Fused quad audio/visual and tracking data collection to enhance mobile robot and operator performance analyses

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ABSTRACT

Collecting accurate, adequate ground truth and experimental data to support technology evaluations is critical in formulating exact and methodical analyses of the system's performance. Personnel at the National Institute of Standards and Technology (NIST), tasked with developing performance measures and standards for both Urban Search and Rescue (US&R) and bomb disposal robots, have been designing advanced ground truth data collection methods to support these efforts. These new techniques fuse multiple real-time streams of video and robot tracking data to facilitate more complete human robot interaction (HRI) analyses following a robot's experiences. As a robot maneuvers through a test method, video and audio streams are simultaneously collected and fed into a quad compressor providing real-time display. This fused quad audio/visual data provides a complete picture of what the operators and robots are doing throughout their evaluation to not only enhance HRI analyses, but also provide valuable data that can be used to aid operator training, encourage implementation improvements by highlighting successes and failures to the developers/vendors, and demonstrate capabilities to end-users and buyers. Quad data collection system deployments to support US&R test methods/scenarios at the 2007 Robot Response Evaluation in Disaster City, Texas will be highlighted.

Keywords: Robotics, Mobile Robot, Urban Search and Rescue, Bomb Disposal, Performance Metrics, Data Collection, Fused Quad Video Data

1. INTRODUCTION

The domains of Urban Search and Rescue (US&R) and bomb disposal are extremely dangerous fields that force first responders to confront a wide-range of challenges in a variety of environments. The Federal Emergency Management Agency (FEMA) considers US&R a "multi-hazard" discipline, as it may be needed for a variety of emergencies or disasters, including earthquakes, hurricanes, typhoons, storms and tornadoes, floods, dam failures, technological accidents, terrorist activities, and hazardous materials releases" [1]. Likewise, bomb disposal is defined as "the process by which hazardous explosive devices are rendered safe" [2]. Robot systems are being developed to allow responders to work more safely and efficiently within these domains. Blitch states that "small robotic platforms are valuable to the US&R community mainly because they can provide access to areas otherwise denied to human and canine search assets due to confined space, structural instability or the presence of hazardous materials…" [3].

As US&R and bomb disposal domain-specific robotic technologies are designed and brought to market, performance testing and validation is critical to ensure that potential buyers and end-users are aware of the systems' specific capabilities within a range of tasks. Personnel from the National Institute of Standards and Technology (NIST) have been tasked by the Department of Homeland Security in 2004 with devising performance measures and comprehensive standards to support the development, testing, and certification of robotic systems for US&R [4] [5]. Likewise, the National Institute of Justice (NIJ) is also funding NIST to perform similar standards development for bomb disposal robots which includes expanding upon comprehensive initial work already performed by the Technical Support Working group and others [6].

These standards will also allow direct comparisons of robotic systems, better enabling responders to select their platform(s) based upon their specific needs. Such testing and validation also enables the product researchers and vendors to see how their implementations compare against one another in completing these various tasks.

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Test methods, must be designed that highlight and exploit precise robot capabilities in order to develop specific performance standards. A robot’s performance in executing a test method is quantified by a set of metrics. Additionally, human-robot interaction (HRI) analyses are formed. For example, the purpose of the maze test method is to “measure the [robot] operator’s ability to remotely traverse/negotiate a random maze of hallways and rooms while operating the robot through the operator interface and communications link” [7]. Operators can be assigned various challenges within this test method including negotiate the maze from end to end, find a path from end to end while performing target identifications along the way, completely traverse the maze (full search), etc. Performance data that can be collected for this test include time to completion, dwell time in specific areas, percent coverage, relative location accuracy, etc. Data must be collected during the evaluation to support these measures and metrics in addition to ground-truth against with which to measure the data. One significant portion of data that is collected (in this test method along with others) is audio/visual data along with robot tracking data. Unfortunately, current methodologies in collecting this type of data to support HRI analyses are limited.

This paper, focusing on performance standards development of US&R robots, will build upon the current data collection methodologies by demonstrating how an innovative UltraWideBand (UWB) asset location technology can be applied for robot tracking. Further mating this UWB robot tracking methodology with a fused quad audio/visual (A/V) data collection system presents an extensive picture of a robot’s and operator’s performance while working within a test method. These A/V capture methods were successfully deployed at the 2007 Robot Response Evaluation Exercise at Disaster City US&R training facility located in Texas, USA. In total, three fused quad audio/visual data collection systems were implemented across numerous test methods with one system being paired with the UWB robot tracking technology.

2. CURRENT DATA COLLECTON METHODS

2.1 Audio/visual collection

In order to study and analyze HRI-related issues dealing with mobile robot performance, it is necessary for researchers to correlate actions performed by a robot’s operator with the resulting robot actions. Data needs to be collected during these operator/robotic events to make this possible. This typically includes making observational notes about, and/or videotaping, the robot, the robot’s interface, and the operator during the event. Yanco et al. found that during their coding analysis of operators and robots that videos captured during the event were the most fruitful sources of information [8].

Some other past robot performance analyses that have been conducted required reviewing and/or coding many hours of collected video of a robot operator and multiple views of the robot being studied [9]. The process of analyzing such video data can be a very time-consuming, meticulous, and tedious task to perform. Such data requires a means to accurately time-align the corresponding independent videos from the operator, the operator interface, and the different views of the robot. Previously, this was accomplished by using the date and time values recorded as part of the video data to align the various video streams. This requires careful synchronization of the dates and times on all video sources being used. If a video source’s time value is not accurate then it may be difficult, or impossible, to match it to the other video sources when reviewing significant events.

Current means of collecting video data involve observer/controller personnel co-located with the robot in the test environment. Such video requires a large field-of-view camera to see the entire test region, or multiple cameras focused on known reference frames. Existing mobile robot performance data collections do not easily provide a comprehensive visual perspective of a robot’s movements/actions within a test environment or an extensive picture of the operator’s interactions with the system’s user-interface.

2.2 Robot tracking

In order for researchers to correlate an operator’s actions with the robot’s actions, it is necessary to document exactly where the robot is within the test method during the data collection. In addition, it is important to capture ground truth of a robot’s position within a test to compare that against any automatically-generated and/or sensor-based mapping capabilities. In the past, this position data was often collected by having a dedicated observer follow the robot and markup, by hand, a drawing of the test method’s layout with the robot’s position and incremental time updates. The observer must be cognizant of staying out of the robot’s camera views so that they do not accidentally give clues to the operator as to the layout/makeup of the test method. It can also be especially difficult in some of the test method environments where the presence of random step fields, roll/pitch ramps and other objects make it very challenging for an observer to gain a sufficient view of the robot. This method is also prone to human markup error and does not give the precise timing of robot position observations that is often necessary for correlating operator actions. Additionally, this data collection method is often inadequate in very large and/or non-uniform test environments where a robot may venture into visually-obstructed areas.

3. PROPOSED FUSED QUAD DATA COLLECTION METHOD

A quad data collection method integrating real-time, automated robot tracking data and audio/video data has been developed to enhance the relevant data collection processes when a robot attempts a test method. Up to four pieces of robot tracking and video data are fused together with an audio source and output as one signal. Both the automated robot tracking and the audio/video quad data collection method will be discussed in the following subsections.

3.1 Robot tracking data collection

NIST personnel have experimented with capturing constant robot position data to enhance quantitative performance evaluations during test methods using an UWB tracking system, developed by MultiSpectral Solutions, Inc[†]. The tracking system functions by triangulating the position of an active tag from time-of-flight measurements made by numerous receivers placed within the environment yielding accuracies up to 10cm (with software averaging). The system is capable of locating these tags in both Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) environments at varying ranges (over 200 meters LOS and over 50 meters NLOS, but heavily dependent upon number and type of obstructions). The receivers detect the tags' communication 'chirps' (frequency is dependent upon a tag's specific update rate which could be 1 Hz, 60 Hz or at another interval) and use time-of-flight measurements to calculate the tags' position. For use in US&R robot performance testing, six receivers are placed at carefully measured positions around the perimeter of the test method site to enable the system's algorithms to locate active UWB tags that are attached to the robot(s). The tracking system is used to capture two-dimensional (2D) or three-dimensional (3D) position data over time. This data facilitates the collection of performance metrics including deviations from desired routes, dwell sites and durations, percent of area covered, thoroughness of team searches, etc.

UWB tracking has been tested for several years within fabricated robot test arenas to capture 2D paths of individual robots, teams of collaborative robots, and dogs. Efforts to track assets within realistic training scenarios have produced mixed results. At a previous event, several first responders were tracked moving through an intact building structure pre-equipped with receivers to produce data and tracking display videos of each responder's 2D path overlaid onto the building floor plan. Assets were also tracked in line-of-sight of the receivers across a large concrete rubble pile. However, attempting to track assets located in tunnels under the concrete rubble pile, or within surface voids on the pile, was unsuccessful due to the overall density of concrete rubble along with the limited power levels of the active radio tags at that time. At Disaster City in 2006, the tracking system was deployed around the wood pile, which provided a more porous prop than the concrete rubble, and higher power radio tags (1000 mW) were used. During the wood pile deployment, robots could be tracked as they performed initial reconnaissance on the street around the pile, yet tracking data could not be produced as they entered the wood pile through buried concrete culverts because the tags lost communication with the receivers. Once inside the pile, tracking remained unsuccessful due to the robots' low ground position while surrounded by the densely-packed wood pile perimeter [10].

The tracking software provides a visual display of the robot's activity and accomplishments. The display has four major components: administrative data, goal achievement, robot motion, and tracking system status.

The administrative data identifies the event, the operator, the environment or track, and the run. This data is constant throughout the run and is available for reference. The tracking software displays the data across the upper edges of the display as shown in Fig. 1. The administrative data helps correlate the robot's performance with information separately collected by the robot operator.

Goals are a major component of robot evaluation and are displayed on a pictorial of the test area. Robot evaluations include specific goals for the robot such as object detection and transit time. The tracking system displays the robot's transit time in the large sub-window in the display's lower left corner (Fig. 1). The tracking system manager inputs numbers and letters over the test method layout prior to the evaluation to signify "interesting" objects in the test area.

[†] www.multispectral.com

Letters indicate objects and numbers show the location of observation points (e.g., placards, signs, etc.). The robot operators must weigh the value of a quicker transit with the detection of objects.

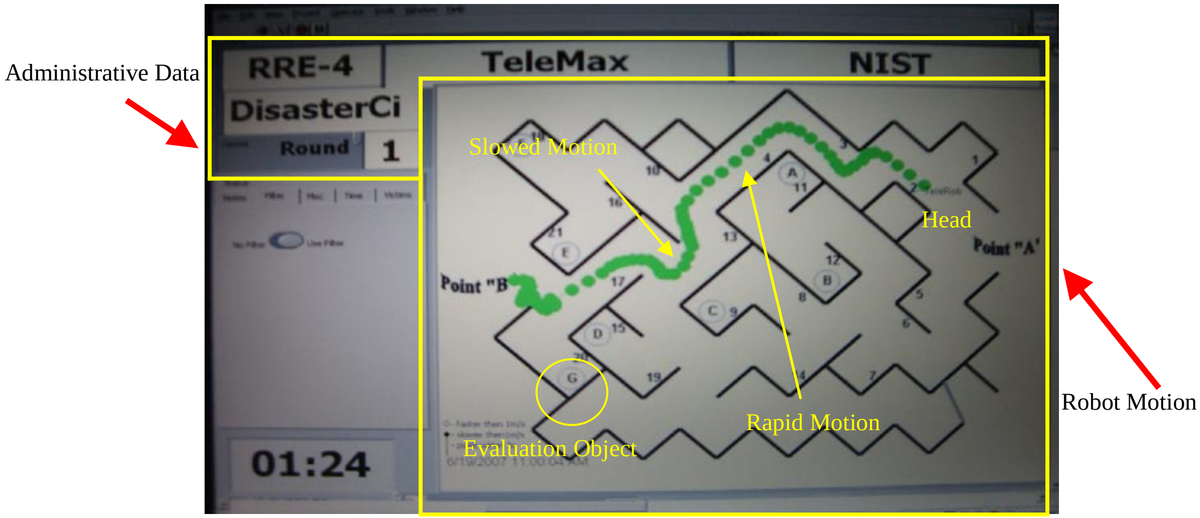

Fig. 1 UWB Track of a Robot Negotiating the Maze Test Method

The tracking software displays the robot's motion via a snake on a pictorial representation of the test area (e.g., the sequence of green dots in Fig. 1). The trajectory display shows the recorded positions of the robot's UWB tags, the combined positions when the robot carries multiple tags, or a filtered representation of those positions. The tracking software may apply a selective filter or a Digital Smoothing Polynomial filter [11]. The selective filter removes data that indicates a substantial and momentary jump (e.g., a sudden 3 m/s motion or a side-step and return). The smoothing polynomial filter (Savitzky-Golay or least squares) is a low-pass filter that is applied to the time domain data and removes small spurious motions. The operator selects the order and the window of the filter as appropriate for the type of UWB tag being used.

The tracking software displays the status (not shown in Fig. 1) of the tracking system to enhance understanding of some anomalies. The tracking system measures the robot location via the arrival time of pulses generated by tags carried by each robot. The system also provides status and quality information with the tag positions. Researchers may disregard robot performance anomalies when the anomaly correlates to a period of reduced collection system performance. The tracking system displays the system status on the lower extremity of the display.

The snake's head, labeled with the robot's name, is at the robot's latest position. The snake's body is a sequence of points that show the robot's position at periodic intervals. From the relative gaps between points, observers can infer speed. Thus, the tracking software helps the developer identify areas the robot maneuvered with relative ease and those situations where geography or perception slowed the robot's advance and where future efforts may be applied for greatest benefit.

3.2 Audio/video quad data collection

A quad video and single audio collection system is designed to present a clear representation of both the operator's and robot's actions and interactions during the test methods by fusing multiple camera streams, the UWB robot tracking feed and operator audio. This A/V data collection system is composed of the control and display hub and supported by *in situ* cameras and an operator station-based microphone (Fig. 2). A laptop computer-output splash screen showing the pertinent run information precedes each separate A/V collection and displays the robot, operator, test method, etc. While a robot operates within a test method, video is captured of the robot from multiple perspectives (includes a combination of ground-based and/or ceiling-mounted cameras), the operator's hand interactions with the robot's control system, the robot's visual user interface, and the PC display output of the robot tracking system (if available at the test method). A microphone mounted next to the operator captures everything the operator says as well as what the operator hears from the robot's user interface (e.g. audio from a simulated victim placed within the test method, structural noises, noise feedback from the robot's motors).

Video and audio feeds are sent into the quad data collection system (without pre-processing). While the audio is directly output to the digital recording device, the video signals go through preview monitors and switchers where four video outputs are selected and fed into the quad compressor and split out to large display monitor and a digital recording device. Typically, the quad system manager has more than four available video sources per test method, and has the ability to pick the two most opportune robot video sources (displayed in the upper-right and upper-left quadrants) while the other two video sources always show the end-user interacting with the operator control unit (OCU) (lower-left quadrant) and robot interface (lower-right quadrant). The only exception is that the robot tracking system output is displayed in the upper-right quadrant (replacing a robot perspective) during a test method that integrates the UWB robot tracking system. Although the system's built-in monitor is small in size, the quad video can be projected on a large screen. Also, all recorded quad footage can be replayed on a large screen/monitor to ease any task that requires a detailed view at specific robot capabilities, tracking details, operator actions, interface windows, etc.

This system was extremely effective in capturing and displaying A/V data in the test methods in which it was integrated. Since the four output video sources to the quad were recorded together on a single device, there was no need to synchronize the clocks of the various video devices. Following the event, DVD videos were created to not only organize the raw footage, but also to create highlights. This data greatly facilitates a more complete understanding of both the robot's and operator's capabilities within a specific test method which laid the groundwork for more efficient and in-depth HRI analyses and autonomous/sensor-driven mapping comparisons. Other potential benefits are that this system would enable vendors to realize how and why their robots were successful (or unsuccessful) within a test method, operators to recognize their strengths and weaknesses, robot operator trainers to see which skills require additional/augmented training, and the evaluation team to iterate and improve upon the composition of the test methods.

Fig. 2 Quad Data Collection System

4. DISASTER CITY QUAD DATA COLLECTION DEPLOYMENT

For the 2007 Robot Response Evaluation in Disaster City, three quad data collection systems were deployed across four unique test methods including the random maze, grasping dexterity, directed perception, and endurance test methods [10]. Only a single UWB tracking system was available for use and it was paired with the maze test method.

4.1 Maze quad deployment with UWB tracking

A quad system with the UWB tracking system was deployed around the maze test method. The goal of the maze test method is to "Measure the operator's ability to remotely traverse/negotiate a random maze of hallways and rooms while operating the robot through the operator interface and communications link." [7] [12]

The operator station was positioned in the same room as the maze, but several meters from one of its external walls. It was not necessary to have the operator completely face away from the test method since the 1.2m high walls prevented the operator from seeing the robot's actual position.

Six overhead cameras were mounted to the ceiling directly above the maze walls and were pointed straight down. All six of these cameras were fed into a multiple input/output video switcher enabling the quad manager to select which camera view would be in the upper-left screen of the quad. The upper-right corner of the quad was populated by the computer output from the UWB tracking system. The bottom-left and bottom-right corners were occupied by the videos of the operator's interaction with the Operator Control Unit (OCU) (captured by a tripod-mounted camera located next to the operator station) and the robot's interface (collected directly by connecting a video cable into the OCU) (Fig. 2).

To install the UWB tracking system, six receivers were setup around the perimeter of the 12m x 9m wooden-walled maze at various heights (Fig. 3) with the reference tag placed on top of a centrally-located maze wall. After receiver and reference tag location measurements were completed, the coordinate data was entered into the hub and final calibration steps were undertaken to ensure adequate data was being captured.

Fig. 3 UWB Tracking System Receiver Positions (circled in red) around the Maze Test Method

Each robot that performed in the maze was outfitted with one to three (depending upon available space) tracking tags (Fig. 4). Low power (30 mW with an update rate of 60 Hz) tags were used as opposed to high power (1000 mW with an update rate of 1Hz) tags because most of the robots could easily 'outrun' the slower update rate of the higher-powered tags which would produce irregular tracks. Using both types of tags during calibration produced a negligible difference in static accuracy. Tracks were obtained from multiple robots while they performed variations of the maze test throughout the week. Referring back to Fig. 1, a track is shown of a robot whose task was to navigate from Point "B" to Point "A." Other maze tasks that were tracked included moving from Point "A" to Point "B" (typically, an entry and exit location) and performing a complete search of the maze.

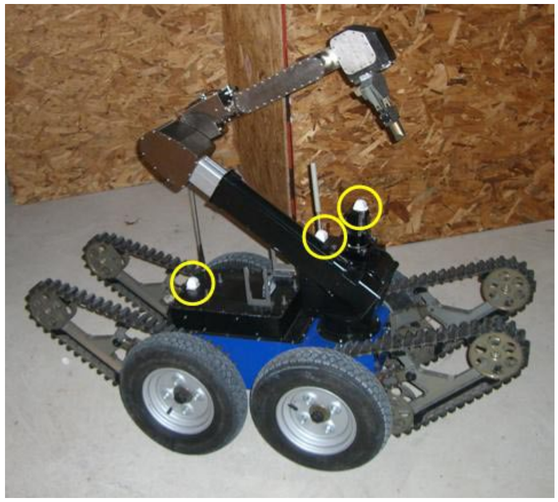

Fig. 4 Robot with Tracking Tags (circled in yellow)

The data captured in this test method from the fused quad A/V collection system has proved to be very valuable. First, spectators, including robot vendors/developers and potential end-users were able to see the quad display of the robot's and operator's performance live on a large screen. This enabled the vendors/developers to directly see their platform's successes and failures along with observing how the end-users/responders interact with their system. Watching multiple operators attempt the maze with their platform reinforced those positive and negative robot/operator interactions when certain behaviors occurred consistently. Additionally, potential end-users were able to see how the robots performed in this type of environment and the strain it put on the operator. Also, the responders were shown a replay, time permitting, of their run to see a third-person view of where the robot was in the maze (from the overhead camera and the tracking data screens) while correlating that to what they were seeing on the robot's user-interface screen and their interactions with the control system. This provided them instantaneous feedback that either verified or contradicted how they believed they performed within the test method.

4.2 Directed perception and grasping dexterity quad deployment

Another quad system was deployed in the center bay of a concrete building. This quad system was used to capture participants of the manipulator-related test methods which included the directed perception and grasping dexterity test methods. The goal of the directed perception test is to "measure the operator's ability to remotely position sensors near holes in box stacks to identify assigned targets placed inside…" while the goal of the grasping dexterity test is to "measure the operator's ability to remotely grasp and place blocks onto shelf stacks…" [7].

The area housing these two test methods was a long rectangular room which permitted one test method to be situated on each end of the room with a common area in the middle which acted as the robot's start position for either test method. These two test methods did not run simultaneously.

The operator's station for both test methods was positioned in the far corner of the room beyond the directed perception test method. While participating, the operator sat with their back to the test methods so that they were not able to directly see their robot during the test.

Cameras were set up in and around the test method to enable comprehensive video capture of the robot's actions within these test domains. These views included two from overhead ceiling cameras, and two close-up views from cameras on adjustable tripods nearby the robot's starting position. These two cameras were easily rotated around when the robot finished one of the test methods and moved on to the other test method. Similar to the maze quad A/V collection, a camera was setup to capture the operator's physical interactions with the robot's interface and video was collected from the robot's interface. A microphone was also positioned at the operator's station to capture any audio including operator feedback and audio from the robot's interface.

The views that made up the video for this quad capture system included the lower two screens showing the operator's control (lower-left quadrant) and robot interface (lower-right quadrant) for consistency with other recorded quad captures. The views for the two upper quadrants were selected by the quad manager, during the data capture, based on the best available overhead or ground-level views that were available at the time. Fig. 5a shows a robot confronting the directed perception test method. Fig. 5b shows a screen capture of the quad display from that same robot peering inside a box within this test method.

Fig. 5 a) Robot participating in the directed perception test method and b) resultant quad screen video

4.3 Mobility/endurance quad deployment

The third quad system was setup to collect data to support the endurance test method. The goal of this test is to "Measure the operator's ability to remotely traverse/negotiate various terrain types within a fixed course to show mobility or endurance…" [7]. Fig. 6 shows two figure-8 endurance courses, each composed of different terrains with the operator station situated on the table at the far left of the image. Although this test method contained two separate tracks, only one was used at a time.

Fig. 6 Mobility/endurance test method layout

Cameras were mounted to the wooden walls throughout this test method to provide extensive coverage of a robot's operations. A tripod-mounted camera was mounted next to the operator station to collect the operator's interactions with the OCU (as was done in the other two quad deployments). Due to equipment limitations, video was unable to be directly captured of the robot's interface screen, so an additional in-situ camera view took its quad position. Fig. 7 presents an image of the quad screen showing a robot in middle of a test. It should be noted that the view of the robot controls was moved to the upper-left corner (as opposed to remaining in the lower-left corner) because of some on-site technical challenges (which have since been addressed).

Fig. 7 Quad output display from the mobility endurance test method

5. RESULTS

The deployment of the three fused quad A/V data collection systems within a range of test methods (with UWB robot tracking in the maze) proved highly successful. The collection system had an immediate impact by enabling first responders, vendors, technology developers, evaluation team members, very important persons (VIPs) and other spectators to focus on one screen's worth of data to obtain an extensive view of what a robot and operator were doing at any given moment within a test method. Numerous people were able to view the maze quad on-site because it was projected onto a larger screen. However, a limited number of individuals were able to view live the quads present at the directed perception/grasping dexterity and mobility/endurance test methods since they were broadcast on smaller monitors. Additionally, operators were able to view their runs to see how they actually performed, where and how they were successful, where and how they had difficulties, etc. The footage from these on-site deployments can also be used for operator training to both introduce soon-to-be operators to common techniques and robot capabilities in addition to refining an operator's technique by having him/her analyze their respective quad footage at points of success and failure. Likewise, potential end-users can benefit from viewing quad footage by observing a robot's capabilities and operator strain, if present and observable. This would be an invaluable tool in further educating users about their robot's capabilities.

Each robot vendor and technology developer that participated in the 2007 Response Robot Evaluation Exercise received digital video discs of their robots' operations within the test methods they attempted. It is expected that quad video provided to these individuals will raise their understanding of their robots' shortcomings along with enhancing their awareness of the test methods and various US&R environments. As a result, design and implementation of robot upgrades should be greatly accelerated.

The quad footage is becoming an efficient tool for assisting in HRI analyses. Four video streams no longer have to be painstakingly synchronized together since now they are output as a single stream. An analyst has a majority of the data necessary to scrutinize a robot within a test method in the quad video (other measures necessary are typically test method specific including noted times, distances, speeds, weights, etc.).

Although the fused quad A/V data collection system proved to be an efficient solution for instantly time-aligning multiple video streams to support the analysis of robot performance, this system would not be sufficient to support data collections requiring greater video resolution and time-stamping capabilities. The current system outputs all four video streams at a combined 1024 pixel x 512 pixel resolution and time-stamps every second. This quad A/V system would not be adequate for those data collections requiring finer resolution and time-stamping. These issues are currently being explored to enable the quad system to be used in data collections with these constraints.

6. CONCLUSION

The fused quad A/V collection system with UWB robot tracking was successfully deployed at the 2007 Robot Response Evaluation Exercise in Disaster City, Texas and has proven to be an invaluable tool for enhancing HRI analyses, aiding operator training, encouraging platform enhancements and demonstrating capabilities to a vast audience. Since this event, quad systems have been deployed at the 2007 RoboCup Rescue – Robot League Competition in Atlanta, Georgia and have supported numerous NIST-based testing efforts [13]. It is envisioned that multiple quad systems will be redeployed at the 2008 Response Robot Evaluation Exercise in Disaster City, Texas in addition to supporting many other efforts that would benefit from this system.

DISCLAIMER

Certain commercial products are identified in this paper in order to explain our research. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose.

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