FCS UGV Safe Operations

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ABSTRACT

The US Army Future Combat System (FCS) will implement Unmanned Ground Vehicles (UGV) in numbers not previously seen before in military operations. Many of these vehicles will also be larger and faster than the small robots typically used today for explosive ordnance disposal and general improvised explosive device handling. More importantly, FCS will implement these UGV's in scenarios were they will be in much closer proximity to soldiers and other non-combatant personnel. This paper describes the plan for developing an appropriate match of technology for autonomous UGV maneuver with the emerging need for safety release verification for these systems prior to fielding. The plan is followed by descriptions of initial data collections with a UGV, that will form the starting point in this safety release process, and stimulate further use and refinement of this process for large UGV's in applications beyond FCS.

Keywords: Unmanned Ground Vehicles, Safety, Experiments, Simulation

BACKGROUND

The US Army's Future Combat Systems includes the first use of large Unmanned Ground Vehicles (UGV) in significant numbers as true combined arms elements in the core force structure. Nominal force structure concepts include on the order of ¼ of the large combat platforms to be unmanned. For this reason, FCS includes UGV system maturation along the same development process as that seen for all large production platform systems. As such, it is departing from previous processes of converting manned systems to unmanned configuration, or adapting a research platform for higher production rates and fielding. This new path for UGV's comes with some uncertainty in the establishment of the safety release criteria for these platforms. Previous UGV's have been implemented with teleoperation and thus the safety release process has focused on confirmation of positive operator control, and for larger platforms such as Panther, on very limited operational constraints.[2] This paper discusses the current plan for successfully obtaining Safety Releases for larger platforms which goes beyond previous constraints by including autonomous maneuver modes, as well as reducing minimum separation distances between the UGV and cooperative humans and other moving vehicles. These extensions are extremely important for FCS as well as other large UGV applications in the public domain. We will then show initial steps that have been taken along this process to stimulate progress towards the certification.

PLAN FOR ACHIEVING UGV MANEUVER SAFETY RELEASE

The plan for expanding current safety release conditions to include autonomy and operations near humans and moving vehicles involves efforts on two fronts. This dual approach recognizes that the solution will not arise from a particular

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magic bullet technology, nor from an Edisonian series of autonomous UGV trials with humans until we find suitable constraints to prevent injury. The first part of this approach (and the topic of this paper) involves methodical development and demonstration of technology advancements while safely conducting verification testing. In parallel to this technology development, alternative operational scenarios and associated constraints must be developed to insure effective use of UGV's in the context of FCS under varying safety constraints. These options allow the Army to develop tactics appropriate to growing levels of UGV safety performance and thus enable corresponding growth in employment flexibility. With these two approaches in mind, we realize that development timeline is very important and desire an approach which encourages safe technology development that allows UGV operations at decreasing range from humans and increasing maneuverability among humans. The following describes in more detail the process expected for maturing the technology and assessing the conditions under which a UGV safety release would be obtained for FCS.

1. Technology Maturation

Movement beyond teleoperation to include autonomous UGV modes in a safety release requires a significant leap of technology over what has been fielded to the military today. Not only must we assure that there is adequate control authority by the Operator over the UGV, but we must also assure that the onboard autonomous capability can adequately detect and force the platform to react safely to conditions prescribed for normal mission operations. In the context of this paper, we are interested in safety conditions related to operation in the vicinity of humans.

There are key improvements needed in the areas of perception and navigation to enable remote and autonomous operation in proximity with humans. The ability to classify humans has been demonstrated to a limited degree but is not nearly reliable enough yet, and has serious limitations with regards to the velocities of both the sensor and the humans (as well significant limitations with regard to the intentional and unintentional obscuration of the humans relative to the robot). Single modality detection (face detection, thermal signature, geometric shape matching, or other) will not likely be adequate to accommodate changing lighting, backgrounds, postures, relative velocities and occlusions which are relevant for combat conditions. FCS will continue to look to the Science and Technology community within DoD as well as commercial technology advancements to increase performance and reduce the safe distance of separation that must be maintained with humans.

2. Strategy for Bringing UGV Maneuver Technology to Qualification Test

Given the need to both mature technology, and to safely verify its capabilities for enabling teleoperation and autonomous operation in the vicinity of humans, a strategy must be formulated which can be understood and agreed to by the US Army Safety Community, the FCS Development Team, and the TRADOC User Community. Below we propose such a strategy which is being circulated for discussion within the FCS/Army Community.

A central theme in the strategy for maturing technology and validating it for UGV safety is the need to estimate performance well before including humans in test scenarios with UGV autonomous control (when not autonomous, a human safety operator using a wireless remote control retains the positive control over the vehicle that prevents hazardous situations and enables a rapid halt of experimentation when hazardous conditions are approached – essentially all operation is human controlled within direct proximity of the vehicle and its actions) We term human controlled modes of UGVs "Manually Controlled UGVs". To create this environment for validation, we follow these steps:

1. Collect sensor data for Manually Controlled UGV movement in the desired operating conditions (including avoidance maneuvers) similar to actual verification test conditions. *Note that our desire is a solution system that is not optimized for a narrow set of test conditions however, so the data collection should be expanded over time to include a variety of representative lighting conditions, background clutter, relative velocities and complexity that one would expect to constrain operations to include in the fielded system.* It is critical that these data collections include real humans (with realistic clothing and behaviors) in the sensor data if at all possible. Substitution of mannequins (even moving mannequins) may not enable the data to capture key features needed to enable robust algorithm development across the various modes available (and expected to be used) in FCS UGVs.

2. Release subsets of this data to approved developers for their use in maturing software approaches to detection, tracking, and possibly avoidance planning for UGV's in the presence of humans. Early availability of this data allows these developers to explore many alternative techniques through simulated playback of this data through candidate algorithms and mature the higher performing options.
3. Utilize reserve (or new) sets of field data from step 1 to allow FCS and the Safety Community to evaluate proposed options provided by developers. The evaluation method would again be through simulated playback of the data, but under careful control of an FCS evaluation team which would compare perception derived detections with ground truth measurements, as well as evaluate false positive results. As candidate perception approaches show value and are included with appropriate UGV maneuver planners, final evaluation would be made based on simulated response of the UGV to the perceived stationary and moving humans. Here one would want to insure that planned UGV maneuvers are appropriately maintaining clearance even with moving humans in the scenes. This simulated performance becomes the justified basis for authorization to conduct autonomous experiments under the same conditions (see step 4). *Note that an excursion here, if time and budget allow, would be to subject the codes to hardware test with the target UGV while retaining manual control (the evaluation would center on algorithm derived control commands for the UGV, which in these tests would be circumvented by the manual control, with an appropriate metric for "appropriate" and "inappropriate" automated control outputs.*
4. Successful perception and avoidance technology is then authorized through the appropriate safety office for use in an autonomously maneuvering UGV in the same conditions (again with real humans in the scene). Note that the experiment would be performed starting at slow speeds, and progressing to higher speeds as successful minimum UGV separations are maintained with the humans. An independent safety stop operator is used here to assure that the vehicle does not create a hazard for the humans. Note that sensor data is collected in this case as well for later simulation verification of behavior and clear understanding of what attributes in the scene governed the maneuver actions of the vehicle. Once success is achieved at the previously simulated level, additional tests can be conducted in the mode described in step 1 to expand the operating conditions and start the cycle again for higher human velocities, levels of human obscuration and camouflage.
5. Successful completion of autonomous experimentation portions of step 4 leads to safety release under these autonomous test conditions. As more test conditions are confirmed using the cycle of 1 through 4, the associated safety release constraints can be relaxed accordingly. Furthermore, as safety constraints are relaxed, the associated operational utility can be expanded to include and increasing number of tactically relevant situations.

With the above strategy for UGV maneuver safety development and verification, FCS expects to achieve relevant performance in close cooperation with the Science and Technology community and the Army Test Community.

INITIAL SAFE UGV DATA COLLECTION

To initialize the process, the FCS Lead System Integrator has teamed up with DARPA to safely generate initial data sets for use in step 1. Two simple data collections were planned and executed during UPI field experiments adjacent to the experiment Command Post. These limited test conditions are relevant to FCS while providing extensive detail in sensor data in multiple sensor regimes with moving and stationary humans. It is expected that once successfully moving through the previously outlined process, that additional data collection conditions can be initiated under even more relevant FCS conditions for eventual use in FCS UGV Safety Release Testing.

Overview

Safety in these data collections is achieved by manually operating a well characterized UGV in direct, remote control (RC) mode while maintaining direct visual observation of the vehicle and all participants at all times. In this mode, the UGV is manually driven through three different scenes, carefully controlling and recording the sensor positions and the positions of the humans. The sensor carrying platform is the DARPA CRUSHER UGV (**Figure 1**) designed and developed at the Carnegie Mellon National Robotics Engineering Center, and the Operator is well trained and experienced in all modes of operation and safety procedures associated with this platform. Prior to data collections, planners reviewed all existing safety protocols related to normal Manually Controlled UGV operation (normal RC operations) around personnel, including speeds, safe distances, and operator proximity[3]. All human participants were briefed on the planned UGV movement and then observe this movement before assuming their specified places in the test area. This trial run of the vehicle through the test area also establishes visible tracks (all of our tests have been conducted in deformable grass or dirt where the path of the vehicle is clearly marked by the tires), which acted also as a dry run for positions, speeds, and timing. Each participant is shown a position and allowed to adjust his position based on the expected UGV movement to allow at least two directions of movement for emergency egress from his position in cases where the vehicle is uncomfortably close. Two participants wear a backpack Real Time Kinematic (RTK) Global Positioning System (GPS) system, accurate in absolute positioning to centimeters, to track their position real time. All other participant's location is logged with RTK GPS and the vehicle carries an RTK GPS positioning system. Hence, all ground truthing is logged to high corresponding absolute accuracy.

Figure 1. Crusher UGV operating autonomously with Safety Observer following in HMMWV.

Test preparation and rehearsal

The method behind the selection of the test scenarios and protocol was predicting the ways the UGV control could fail, and minimizing exposure to these risks. In a city, you might think nothing of walking down the street on a sidewalk while cars drive past at 30mph a few meters away. We all have mental rules about how cars move (they stay on the road, we stay on the sidewalk) and that allows us to be in close proximity. With a machine as mobile as Crusher in an unstructured environment this isn't the case. We need to determine what motions are possible in the test circumstances and ensure we don't have people and UGV's in the same spaces. An overview of the possible failures -

- Continues on path when commanded to stop (due to vehicle hardware/software failure) – To deal with this failure mode, we keep test participants out of the forward path of the UGV as much as possible, and also require participant to select multiple escape routes for this case. We also limit the maximum speeds available to the remote control operator so that such a "runaway" condition would be capped in vehicle speed.
- Accelerates unexpectedly (due to vehicle hardware/software failure)– this failure mode is addressed as above, minimizing the time participants are in line with the path of the UGV, and ensuring sufficient distance between the UGV and participant.
- Changes direction unexpectedly (due to vehicle hardware/software failure)– this failure mode is addressed by maintaining sufficient distance between the UGV and the participant. The mass of the UGV is high enough that some warning will be present as it can't change direction instantaneously.
- Stops unexpectedly (due to vehicle hardware/software failure)– This failure is lower risk, but is mitigated by maintaining sufficient distance that a participant will not walk into a stopped UGV.
- Remote control operator error – This failure would be that the remote control operator controls the vehicle on a path or at speed that is drastically other than that agreed upon prior to the test and practiced. To mitigate this

[3] Stager Safety Procedures for NREC and Crusher

risk we require that the RC operator can see all persons and that all persons can easily see the vehicle. The vehicle is operated with the engine off to create a quite test environment enabling people to hear each other if needed. Finally, our RC control device requires pressure on the joysticks to continue motion. If the RC operator became incapacitated for whatever reason (heart attack, bee sting, etc), we believe it unlikely that he would continue to depress both paddles. More likely would be complete drop of the RC unit which would cause both paddles to center and the vehicle to halt. An additional procedure of slower response time is available through the independent test director, who can radio the Crusher command center for a remote shutdown of the vehicle. This is practiced to a 1-3 second response time and therefore is not considered a primary safety link for testing. In the future, we recommend a secondary operator located in the command truck also be capable of invoking an emergency stop in the event the primary remote operator be incapacitated.

The UGV RC operator selects an area to operate from with a good view. He then drives the UGV in the maneuver desired for that test. This leaves a track on the ground as a reference for the operator and for placement of test participants at safe distances. Each test participant is selected to represent either a stationary or moving human. Stationary humans are placed in scattered positions at safe distances from the practiced path of the UGV in either standing or kneeling positions. Kneeling humans are instructed to rest on one knee only as a precaution allowing for escape if necessary. Stationary humans are placed in the open and also around vegetation clumps and other sensor-confounding features. The position of all stationary humans is logged by a person with a GPS rover backpack walking a tight circle around their location (The ground is also marked in case the person needs to move temporarily between test runs). Test participants designated as moving humans walk straight predetermined paths from pre-marked positions if they are not instrumented with a GPS rover backpack. If they are instrumented, then they are allowed to select an arbitrary path, but instructed to stay further away from the robot than the RC operator or the stationary humans. The rationale for this being that the stationary humans have already been placed a safe distance from the UGV, so movement further away than that will generally be acceptable. As an additional safety measure, these arbitrary paths are selected before the test, and the test participants (wearing GPS rover backpacks) are obligated to walk their paths consistently during the test.

Test Scenarios

A series of test scenarios were selected to provide a wide variety of relative motions between the vehicle and humans, while keeping the human out of the UGV path as much as possible. This was accomplished by having the humans stand outside the vector of UGV motion as much as possible and designing the tests so that the UGV sensors sweep past humans, but limit the amount of time a human is located in the direct path of the UGV. Diagrams of the test configurations are shown in **Figure 2**.

1. **Static Test**. The first test was a static vehicle test, where the UGV remained motionless, while humans stood still or moved through the field of view of the sensors. This allows collection of sensor data with human subjects against a static background.
2. **Spin Test**. Here the UGV, which in our case was a differential-drive or skid-steer design, is pivoted about its center. Stationary humans were placed at a safe distance from the rotating UGV, while moving humans walk in tangential paths – either with the direction of rotation of the UGV or against it – such that the UGV sensors are swept past the humans. This test introduces a moving background to the sensors which is an extra complication over the static test. The UGV motion is in the simplest prescribed path – full differential-drive pivot – so that the motion is predictable by everyone in the test.
3. **Stager Test (Reverse Straight Test)**. This test was named for David Stager (NREC Crusher Lead Engineer) who first proposed it as a safe means to capture sensor data of a human crossing the path of the UGV. Here the UGV is driven straight backwards in a set path. Human participants start on one side of the path, and cross over to the other as the UGV passes. In this way, the humans are kept out of the vector of UGV motion at all times. The momentum of the backwards-moving UGV is high enough that the humans can pass safely in front of the UGV as it passes without worry that it will suddenly slow, stop, and begin moving forwards. The data, when replayed backwards, will look like people crossing in front of the UGV at distances at would have been unsafe had the vehicle been traveling forward.

4. **Straight Test.** In the Straight Test, the UGV drives a straight path. Stationary humans stand offset from the UGV forward path. Moving humans cross the path of the UGV at a safe distance, farther than is possible during the Stager test.
5. **Arc Test.** The Arc Test is designed to sweep the UGV sensors past moving and stationary humans, while the vehicle is in motion. This is similar to the straight line tests, except the UGV drives in an arc or gradual turn and the moving humans walk either across the path of the UGV or tangentially to the arc of the motion. This is one of the more complicated tests, so several test runs are performed (prior to humans assuming their final positions) so that the UGV RC operator is sure of the path he can maintain with the UGV.

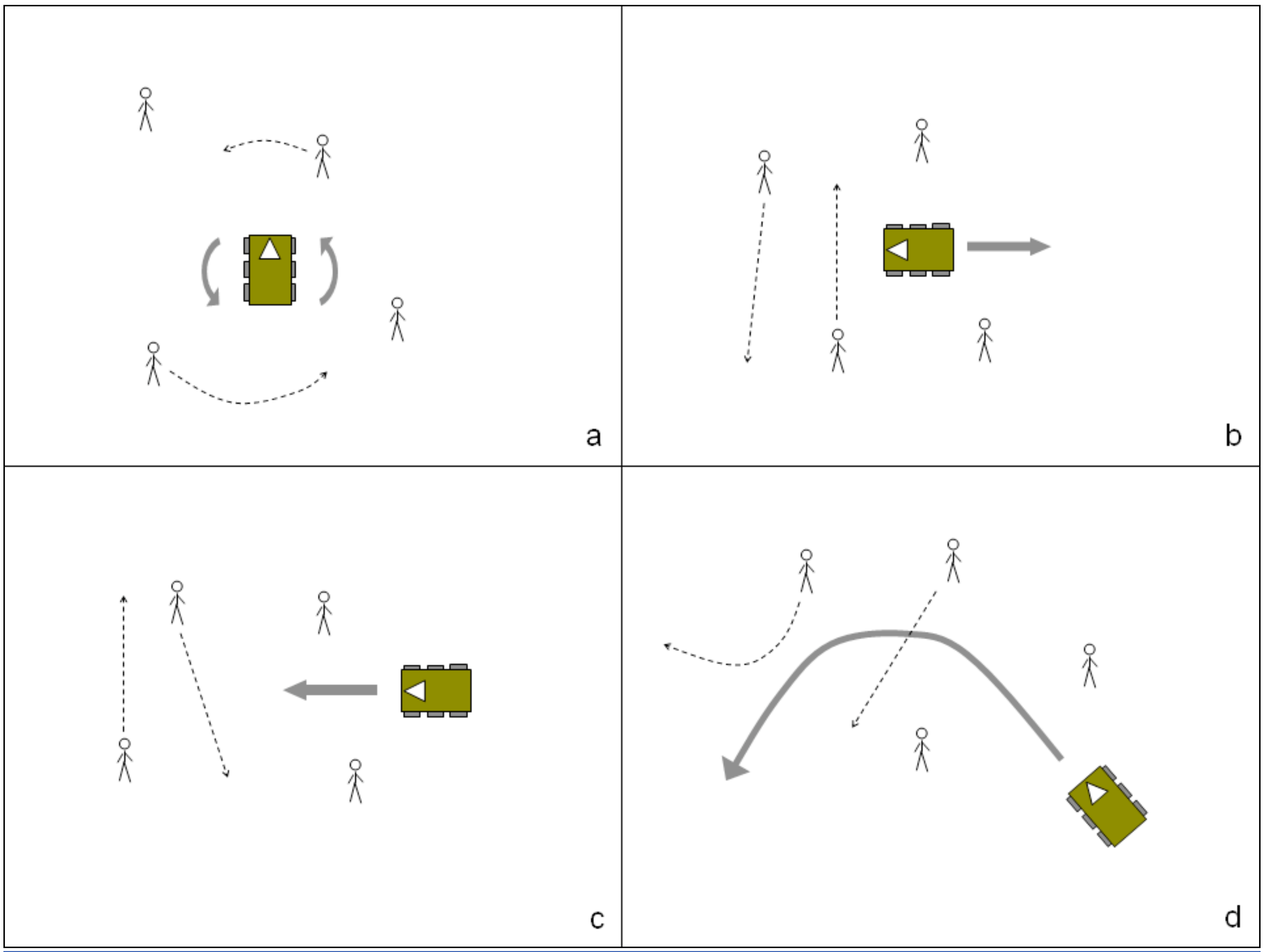

Figure 2. a-Spin Test , b-Stager/Reverse Straight Test, c–Forward Straight Test, d-Arc Test. Dashed lines are representative of motion of GPS instrumented participants.

Test Hardware

The Crusher vehicle is equipped with a GPS receiver and an inertial measurement unit for the estimation of global pose which includes GPS referenced position and also angular orientations. The current configuration of Crusher employs WAAS augmented GPS, while a L1/L2 real-time kinematic (RTK) GPS system records ground truth for post-test analysis at a nominal 2cm standard deviation at a 20Hz rate (Novatel SPAN system: Propack-LB+HP-RT2i).

The perception system on Crusher consists of 6 LADAR scanners (SICK LMS with 90deg scan FOV, 0.5deg beam spacing, 181 pts/scan, 75kHz scan rate), with 4-aimed in the forward direction with the beam horizontal, mechanically swept up and down to cover a wider field. Two more SICK LADAR units are mounted - one on each side - with the beam vertical. These are mechanically swept side-to-side.


Figure 3: Crusher Vehicle

In addition to the LADAR units, several cameras are used. Eight Point Gray Research Bumblebee stereo modules (each with two integral cameras with a short baseline) are mounted on Crusher, but they are not employed in stereo mode (although stereo processing could be performed on the archived images). The modules are mounted in pairs, so that there are 4 fields of view, each covered by 4 cameras – one left, one right, and two fields covering the forward direction. The front two sets of 4 cameras are visible in **Figure 3**, between the SICK LADAR units. Likewise the left set of 4 cameras of the left side of the vehicle is visible above the left side laser scanner unit. In a set of 4 cameras, two are configured as color cameras with different exposure levels so extended-dynamic-range images can be constructed from an under-exposed and an over-exposed image. This is very useful for outdoor use and resolving features in shadows on sunny days. Of the two other cameras in the set, one has a red-pass filter, and the other has a near-IR pass filter. The isolation of these two wavelength bands can be useful to help identify vegetation in the scene. **Figure 4** depicts the four images that are available from one of the views. Note also that image pixels are combined with LADAR points to create colorized LADAR range points.

Data products that were collected include the UGV and human rover positions at 20Hz sample rate. Humans that participated in the test and were stationary were marked in the rover's position log by having one of the rover-backpack equipped persons walk a circle around each stationary test participant before the test began. The UGV also records a substantial amount of information including the commands to the UGV, the UGV state and pose, the time-stamped scans from the six SICK LADARs, and the time-stamped images from all 8 Bumblebee modules (16 images per capture).

Figure 4, a four-camera cluster of image pairs from an Arc Test. Each image is taken at two exposure levels to increase the recorded dynamic range. Top left pair - red band. Bottom left pair - NIR band. Top right pair - color image. Bottom right pair – a second color image. the second color

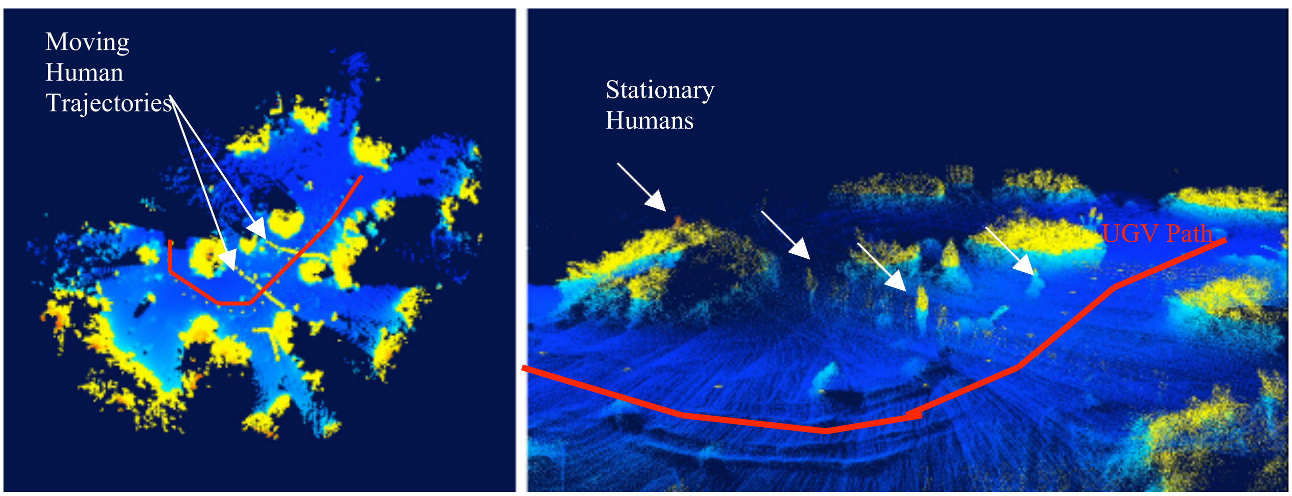

Figure 5. Two views of LADAR data accumulated during a test. Points are color tagged for elevation. Left – aerial view. Right – an observer's view of the curved track displayed in figure 4.

For the human movers, an RTK-capable GPS receiver backpack was used to determine their location for post-test analysis. These rover backpacks contained an L1 antenna and GPS receiver, as well as data radios configured to receive GPS signal corrections from Crusher's GPS base station. A notebook computer was used to record the logging data at a rate of 20Hz. The rover receivers used L1 RTK corrections only, so their position was known to a standard deviation of 20cm. Using the same base station for GPS corrections allowed the recording Crusher and the rover positions in terms of the same reference point, minimizing position errors between the measurement sets. Complete ground truthing of all subjects is 100% desired, likely via the RTK GPS units utilized. Future tests could use additional RTK tracking units on the humans for more random and/or complex movement, but the current configuration did not present a real burden on test time for the test configurations described in these initial data collections.

Terrain at Test Sites
These tests have been performed at two tests sites in an attempt to vary the type of terrain in the data set. See **Figure 5**. Real-world factors that affect the quality of the sensor data include wash-out of cameras at low sun angles, obstruction of LADAR rays by grass and vegetation, and other factors.

The first set of tests were performed at Ft Carson, CO in August of 2006. The terrain was generally flat or slightly rolling with mostly rocky soil, with some high grasses and a few sparse trees. Terrain obstructions include groups of trees, slopes, and dry washes. At Ft. Carson, the human participants are generally in view of the sensors, but may be standing, crouching or partially obstructed by trees brush or high grass.

The second set of tests were performed at Ft. Bliss TX in January of 2007 where the terrain was dominated by raised, vegetation-covered dunes of approximately 50m^2 in area that rise up to 1.5m above the surface which is mostly barren and composed of sandy soil. There are few trees and the terrain is mostly flat. At Ft. Bliss, the human participants may be in plain view of the sensors or, at times, completely obstructed by a vegetation-covered dune.

Figure 6. a - Ft. Carson, CO b - Ft. Bliss, TX

CONCLUSIONS

The previous sections have described a safe, progressive strategy for developing, assessing, testing, and finally releasing UGVs for safe operations in the presence of humans which can be used to iteratively match the challenging technical developments required for autonomous operation with the equally challenging goals of obtaining safety releases for use of these systems in the field. Sample data sets have been collected and described here which should form the foundation for this cyclic process to accelerate development across a broad range of technical approaches to improving autonomous performance in the presence of humans without creating unsafe test conditions. It is hoped that researchers which can show promise in providing solutions to FCS safe operations needs will get an opportunity to work with this data and demonstrate their capability for the Government and the FCS Program. It is expected that some form of this process is equally useful for the certification of autonomous software for other applications of autonomous UGVs in close proximity with humans and human occupied vehicles.

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