2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING and TECHNOLOGY SYMPOSIUM
Modeling & Simulation, Testing and Validation (MSTV) Mini-Symposium
August 17-19 Dearborn, Michigan

STEREO VISION FOR EXPLOSIVE THREAT DEFEAT: TEST AND RESULTS

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ABSTRACT

In this paper, we report on the use of a 3D vision field upgrade kit for the TALON robot consisting of a replacement flat panel stereoscopic display, and multiple stereo camera systems. An assessment of the system's use for robotic driving, manipulation, and surveillance operations was conducted. A replacement display, replacement mast camera with zoom, auto-focus, and variable convergence, and a replacement gripper camera with fixed focus and zoom comprise the upgrade kit. The stereo mast camera allows for improved driving and situational awareness as well as scene survey. The stereo gripper camera allows for improved manipulation in typical TALON missions.

INTRODUCTION

Background

The United States (U.S.) Army's use of tele-operated robots in executing combat operations has exponentially increased during the past decade. This has especially been true during Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF), in which robots were used for a wide variety of combat tasks. Robots provide a means to execute dangerous missions at standoff distances, which greatly increased the protection of Soldiers.

The biggest challenge that Soldiers must overcome when operating robots at standoff is the reliance upon the perspective presented to them via current two-dimensional (2D) displays, rather than the three-dimensional (3D) perception that they get from their personal senses. Two-dimensional displays do not provide the necessary depth perception for superior performance of many tasks, especially those requiring tele-manipulation[1,2,3]. Anecdotal information from the field suggests that this has a negative impact on mission accomplishment and that a 3D visualization capability would greatly improve Soldier performance in tele-operating robots.

In 2006, Researchers from the Fort Leonard Wood Field Element of the US Army Research Laboratory - Human Research and Engineering Directorate began an effort to integrate 3D cameras and displays into tele-operated systems used by the US Army Combat Engineers and conduct tests and experiments to determine the utility of the 3D capability and determine requirements for a usable 3D vision system that could be fielded on these existing systems. Prototype systems were first integrated onto the Buffalo Mine Protected Clearance vehicle[4,5] and a tele-operated backhoe[6].

These initial integrations found some level of benefit to the 3D vision capability, but results and Soldier feedback were not significant enough to fully pursue replacement vision systems for these systems.

In 2007-2008, the Leonard Wood Institute, Army Research Laboratory (ARL), Polaris Sensor Technologies (PST), Inc., and Concurrent Technologies Corporation (*CTC*) conducted an experiment to determine the effectiveness of the Polaris 3D vision technology mounted on a TALON® Robot in executing typical combat tasks. The results clearly indicated the 3D visualization capability greatly enhanced the Soldier's ability to perform these tasks[7]. Time savings of 22-43% were found when performing tasks with 3D vision as opposed to standard 2D cameras and displays.

The 3D visualization used in the 2007-2008 experiment was not integrated into the TALON Robot platform or control unit. There were separate controls for operating the 3D and robotic system which led to some human factors issues that in some cases limited the effectiveness of the 3D system. For the 2009 experiment, much work went into integrating the 3D system into the TALON Robot. Foster-Miller (the developer of the TALON Robot) was a critical member of the team. Rockwell Collins assisted in design improvements that addressed glare and daylight readability. The result was a combined robot and 3D system that estimated at Technology Readiness Level 7.

Purpose

This report provides a brief discussion of the components used to create this stereo vision upgrade kit, and further discusses an experiment that evaluated the effectiveness of the PST 3D visualization system integrated into a TALON Robot (see Figure 1). The hypothesis for the field test was that using 3D visualization systems to perform certain tasks would demonstrate an improvement over performance using 2D visualization systems. Improvement was defined by faster task performance, higher performance quality, and increased accuracy. The field test also explored 3D visualization system use in an area of darkness in order to identify potential problems operators encounter in areas with limited or no lighting. Additionally, the field test observed operators performing manipulation tasks such as precisely controlling the robotic arm in picking up items (e.g., plastic bottles, trash bag) and in placing a chemical agent monitor within one (1) inch of an object suspected to be contaminated.

METHODOLOGY

Participants

This field test was conducted on 21-25 September 2009 on Fort Leonard Wood, Missouri. Ten U.S. Army Soldiers from the Maneuver Support Center and Fort Leonard Wood participated in this experiment. Participants consisted of noncommissioned officers ranked between Sergeant and Sergeant First Class, aged between 24 and 40 years old, and with time in service between 4 and 21 years. Participant experience with Robotics and Visualization Systems ranged from none to just over two years.

Equipment

The TALON Robot is an unmanned and lightweight tracked vehicle that is widely used by the U.S. Army for

Figure 1. TALON 4 robot (top) and Operator Control Unit (bottom) equipped with the Polaris 3D vision upgrade kit, including stereoscopic cameras mounted on the rear mast and on the gripper, and 3D display.

Figure 2. 2008 TALON 2 system used for evaluation; note the required shroud for daylight viewing, the additionally control unit along side of the OCU, and the additional multiplexing and communications hardware mounted in the base of the robot.

numerous missions in OIF and OEF including reconnaissance, sensing, and Explosive Ordnance Disposal. The TALON weighs around 125 pounds, maneuvers at about five miles per hour, and has a battery life of 2.8 hours or 4.5 hours depending on the type of rechargeable battery used. Its arms can lift up to 10 pounds at full extension, with a 20-pound maximum capacity when retracted. The gripper has a gripping strength of 20 inch-pounds and can open to a width of six (6) inches. The TALON provides situational awareness with its ability to hold up to four (4) color cameras, including thermal, night vision, and zoom options. The TALON communicates wirelessly via digital data and analog video signals to its Operator Control Unit (OCU) at distances of up to 800 meters line-of-sight. The OCU is equipped with a 2D LCD display which can display images from each camera or from four cameras at one time on a quad split screen.

The Polaris 3D Vision System is an upgrade kit to the TALON robot platform that enables the user to use 3D technology to gain situational awareness. The basis of this upgrade is the flat panel polarized 3D display that has been fully integrated into the TALON OCU (Figure 2). This is a major improvement over the 2008 version of the system, seen in Figure 2, that was intended to discern the utility of stereo vision on TALON robots. At that time the 3D display was not integrated into the OCU, the camera systems were not designed to allow full function of the robot, and the control of the stereo vision system was done with add-on hardware that sat beside the OCU, and required the use of standalone stereo video multiplexer and demultiplexer hardware. The new upgrade kit provides exceptional depth perception in a full resolution, full color display. The upgrade package is made up of three pieces: replacement cameras, replacement display, and a software update.

The cameras are field upgradable on a standard TALON mount, using the factory electrical connections. Stereo vision multiplexing is built into the cameras' electronics for use over the standard video link. The upgrade kit includes support for 3D vision on Mast and Gripper camera positions. Configuration of the cameras is controlled by the optional touch screen interface on the TALON OCU. By using the factory mounting positions and electrical connections, full functionality of the robot is maintained.

The display is a field upgradable drop-in replacement of the stock display in the OCU. The displays have high brightness backlight and enhanced anti-glare and anti-reflective coatings for daylight viewing. The upgrade kit was designed to incorporate demultiplexing built into the display electronics. The display uses the factory mounting and electrical connections. The display is capable of displaying either 2D or 3D video, and has a single-button 2D/3D toggle built-in to the bezel to allow the operator to choose to view 3D content in 2D in situations where 3D is not desirable. The system is capable of showing mixed 2D and 3D camera view in the "quad-view" mode which shows all four robot camera views simultaneously.

The viewer wears passive polarized glasses while operating in 3D vision mode. Polarized lenses are specially cut at prescribed angles for viewing stereo pairs projected through left and right polarizing filters. Figure 1 shows the TALON with the Polaris 3D Vision System. Figure 3**Error! Reference source not found.** shows a Soldier operating the TALON with the Polaris 3D display integrated into the OCU.

System Design

The 3D display design was based largely on a display electronics design paradigm that had been developed in late 2008, and demonstrated in early 2009. This involved the use of a three module electronics package where each module performed a function required in the display – input decode, 3D conversion, and LCD output. The core of the display electronics that converts the left/right video to the signals required for 3D viewing was functional and was leveraged from prior work. A new input module that decoded NTSC and demultiplexed the video was developed.

Figure 3. Soldier using the TALON operator control unit equipped with the Polaris 3D upgrade kit. The operator is wearing polarized glasses. Note that the display is daylight readable, and does not require the shroud used in 2008.

The main driver in meeting the display size requirements was selection of LCD panels which would fit in the volume required. The design is based on the use of a pair of COTS LCD panels. The panels are driven with electronics on a circuit card that connected to the panel via flexible cables which are meant to wrap around the backlight module, allowing for the LCD panel itself to consume the majority of the front of the display. Unfortunately, because this type of display requires a pair of LCD panels it is not possible to wrap both of these cards around the backlight. In previous models of displays, these cards have been wrapped part way around the backlight, allowing for more utilization of the front of the display by the LCD, but this was done at the expense of added display depth. In this upgrade kit the LCD tabs were left nearly flat so as to allow us to meet the 1.5" depth requirement. This did require that we stretch the dimension of the display 1/2" in height, a trade off which still allowed the display to fit in the available volume. The result was a display that met the depth requirement, and was still able to fit in the available volume. The trade off was that a 10.4" LCD panel was used in lieu of the standard 12" diagonal.

An orthostereoscopic design approach was used for the gripper camera design, per the design criteria contained in the Merritt/Woods Stereoscopic Display Application Issues short course material[8]. This method requires matching the relationship between the field of view of the display relative to the viewer to the field of view of the camera detector relative to the camera lens. In the case of the TALON robot operator, it was assumed that the operator would most likely be seated near the bottom of the suitcase OCU so that use of the knobs and switches is convenient. This forced a viewer offset from the display of approximately 18", which for a 10.4" diagonal display means that the horizontal field of view (HFOV) of the screen relative to the viewer is 2 * arctan(4/18), or approximately 25 degrees. To achieve a matched field of view for a 1/3" CCD camera also placed 18" back from the convergence point a focal length of approximately 10 mm is required.

Upon initial testing of the prototype upgrade gripper camera it was determined that this focal length lens did not provide enough situational awareness of the gripper. The stock 2D cameras shipped with the robot use very short focal length lenses to provide this situational awareness. A tradeoff was made based on the availability of COTS "bullet cameras" which were similar to the stock cameras which could be used to create a stereo camera that worked toward an orthostereo solution, but still provided context to the operator. The solution was a COTS security camera with a 6mm focal length lens. Though the scale of the objects in the scene is not 1:1 with what the operator would see if looking through a window to the gripper, it is close enough that the operators were comfortable with judging distance and placement of the gripper when using 3D. The gripper camera is shown in Figure 4.

Figure 4. The stereo gripper camera.

The mast camera (shown in Figure 5) is used primarily for driving, survey at longer standoff (utilizing the zoom feature), and for the ability to gain situational awareness by panning. All three of these objectives were deemed to benefit from 3D, so a stereo zoom camera was devised utilizing the same family of Sony block zoom cameras that is supplied with the stock robot. The challenge is that with the zoom feature it is impossible to choose a toe in configuration for the cameras that allows for proper convergence. Unlike the gripper camera, the mast camera is used to examine objects both near the robot, and at a long standoff. If the convergence angle were set to a fixed value then the viewer could potentially have difficulty fusing imagery near the camera, and perhaps worse, could have no common scenery in the left and right views at full zoom. The solution is the use of a variable convergence camera pair. The operator is able to use the full range of zoom of the cameras, and adjust the toe in angle using a control on the OCU. The benefit is a 3D camera that serves a wide range of applications for the operator.

In order to implement the variable convergence stereo camera it was necessary to tie one camera to a servo motor. The position of the servo motor is set by sending a serial command to the camera. Two hundred fifty six discrete positions are possible. This represents a variable toe in angle ranging from parallel to 10.5 degrees, or a convergence point that varies between infinity and 13 inches. Selection of the convergence position is done using a touchscreen panel mounted in the OCU (Figure 6), giving the viewer full control over the mast camera convergence depending on the type of operation being performed.

Test scenarios

This evaluation consisted of a series of seven scenarios, representative of common tasks using small tele-operated robots in the Army Engineer, Military Police and Chem-Bio domains. These scenarios were: Improvised Explosive Device (IED) removal from a fuel storage site; IED search in a roadside rubble pile; Conduct a route reconnaissance; Conduct a search in a cave for targets; Sensitive site exploitation (SSE) for chemical, biological, radiological, and nuclear (CBRN) hazards; Conduct point monitoring; Explosive charge emplacement on a guardrail.

Figure 5. The stereo mast camera mounted on pan / tilt stage with illuminator.

Test procedures

Participants received an overview of the field test, details of the procedure, and information about any risks involved with their participation. The participants read and signed an informed consent form indicating their voluntary participation in the field test.

Participants completed visual acuity, color vision, and stereo depth perception tests using a Titmus2A Vision Screener. All participants were determined to have normal vision and were allowed to proceed with the system evaluation. Participants also completed a short survey to collect demographics data.

Each participant received instruction and training on how to control both the TALON Robot and the 3D visualization system. Participants proceeded to the scenario execution phase of the field test after achieving a baseline proficiency of the TALON Robot and 3D visualization system, which consisted of moving the robot in all directions, controlling the robot's arm and gripper, and controlling the cameras.

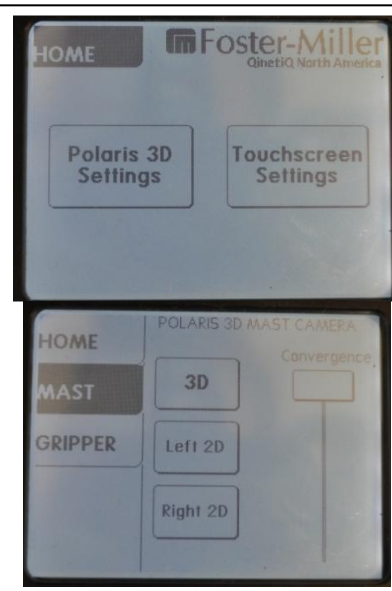

Figure 6. Touchscreen interface used to adjust 3D stereo convergence on the mast camera and other 3D settings.

Participants were briefed on the mission for each scenario prior to execution. Participants performed each scenario in each visualization mode, in a randomized treatment order. Using a performance evaluation checklist, observers rated task performance and collected completion time for each task step. Additionally, participants completed a task survey after performing the task in both modes to capture their perceptions on the value of 3D visualization systems compared to 2D in executing the tasks associated with the scenario. Participants were not allowed to observe other participants performing a task.

DATA

Observers evaluated task performance using a performance evaluation checklist in which they rated performance quality on a scale of five to one, where five represented "completed task with no difficulties" and one represented "unable to complete task step." Observers also recorded completion times for each task. On the Route Reconnaissance scenario, observers collected data on participants' accuracy in avoiding obstacles within each segment of the route. In the Point Monitoring scenario, observers measured the distance between the simulated chemical agent monitor and the target object in each visualization mode.

Task performance time

The mean times for completing each of the seven scenarios, and the percent change in performance, are presented in Table 1 below.

Table 1. Mean time to complete scenario by view mode (m:ss).

Scenario	2D	3D	% Change
Fuel Site	9:20	8:03	-13.8%
Rubble Pile	2:43	2:28	-9.2%
Route Recon	4:35	4:17	-6.5%
Cave Search	1:56	1:19	-31.9%
SSE	9:53	8:10	-17.4%
Point Monitor	2:11	2:18	5.3%
Guardrail	3:02	2:23	-21.4%

Task performance score

The mean score ratings for performance in each of the seven scenarios, and the percent change in this performance, are presented in Table 2 below.

Table 2. Mean task performance scores by view mode.

	2D	3D	% Change
Fuel Site	13.2	13.7	3.8%
Rubble Pile	9	8	-11.1%
Route Recon	3	4	33.3%
Cave Search	3	4	33.3%
SSE	3.5	3.6	2.9%
Point Monitor	3.6	4.3	19.4%
Guardrail	4	4.3	7.5%

Obstacle avoidance

As seen in Figure 7, the mean number of unintentional collisions was 5.1 in 2D and 4.3 in 3D. This is a reduction of 15.7%. Six participants experienced more collisions in 2D, while only 2 experienced more in 3D.

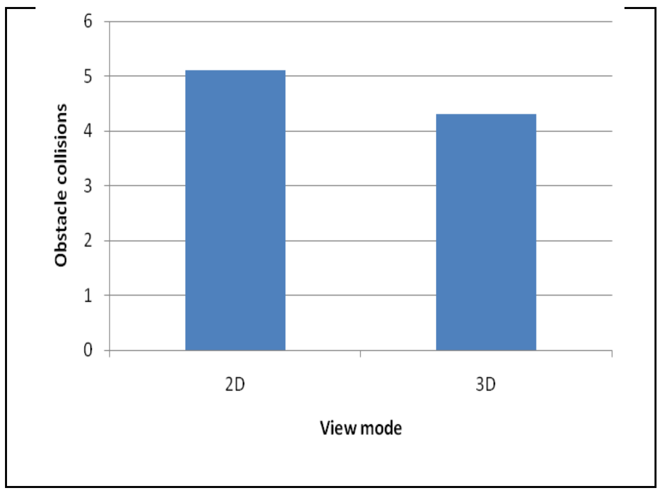

Figure 7. Mean number of collisions during the route reconnaissance scenario by view mode.

Point monitor positioning accuracy

Each trial in the point monitoring scenario yielded one of three outcomes. The trial was a "success" if the operator was able to position the monitoring sensor within a known range from the target without contacting the target. The trial was a "miss" if the operator positioned the monitoring sensor outside the known range from the target, but still without contacting the target. The trial was a "collide" if in the act of positioning the sensor, the operator touched the sensor to the target. Figure 8 presents the distribution of these outcomes by view mode.

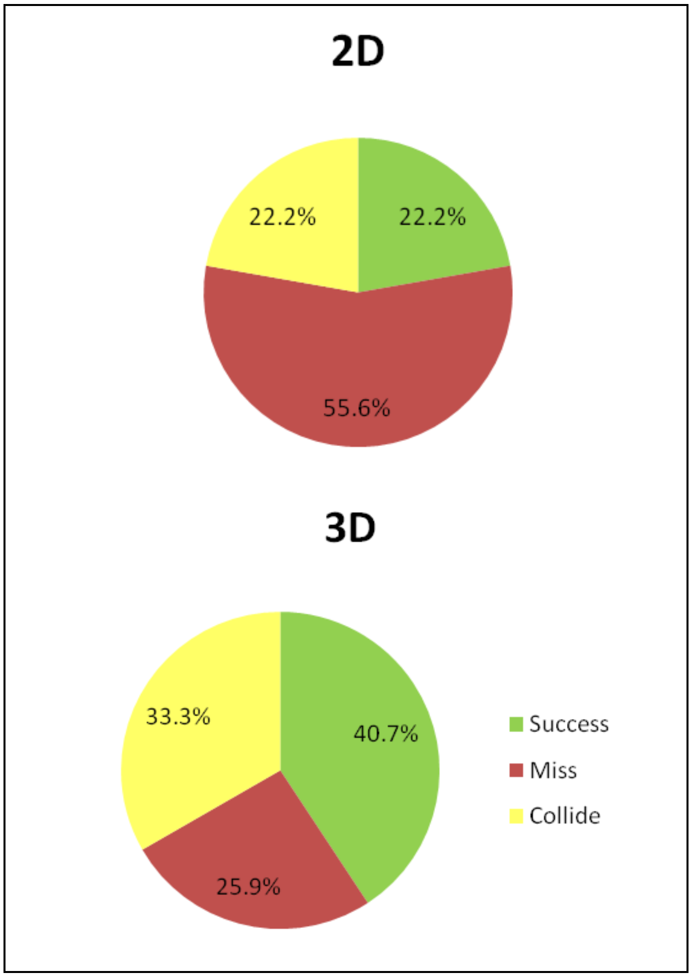

Figure 1. Distribution of point monitoring scenario outcomes.

Operator feedback and task survey

After performing each scenario in both visualization modes, participants completed a task survey to capture their opinions on how the 3D visualization system affected their performance. A total of 70 surveys were collected with the results outlined in Table 6. The highlighted rows indicate the responses selected by majority of the participants.

Results indicate that in 73% of cases participants felt that the 3D visualization system improved their ability to manipulate the TALON Robot, in 83% they felt that 3D improved their depth perception, in 79% they felt that 3D improved their overall mission performance, and in 94% they did not experience any discomfort during operations in 3D visualization mode. Overall, in 96% of the cases participants stated that they would recommend 3D visualization systems for robotics operations. The full breakdown of participant responses is presented in Table 3.

Table 3. Task survey and Soldier feedback responses.

Survey Question	Responses	Percentage
1. Compared to 2D, how did the use of a 3D visualization system affect your manipulation of the robot?		
Greatly improved my performance	51	73%
Somewhat improved my performance	16	23%
No difference in my performance between 2D and 3D	1	1%
Somewhat hampered my performance	2	3%
Greatly hampered my performance	0	0%
2. Compared to 2D, how did the use of a 3D visualization system affect your depth perception?		
Greatly improved my performance	58	83%

Survey Question	Responses	Percentage
Somewhat improved my performance	9	13%
No difference in my performance between 2D and 3D	1	1%
Somewhat hampered my performance	2	3%
Greatly hampered my performance	0	0%
3. Compared to 2D, how did the use of a 3D visualization system affect your OVERALL situational awareness?		
Greatly improved my situational awareness	54	77%
Somewhat improved my situational awareness	13	19%
No difference in my situational awareness between 2D and 3D	2	3%
Somewhat hampered my situational awareness	1	1%
Greatly hampered my situational awareness	0	0%
4. Compared to 2D, how did the use of a 3D visualization system affect your OVERALL performance of the mission?		
Greatly improved my performance	55	79%
Somewhat improved my performance	11	16%
No difference in my performance between 2D and 3D	2	3%
Somewhat hampered my performance	2	3%
Greatly hampered my performance	0	0%
5. Did the operation of the 3D visualization system cause you any physical discomfort?		
No discomfort experienced	66	94%
Some discomfort experienced	4	6%
Felt very sick during 3D operation	0	0%
6. Do you object to wearing the glasses while operating the OCU?		
Yes	3	4%
No	67	96%
7. Would you recommend the use of a 3D visualization system in robotics operations?		
Strongly recommend	67	96%
Recommend	3	4%
Somewhat recommend	0	0%
Do not recommend	0	0%

RESULTS

It was found that the use of the 3D vision system produced reduced time benefits and improved task scores in six of seven scenarios. This finding and the magnitude of the improvements are similar to the results from the 2008 prototype testing. Due to the limited number of participants, only descriptive statistics were used in the analysis of the 2009 data; the 2008 prototype data did in fact show statistically significant results for the majority of the similar tasks[7].

The most surprising finding, which was also seen in the 2008 prototype testing, was that operators failed the "point monitoring" task by collision error more in 3D than in 2D view mode. This is perceived to be due to a slight over confidence in the 3D view and the perceived goal to get the sensor as close to the target as possible.

Verbal feedback from the Soldiers indicated that the 3D view at the manipulator was more valuable to them than the 3D view at the driving camera. However, it should be noted that robot navigation performance for the missions selected for this test was limited to obstacle avoidance on level routes, not navigating in an off-road area.

CONCLUSIONS

The results of this experiment indicate that the 3D vision upgrade kit benefits robotics system operators and improves performance of certain tasks. Increased depth perception in 3D resulted in improved situational awareness which in turn increased performance quality (participants performed tasks faster with fewer errors) compared to 2D. However, this improvement was not universal among all participants and tasks. Thus, it is important to maintain the ability to switch between 2D and 3D modes.

At the conclusion of this test, the Technology Readiness Level was determined to be a TRL 8. Due to interest generated within the US Army Maneuver Support Center of Excellence and the Robotic Systems Joint Program Office after this testing, this 3D Vision Upgrade Kit for the TALON robot subsequently underwent independent Military Utility Assessment by the Maneuver Support Center of Excellence Battle Lab with the potential result of near-term transition and fielding to combat units.

ACKNOWLEDGEMENTS

Funding for this project was provided by the Leonard Wood Institute (LWI) located at the University of Missouri Technology Park at Fort Leonard Wood. LWI is a not-for-profit, tax-exempt organization incorporated in the State of Missouri in 2004. LWI was formed to support the development, transfer and utilization of new technologies developed or provided in Missouri that have applicability to the U.S. Army's mission at Fort Leonard Wood and to the technology needs of the Department of Defense on a world-wide basis.

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