmanned Vehicle (XUV) sensors and the pan/tilt unit from DARPA's PerceptOR program. This pan/tilt unit integrates all of primary AM sensors into a single space-saving unit and ensures that all of the sensors are co-aligned.

ON-ROAD CONVOYING TECHNOLOGY

On-road convoying technology includes edge detection techniques to maintain lane integrity and vehicle tracking during road following scenarios. High speed, on-road driving is a significantly different task than off-road vehicle navigation. Systems that perform this task automatically usually have the advantage of being able to exploit the man-made characteristics and features of the roadway and the driving task – road markings, traffic rules, and road building guidelines for example. This is fortunate, as the vehicle must be able to operate at significant speeds and interact with other vehicles, being driven by humans or otherwise. To enable robust performance in this domain, low level sensing and control actions (road following, obstacle detection, steering, throttle, braking) are coupled with higher level tasks such as lane changing, obstacle avoidance, highway entry and egress, and convoying functions.

Lane Tracking

The first significant technology that must be in place to support robust, high speed, on-road driving is lane tracking. Lane Tracking Algorithms (LTAs) incorporate many novel features not found in other systems. In order to locate the road ahead, the LTAs first resample a trapezoid shaped area in the video image to eliminate the effect of perspective. They then use a template-based matching technique to find parallel image features in this perspective free image. These features can be as distinct as lane markings, or as subtle as the diffuse oil spots down the center of the lane left by previous vehicles. When put in road convoying mode, the follower will apply LTA's coupled with the path it is receiving from the leader to achieve the high accuracy demands necessary to maintain lane integrity.

Vehicle Tracking

Vehicle tracking is an essential requirement for the robotic follower system to support convoy operations, provide safety on heavily trafficked roads, enable operations in cluttered depot environments, and to support formation driving. This approach includes development of visual servoing techniques for convoying that enable a following vehicle to keep the lead vehicle laterally centered in its horizontal field-of-view. A scene acquired by a camera mounted on the following vehicle is processed using feature classification techniques to determine the relative position of the lead vehicle. The following vehicle is autonomously steered to maintain a position directly behind the lead vehicle.

A fundamental difference between this program and other on-road driving programs, is that a priori information about the road to be traveled is available from a leader vehicle. The lead vehicle builds an annotated map that contains locations and characteristics of significant road features. This map contains basic geometry information, including the GPS path of the lead vehicle, sensor-specific details such as lane marking type (missing, solid, dashed) and color, obstacle location, extent and visibility, sensor performance information such as usefulness of laser and radar sensor for encountered obstacles, and dynamic information such as road smoothness and banking. By using these types of features, performance of following vehicles can be carefully tuned for the conditions they are likely to encounter.

SOLDIER-ROBOT INTERFACE

The final focus area is concerned with the interface between the soldier operator and the robotic entities. Through this interface, the soldier conducts mission planning and maintains current health status of the robotic entities. This interface allows the soldier to choose from a number of follower modes such as cross-country, on-road, etc, and permits him to set following parameters such as desired following separation time or distance, maximum speed, and maximum allowable path deviation. As a departure from previous robotics efforts that utilized dedicated soldiers and operator control units and as a step toward FCS requirements, this functionality was embedded into the Crew integration and Automation Testbed (CAT) vehicle. The crew of the combat vehicle executes its own vehicle's mission while controlling the robotic follower. The interface utilizes associate technology to provide the soldier with need-to-know information based on current situation assessment and intent and advanced interfaces (e.g. speech recognition) that optimize his performance.

Another development effort in this area is for an operator control unit (OCU) for the dismounted soldier (Fig. 4). The dismounted OCU is a portable, integrated unit that enables a robotic follower to track a soldier on foot. As sensor data for map registration is not a viable alternative for the dismounted follower application, the approach uses a GPS-based system with dead-reckoning to compensate for GPS fallout.

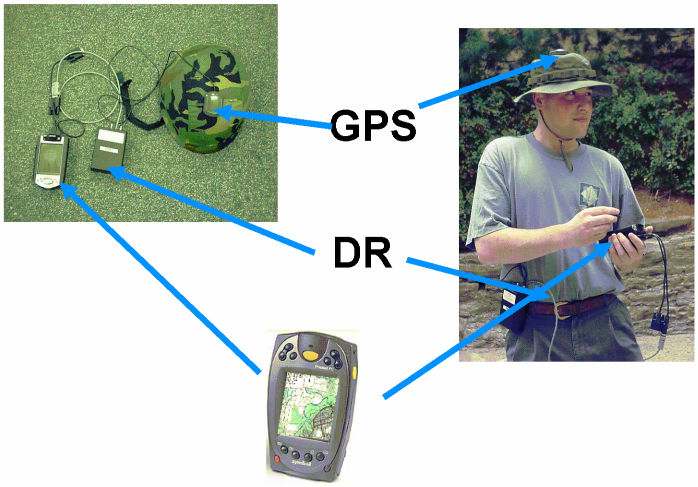

Figure 4. Dismounted Operator Control Unit.

EXPERIMENTATION RESULTS

The objective of the Engineering Evaluation phase of the Robotic Follower ATD was to characterize system performance against a set of controlled test experiments. The Engineering Evaluation phase also verified the technical parameters of the relevant subsystem and system components as well as the overall system performance. These measured, demonstrated and/or analyzed values were used to characterize and verify compliance to the system specification and applicable technical design compliance. More importantly, the acquired experimental data was delivered to the FCS Lead System Integrator (LSI) to substantiate technical readiness assessments that leader-follower technology was mature and available for insertion into planned Increment I unmanned and manned ground vehicles. The following gives an overview of the test regiment conducted and provides details on several critical aspects of the Robotic Follower program: namely, path following accuracy for on-road and cross-country mission scenarios.

The following trials were conducted and successfully demonstrated for Vehicle following on Primary Road:

Test 1: 30kph @ 50m separation
Test 2: 40kph @ 50m separation
Test 3: 40kph @ 100m separation
Test 4: 40kph @ 150m separation
Test 5: 40kph @ 50m separation

The following trials were conducted and successfully demonstrated for Vehicle following Cross-country:

Test 1: 20kph @ 100m
Test 2: 20kph @ 50m

The following test was conducted to characterize maximum time delay:

Test 1: 30kph with 360min delay

The Robotic Follower and leader, Crew integration and Automation Testbed (CAT), vehicles were driven to the start point. Convoy mode was setup with a 6hr delay. The CAT drove the entire 15km course. The robotic follower was taken off the network and both vehicles were taken back to the Motor Pool. After 5 ½ hrs the robotic follower was driven back to the start point. 30 minutes later it started its engine and followed the path originally taken by the CAT 6 hrs earlier.

The following test was conducted to demonstrate multiple vehicle convoying:

Test 1: 30kph @ 100m

This test had the robotic follower vehicle following the CAT, and the Experimental Unmanned Vehicle (XUV) following the robotic follower vehicle. The software was such that the following vehicles could move at speeds up to 20% higher than that of their lead. After about half way into the course all vehicles achieved formation following (100m between them and speed matching).

The following trials were conducted to characterize maximum speed following

Test 1: 30kph @ 100m on 15.9km course
Test 2: 40kph @ 100m on 15.9km course
Test 3: 50kph @ 100m on 15.9km course
Test 4: 65kph @ 100m on 31.8km course

ON-ROAD FOLLOWER ACCURACY

Test results acquired from vehicle following on a primary road surface are presented in Figures 5-7. In these figures, absolute position (in meters) is shown on both the x and y axes. Vehicle position was acquired using on-board differential GPS. Figure 5 shows the entire 15.9 km loop which was traveled at a speed of 30.4 kph with a 50 meter separation distance. Figure 6 shows a magnified image of the dashed rectangle in Figure 5. Likewise, Figure 7 shows a magnified image of the dashed rectangle area depicted in Figure 6. Most notable in Figure 7, the red line shows the actual path of the leader vehicle and the blue line shows the actual path of the follower vehicle. An analysis of the entire route was conducted, and from Figure 7, we conclude that the maximum lateral error for the entire 15.9 km circuit was 0.45

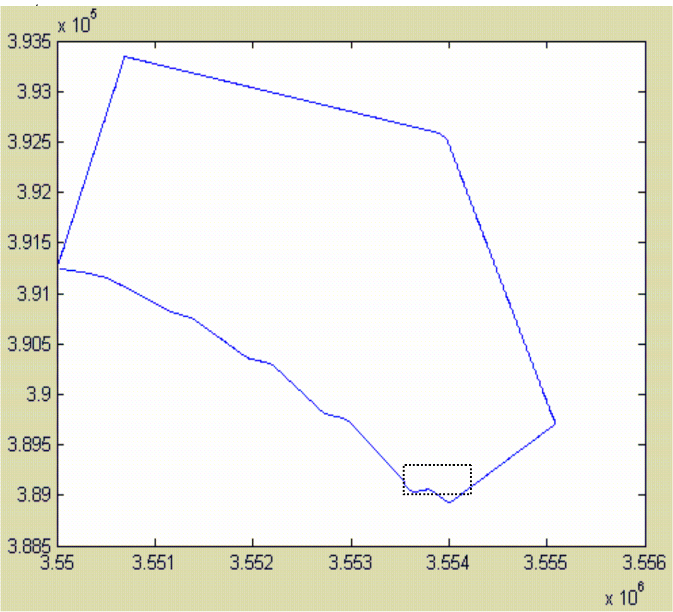

Figure 5. On-Road Vehicle Following.

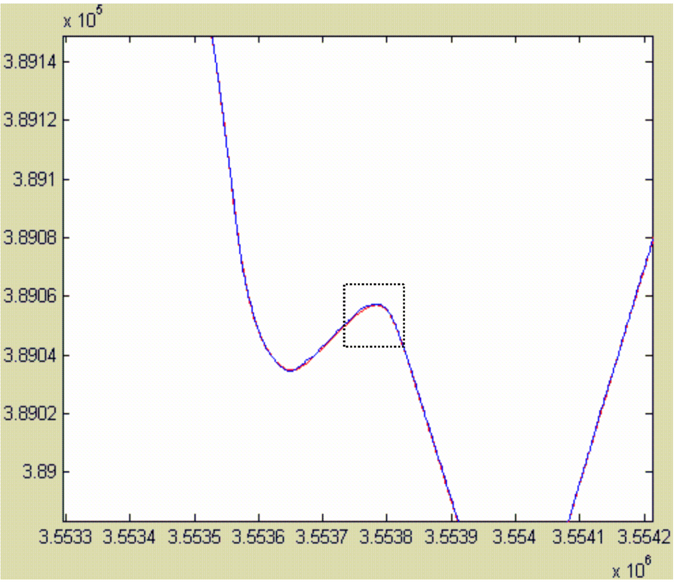

Figure 6. On-Road Vehicle Following.

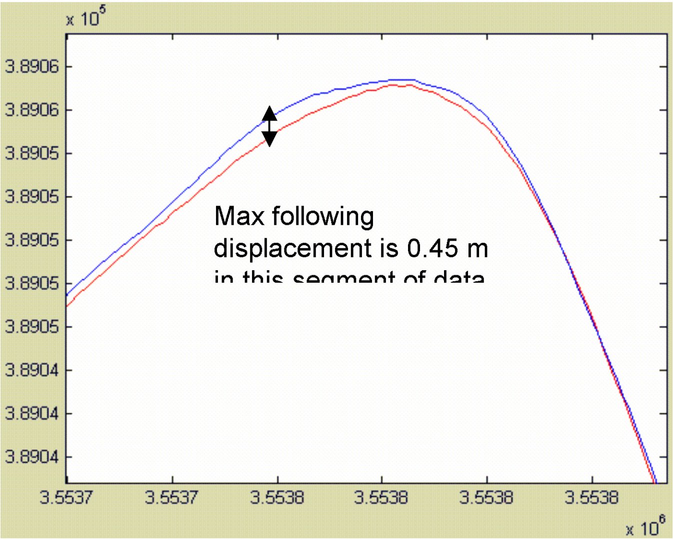

Figure 7. On-road Vehicle Following.

OFF-ROAD FOLLOWER ACCURACY

Test results acquired from vehicle following on a cross country surface are presented in Figures 8-10. In these figures, absolute position (in meters) is shown on both the x and y axes. Vehicle position was acquired using on-board differential GPS. Figure 8 shows the entire 3.0 km loop which was traveled at a speed of 19.2 kph with a 50 meter separation distance. Figure 9 shows a magnified image of the dashed rectangle in Figure 8. Likewise, Figure 10 shows a magnified image of the dashed rectangle area depicted in Figure 9. Most notable in Figure 10, the red line shows the actual path of the leader vehicle and the blue line shows the actual path of the follower vehicle. An analysis of the entire route was conducted, and from Figure 10, we conclude that the maximum lateral error for the entire 3.0 km circuit was 7.0 meters.

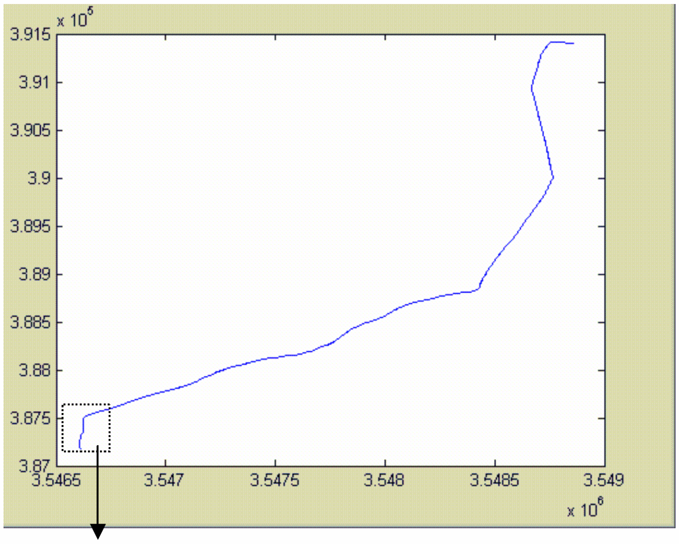

Figure 8. Cross-country Vehicle Following.

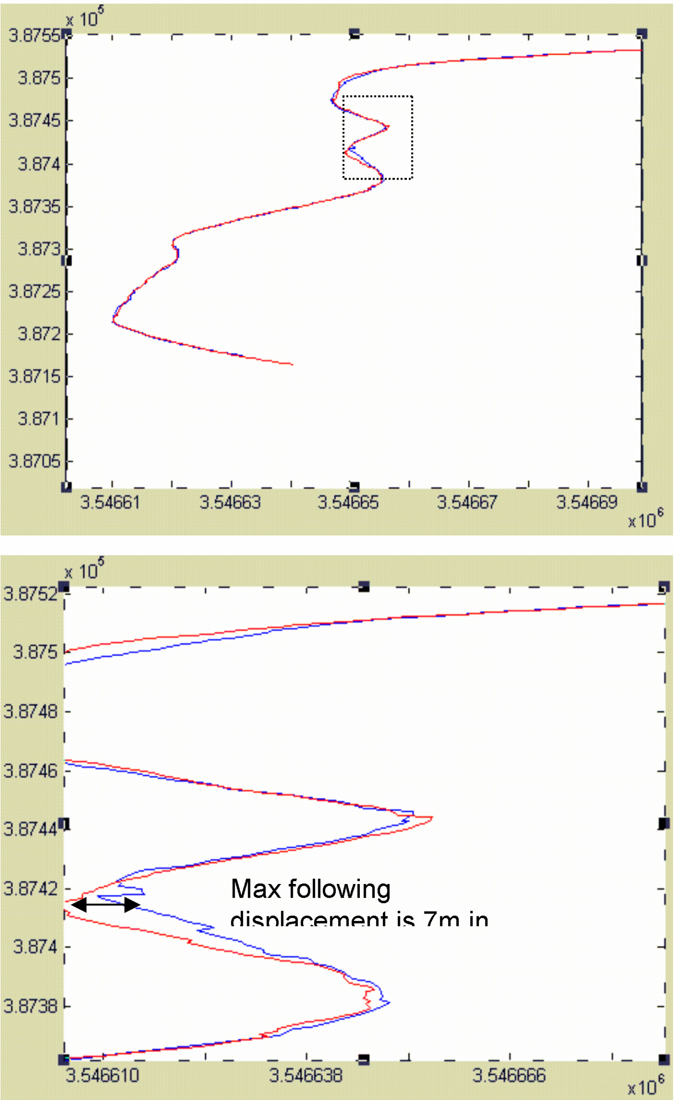

Figure 9. Cross-country Vehicle Following.

CONCLUSION

The Robotic Follower ATD is focused on providing baseline robotics capabilities to support initial unmanned systems for Increment I of the Future Combat Systems program. The Tank Automotive Research, Development & Engineering Center (TARDEC) has successfully demonstrated the robustness and readiness of core leader-follower technology, on-road convoying technology, and Soldier-Robot Interface technology for FCS. The engineering experimentation results and achievements presented in this paper lay the foundation for further maturation and testing to include higher levels of performance in terms of speed, follower accuracy and separation distance, as well as additional capabilities including operation in light traffic, urban environments and in the presence of pedestrians. Subsequent field experiments are planned for late 2004 and early 2006. The Robotic Follower ATD will continue to provide unmanned system enabling technologies for the Army as it strives to reach its transformation vision.

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Figure 10. Cross-country Vehicle Following.

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