Experiences Building the Integrated RSTA System

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Abstract

Building the Reconnaissance, Surveillance and Target Acquisition (RSTA) system and integrating RSTA co-contractor technology was an enormous undertaking. This paper describes experiences that the UGV / Demo II program's system integrator had creating and fielding the integrated RSTA system over three years.

1. Introduction

The key tasks and responsibilities associated with the collaborative RSTA effort that started in the fall of 1993 are outlined in Table 1. Achieving the four annual UGV demonstrations involved the following general tasks for the integrating contractor and its internal RSTA team:

- **SSV System Hardware.** The system integrator designed and constructed the SSV system hardware, including the RSTA hardware and its integration onto the SSVs. This involved all the RSTA sensors, a dedicated custom pan/tilt unit, and the processing hardware.
- **RSTA System Design, Implementation and Integration.** The system integrator designed and constructed a high level modular software architecture for the RSTA system, including a graphical user interface to RSTA system functions. Processes were defined and partitioned among the available processors, and associated communications and control protocols were specified. Individual modules ranging from low-level sensor controls to map-guided sensor search were designed, coded and tested.
- **Core RSTA Capabilities.** The system integrator provided an initial set of core RSTA capabilities to detect targets and locate them in map coordinates. Core capabilities are inter-faced with all SSV subsystems, and thus are available for use during autonomous missions. Advanced RSTA capabilities provided by RSTA co-contractors were also integrated to provide additional core RSTA capabilities.
- **Field Work.** The complete UGV RSTA system was field tested extensively. The testing served to uncover software systems problems (e.g., incorrect interfaces and control) as well as system performance issues (e.g., pan/tilt operations, target detection performance). Extensive periods of operational "runs" of the planned demonstration or field exercise were repeated in order to debug and harden the system. These runs culminated in the annual UGV demonstrations.

The UGV / Demo II and RSTA efforts were iterative design and build cycles with incremental improvement over the period of four annual demonstrations. Thus, many details of the RSTA system design were modified or added each year. The nature of this research program has been that new issues, ideas for improvement, new requirements, etc. occurred regularly throughout the program.

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Table 1. Principal tasks and responsibilities in the collaborative RSTA program.

System Integrator	RSTA Co-Contractors
• SSV system design / integration • RSTA system design • RSTA system implementation • RSTA systems integration • Field checkout and test • User demonstrations and field experiments • System evaluations	• UGV workshop participation • Advanced RSTA algorithm design, code and test • Laboratory demonstrations in concert with UGV demos • Algorithm evaluations
Collaboration Between RSTA Co-Contractors and System Integrator • Coordination at UGV workshops • Data collection and distribution • Design coordination between RSTA system and co-contractor technologies • Integration of RSTA co-contractor technologies onto vehicle • Field checkout and test • User demonstrations and field experiments	

This paper is organized as follows. Each of the above general tasks is addressed in a separate section. The evolution of individual elements of the system design over the yearly demo cycles is described within each section.

2. SSV System Hardware

The evolution of hardware elements that had great significance on the RSTA system is summarized in Table 2.

SSVs Available. A fundamental issue affecting work every year was that a new vehicle was produced each year of the program. The Demo A and Demo B years were particularly difficult because the one vehicle that would be used in each year's demo was being constructed in the preceding months, and was not available until literally weeks before the demos. Pressures in the Demo C year were considerably less, since one vehicle was available from the year before. However, field testing the new cooperative target verification technique was a struggle, since it required waiting for construction of the second vehicle, and more resources were required to simultaneously field two vehicles. The issue of SSV builds, SSV access and related program priorities is discussed more completely in Section 5 "Field Work". The primary effect was that less vehicle time than desired was available for RSTA field work, and availability occurred just before the demos. This necessitated working in shifts to get time on the vehicles.

Color Camera. The color camera and lens performed well through all the years. RF shielding of the camera and auto-iris lens was required to prevent interference from the packet radios. A new mounting fixture built for Demo II was more rugged, provided a dust-proof enclosure and a more solid mount to the pan/tilt platform, which in turn permitted more precise sensor boresighting alignment.

FLIR Sensor. Both the FLIR and LADAR sensors were specified as government furnished equipment (GFE) at the beginning of the program. While no existing GFE FLIR sensors (either second generation scanning sensors or low cost uncooled sensors) were available from various government agencies, a viable commercially available FLIR was identified and four units were purchased to support the program. One of these units had a telephoto dual field-of-view lens for RSTA operations. This unit and its lens were installed on SSV-B for Demo B. The other three units had cheaper wide field-of-view lenses, and

Table 2. Evolution of key RSTA system hardware. Entries listed are additions or upgrades made during the first year listed.

	Demo A	**Demo B**	**Demo C**	**Demo II**
SSVs Available	Single vehicle (initial design)	Single vehicle (new design)	Two vehicles	Three vehicles
Color Camera	Installed			
FLIR Sensor	None	Installed		
LADAR Sensor	No appropriate GFE unit was available			
Pan/Tilt Unit	Commercial pan / tilt		Custom pan / tilt	
Laser Range Finder	None		Surveyor's unit	Melios unit (SSV-C only)
Laser Designator		Installed, but h/w suspect	Installed, and h/w verified	
Processing Hardware	Sparc boards, Datacube	DAP SIMD processor		
Radio Data Link	LPR		SPR	
Global Navigation System	Homegrown system		Partial MIAG system	MIAG system

were located at various co-contractor sites. Later, these units were installed on the SSVs. Some delays were encountered while obtaining approval to purchase additional dual field-of-view lenses (not included in the original buy due to cost constraints at the time). Fortunately, a FLIR unit and new lens were eventually obtained each year for Demo C and Demo II.

FLIR camera and lens parameters could be set using buttons on the outside the respective enclosures. Calibration of the camera (required every time it was turned on), changing integration times, changing lens parameters, etc. required a person to physically climb on top of the vehicle to access these buttons. For Demo C, a computer controlled interface for reading and setting these parameters was operational, which greatly eased the camera setup process.

LADAR Sensor. An exhaustive trade study and search was conducted for a suitable GFE LADAR, with the key requirements that it be eye-safe to support unencumbered field experimentation, that it fit within a size / power / weight envelope suitable for the SSV, and that it have an effective operating range of at least 1 kilometer. All existing GFE LADARs needed modifications or redesigns costing $1-2 million to meet these requirements, and such funds were not available at the time. DARPA planned to procure a new LADAR designed specifically to meet the UGV requirements, however this procurement was delayed several years. This new LADAR was eventually built, but was not completed until after Demo II.

The continuing delays in the LADAR build were a constant source of difficulty within the RSTA community -- five groups were originally involved in LADAR algorithms. The community wanted a single common source of LADAR data, which could provide volumes of data for development and common evaluation efforts, and which would be free of the artifacts and limiting characteristics of the few existing LADAR datasets (with respect to UGV mission scenarios). By the end of the program, many of the LADAR groups had reduced their focus on LADAR algorithms, and the three major groups that remained used three different datasets from three different LADARs to evaluate their work. None used the same datasets.

Pan/Tilt Unit. The original pan/tilt unit, a commercial unit intended for underwater applications, proved too lightweight for the RSTA sensor load (heaviest were the FLIR unit and lens, and the MILES transmitter unit) and exhibited control problems during extremely hot days (most prevalent in the weeks preceding Demo B). The heavy payload and stepper motor actuators translated into inaccurate pointing and tracking performance. The original pan/tilt also could not accommodate the expected new RSTA LADAR. The custom pan/tilt constructed for Demo C eventually proved excellent for RSTA operations. Hardware build delays and programmatic priorities delayed the time before the new pan/tilt was available and the control software was working. This unit was available shortly before Demo C.

Laser Range Finder. A commercial (surveying) laser range finder was added to the Demo C configuration. Its purpose was to support better target detection and false alarm rejection in the core RSTA system, provide better target location data, and enable hill cresting maneuvers. It was well understood that this commercial range finder, with a 400 meter maximum range, was inadequate for most mission scenarios, however it was sufficient for development purposes and for tech demos.

The Melios range finder was considered to be the unit of choice, but it was expensive, one was not available, and at the time there were concerns about eye safety and electronic interface issues. Cost for additional RSTA hardware components, when the hardware budget was quite small, was a severe problem -- the required second dual field-of-view FLIR lens was somewhat expensive, and a desired second DAP was very expensive. Cost and time constraints ultimately decided the matter. As work progressed towards Demo C, it became more and more obvious that the target detection (and verification) system needed accurate target locations. The calculation of these locations required either data from a range finder with adequate range or an improved method for determining sensor orientation (for ray-tracing to the digital elevation map).

A renewed effort to acquire a Melios range finder was mounted for Demo II. One unit was eventually obtained and used at Demo II. It performed well, but the 7 second cycle time for measurements proved to be a great hindrance. While a single 7 second delay is not considerable, the accumulation of these delays during multiple ranging activities made the system performance appear to be slow to the soldiers that used it.

Laser Designator. The MILES laser designator system was installed and interfaced with SSV-B for Demo B, in anticipation of using it to designate a tracked moving target. The original mounting brackets for the FLIR and MILES laser were not well suited to the extremely fine mechanical boresighting adjustment required for the MILES laser spot. The residual boresighting error was corrected in software. New mounting brackets were designed for Demo C. Eye safety issues and required procedures were a great encumbrance for field testing the MILES. A minimum of five people were required for most of a day (SSV in-vehicle operator, safety director, two area perimeter guards, target receiver operator). A moving target was detected, tracked and successfully designated once in preparation for Demo B. The TOW transmitter required many seconds of high-quality tracking, which the Demo B pan/tilt could not provide, so the 25mm cannon / coax gun transmitter, which fired numerous discrete “shots”, was used instead. MILES systems were installed on all SSVs for Demo II.

Processing Hardware. The components in the RSTA processing architecture effectively did not change after Demo B, and proved adequate for RSTA functions at all times. (The processing power was adequate for a research prototype system. The soldiers operating the system at Demo II desired processing times far faster than could be provided within the constraints of the Demo II program structure.) However, obtaining copies of the RSTA processing components for subsequent vehicles, SSV-C and SSV-D, proved difficult, especially the DAP processor, the highest cost item. The system integrator eventually obtained a DAP processor for SSV-C through negotiations with the manufacturer. By Demo II, the cost issue was resolved and a new DAP was purchased by the program for SSV-D.

A single software subsystem originally (for Demo B) controlled the two sets of Datacube boards belonging to the RSTA and mobility / stereo subsystems. Part of the original SSV system design, strongly encouraged by the original DARPA program manager, was that the RSTA system be integral with the SSV system and not be treated as a separate “payload”. Also, two separate Datacube systems would require two host processor boards (i.e., the cost of an additional one) and would require that staff support two software systems instead of one. Maintaining and creating two large Datacube subsystems -- moving target detection and tracking for RSTA, and stereo obstacle detection for mobility -- required considerable manpower. A performance issue finally forced the issue. RSTA operations on the RSTA Datacube boards caused VME-bus contention that affected timing signals. This interfered with the implementation of stereo obstacle detection running on the other Datacube boards. The mobility and RSTA Datacube board sets were separated into two VME card cages for Demo C, and separate Datacube software subsystems were maintained from that point onward.

Radio Data Link. The digital packet switch radios provided the only link between the remote operator workstation and the SSVs. It also served to transmit differential corrections for the differential GPS system. The initial vehicle communication system, using a low-cost packet radio (LPR), had reliability problems that threatened the ability to perform Demo B and Demo C, and added a severe burden to field work. Software errors would necessitate a manual restart of all radios on the network, and thus a restart of all SSV system software. The addition of another node on the radio network for Demo C would have further reduced system reliability. Therefore, leading up to Demo C, it was determined that the system was inadequate for use during future demos. A new, improved packet radio product, called the secure packet radio (SPR), became available from the same manufacturer about two months before Demo C. It was installed into the SSV system, and after a period of modifications was working satisfactorily several days before Demo C. Subsequently, the SPR-based system performed superbly.

The SPRs also delivered a much improved effective bandwidth of 150 kilobits per second, an order of magnitude improvement over the LPRs. The LPR bandwidth had caused notice-able delays (about 6 seconds) for transmission of an image to the operator work-station, but this was only a minor inconvenience. The improved SPR bandwidth was obviously much more convenient for development purposes, and the faster image transmission times were invaluable for the time-conscious solders operating the system at Demo II.

The primary effect of reduced communication reliability on the RSTA group was that the remote communication system was used as little as possible during field work. Rather than rely on differential GPS, the vehicle was parked at marked survey points and the vehicle position was manually entered during a setup stage. The RSTA operator interface functions could be run on the workstation monitor inside the SSV at the time of Demo B, thus eliminating the need to use the packet radio to communicate with the BASE vehicle, where the operator interface normally is run. The remainder of the SSV operator interface could not be run inside the SSV until the following year. When the full commun-ication system was used, the primary effect on productivity during RSTA field work was that the communication hardware had to be reset periodically. Up to 15 minutes were lost each time to get back to the point where the system was brought down. Far greater system reset times were required when field testing mobility functions, particularly with multiple vehicles.

Global Navigation System. A GFE global navigation system (the MIAG unit), designed to give the vehicle’s six-degree-of-freedom world location, was planned to be available for Demo B. An interim, low cost solution (D-GPS, flux-gate compass, accelerometers, Kalman filters) was designed and built by the system integrator and used through Demo C. Accurate orientation data is critical in order for the RSTA system to execute search operations of specified map regions and in order to locate detected targets in the world coordinate system. The interim system proved inadequate for these needs. Vehicle heading data had the worst inaccuracy (as much as 8 degrees), tended to drift over time, and was effected by overhead power lines. For Demo B, image-based methods to estimate vehicle orientation were developed, which utilized known landmarks or horizon lines generated from digital elevation

Table 3. Growth of the RSTA system architecture's design. Entries listed are additions or upgrades made during the first year listed.

	Demo A	**Demo B**	**Demo C**	**Demo II**
Inter-process Communications	TCX	Improved TCX	New implementation, called IPT	Improved IPT
Operator Workstation	Manual Remote Sensor Control	Baseline operator workstation	Minor improvements: detection icon	Major improvements: integrated design; fire control
RSTA Executive	None	RstaVeh	RstaATR	
Cooperative RSTA	None		Cooperative verification	
Precise Vehicle Geolocation	None	Landmark orientation correction		Horizon orientation correction
Additional Capabilities			Hill cresting	Observation point planner

maps. This system provided acceptable orientation data, but required time-intensive acquisition and transmission of several images to the operator workstation. The MIAG system performed better than the interim system. Its orientation data was good enough to perform most search operations. However, highly accurate location of targets still required the use of the manual orientation correction method. The Melios laser range finder, available on one of the SSVs for Demo II, was also used obtain highly accurate target location data.

3. RSTA System Design, Implementation and Integration

The design of the RSTA architecture did not change significantly from its inception for Demo B. The primary elements of the RSTA system and how they grew over time are summarized in Table 3. Core RSTA capabilities are discussed separately in Section 4.

Inter-process Communications. The implementation of the message passing system used for inter-process communications, both within a vehicle and over the packet switched radios, changed over the years. The general problems with the original remote communication system resulted in increased scrutiny of the message passing system. A variety of low-level problems were uncovered in the original message passing system, and the internal implementation of the system underwent a total rewrite and a number of improvements after Demo B. There was no notable effect on the RSTA system, but there were continual minor modifications.

The effort to maintain the inter-process communication interface within the RSTA subsystem is typical of a huge number of software tasks best described as RSTA system maintenance. For example, the RSTA system is built using seven major C++ class libraries. The core functionality of these libraries existed for Demo B, but their design and implementation was significantly upgraded for Demo C. Maintenance of DAP and Datacube code is another such example.

Operator Workstation. A very simple RSTA capability was provided for Demo A. An operator at the remote workstation could point and control the only available RSTA sensor, a color camera, and retrieve compressed, digitized images from the vehicle. A new graphical user interface for all RSTA functions was designed and implemented for Demo B. Improvements were made in the following two years, but the same basic design and functionality served through to Demo II.

When a target was detected in the Demo B version of the system, a pop-up window would immediately appear on the operator workstation showing the results of the detection along with an image chip. This proved to be distracting to the operator, particularly with the higher number of false alarms before the target detection algorithm was better understood and tuned. A minor change done for Demo C was to have target detections appear initially as icons on the map display. The operator could then click on that icon to obtain a popup window showing the image chip and other data about the detected target. The user interface was extensively re-engineered for Demo II to make the interface more intuitive for the soldiers conducting the field experiments. The original RSTA user interface was designed and implemented separately from the rest of the user interface for the SSV system. This proved to be invaluable for RSTA field work. For Demo II, the design of the RSTA interfaces was made more consistent and more integrated with the remainder of the operator interface. The largest design change was the creation of a totally new and more user friendly fire control interface. The fire control interface was required for the Forward Observer vignette. It was also anticipated that the soldiers would want to perform a significant amount of manual RSTA searching during Demo II, and the fire control interface also served that need.

RSTA Executive. The central process in the RSTA architecture, created for Demo B, was called RstaVeh. RstaVeh runs on each SSV, receives all RSTA commands for that vehicle, and calls the appropriate RSTA subtasks to execute the command. For Demo C, the management and running of ATR algorithms was split out of the original RstaVeh, creating a new process called RstaATR. RstaATR receives commands only from RstaVeh. It acquires FLIR and color images as needed, executes target detection algorithms, fuses the results, executes the details of moving target detection and tracking operations, executes target recognition algorithms, etc. and passes the final results back to RstaVeh. Operations performed by RstaATR may run for a long time, whereas RstaVeh is not loaded by computation and can perform its high-level executive functions in a more timely fashion. This new RstaVeh / RstaATR design was crucial for integrating the large variety of RSTA capabilities provided by RSTA co-contractors. Every RSTA co-contractor was expected to have a tech demo of their work at Demo C. Some of these tech demos would be relatively stand-alone demos, while other were expected to span all the way to fully integrated capabilities. It was not possible to anticipate which organizations would achieve the level of full integration, so the system (RstaVeh / RstaATR) was designed to accommodate nearly all possibilities.

Cooperative RSTA. Cooperative verification of a target detection by a second vehicle was introduced for Demo C. This capability is provided by the RSTA Executive and was a requirement for Demo C, which stressed cooperative operation of the two SSVs. There were numerous details and difficulties associated with achieving this goal. The most significant overall problem was to obtain highly accurate location estimates for the original detection. This need helped drive the development of a precise vehicle geolocation capability (see below). Precise sensor transforms, needed to determine the exact pointing direction from the second vehicle, and field testing also consumed considerable time.

Precise Vehicle Geolocation. A highly accurate estimate of the SSV orientation is critical for a number of RSTA operations. It effects the accuracy of the actual scene areas viewed during a search based on map regions. The target detection algorithms require accurate range estimates to function properly. Cooperative verification requires an accurate estimate of the world location of the original detection, and required an accurate estimate of the verifying SSV's orientation. Accurate target location was also necessary to call in fire. Without a laser rangefinder usable out to typical target ranges, the solution became a manual landmark- or horizon- based orientation correction in which the positions of known landmarks or horizon points were manually associated with their positions in the image to provide the necessary correction constraints.

The landmark-based orientation correction capability was created for Demo B and worked satisfactorily. The method was slow, since a panorama of images had to be acquired and transmitted to the operator interface so the

Table 4. Approximate amounts of code contained in the RSTA system architecture.

Lines	Component of the RSTA system
61,201	RSTA operator workstation components
12,177	Target database
20,485	RSTA executive: RstaVeh
52,103	RSTA executive: RstaATR and ATR modules total -- C++
4,059	RSTA executive: RstaATR and ATR modules total -- DAP FORTRAN
6,999	All RSTA Datacube code, except moving target detection
8,024	RSTA library: Comm
2,211	RSTA library: ElMap
1,778	RSTA library: GenSearchSeq
2,583	RSTA library: Horizon line extraction
7,593	RSTA library: PctInterf -- C++ & C
1,303	RSTA library: PctInterf -- DAP FORTRAN
2,802	RSTA library: RstaXforms
6,557	RSTA library: VcsInterf
697	RSTA library: View
6,043	RSTA library: Xforms
5,214	Manual sensor & pan/tilt control utility
30,469	FLIR camera test utility
13,891	RSTA include files
246,189	**Total for entire RSTA subsystem**
1,468,860	**Grand total for entire SSV system**

operator could match the landmark points. This process could consume five minutes. Image transmission time with the slower LPR radios was the primary bottleneck, although moving the pan / tilt to acquire the images also took a considerable fraction of the time. Obviously, landmarks at known world locations were also required.

For Demo C, the idea of a fully automated orientation correction technique based on horizon lines was investigated. All processing could potentially be performed on the SSV, eliminating the need for image transmission and eliminating the need for operator involvement. Considerable time was invested to create an initial manual technique for horizon-based orientation correction, but the original landmark-based technique worked better in practice at this time. However, this effort laid the ground-work for the ultimate solution to this problem before the end of Demo II.

For Demo II, considerable time was also spent examining and evaluating the new vehicle global navigation system (the MIAG). The result of the evaluation was ultimately that some type of orientation correction was still required for RSTA operations. Thus, considerable time was spent fixing the horizon-based orientation correction method, ultimately making it work satisfactorily. Some steps were also taken towards automating the orientation correction process. An automatic horizon extraction algorithm from Colorado State University was integrated onto the vehicle. However, the software required to do the matching was not integrated.

Additional Capabilities. Hill cresting, in which the SSV uses its laser range finder to monitor the crest of a hill being approached so that the vehicle can stop at the point where only the RSTA pan/tilt is visible over the top of the hill, was implemented for Demo C. The observation point planner for pre-mission planning purposes was integrated for Demo II.

Amount of Code. The major elements of the RSTA system architecture, including libraries, are listed in Table 4 along with rough estimates of the amount of code written for each. The table lists the number of lines in the source code files, including comments and blank lines. On average within the SSV system, 30-40% of the total number of lines of source code are comments and blank lines. A majority of the RSTA system is implemented in C++. Core RSTA capabilities are discussed separately in the following section and in Table 6.

4. Core RSTA Capabilities

Table 5 outlines the growth of core RSTA capabilities over the years. A core RSTA capability is interfaced with all necessary SSV subsystems, and thus is available for use during autonomous mission runs. The system integrator

Table 5. Growth of core RSTA capabilities. Entries listed are additions or upgrades made during the first year listed.

	Demo A	Demo B	Demo C	Demo II
FLIR Target Detection	Manual RSTA	Integrated		
FLIR Moving Target Detection and Tracking		Integrated (with hot spot tracker)	Correlation tracker	
Color Target Detection			Integrated	
FLIR Target Recognition			Nearly complete integration	Integrated

created the initial set of core capabilities. RSTA co-contractors supplied more advanced capabilities that were integrated as additional core capabilities.

From the outset of the collaboration, the DARPA sponsor made a policy decision that it would be neither necessary nor practical that all nine RSTA co-contractors be fully integrated into the SSV system. All would benefit from involvement within the community and from experimental data collections, and all were required, at minimum, to develop laboratory demonstrations of their work for the annual UGV demonstrations. Only the most mature and promising (in terms of delivered mission capability) would be considered for inclusion into the SSV system.

FLIR Target Detection. The system integrator created a basic capability to detect targets in FLIR imagery for use during integrated mission runs. In particular, the algorithm had to run fast enough for use in the demos, which implied an implementation on the DAP SIMD processor. The resulting capability, available for Demo B, was a hybrid algorithm combining two algorithms from the literature, a double window algorithm for detection followed by a target boundary probing algorithm for pruning the initial detections. The algorithm was improved for Demo C, incorporating dynamically estimated target distance and target size constraints to eliminate anomalously sized false alarms. Field experience showed generally that false alarm rates were low in benign environments (cool mornings and targets with engines running), while false alarms were more numerous after late morning on sunny, hot days, when bare ground and rocky earth heated up and appeared as "hot spots". The algorithm and an evaluation of its performance are described elsewhere in this book.

Since the algorithm worked best with targets whose engines were running, part of the daily field work routine was to (1) start up the engines, (2) keep them fueled, and (3) turn them off at the end of the day. This required a person or often several people who knew how to start and occasionally drive (for refueling or target repositioning): HMMWVs, M35 trucks, the multi-gear M543 truck, an M113 APC, an M60 tank, and two M2 Bradleys. The M60 and Bradleys could not readily be driven to the company fuel pumps (they tore up the roads too much), so a fuel truck had to drive out to them instead. A considerable amount of maintenance was also required for the target vehicles. The Colorado Army National Guard provided invaluable support to the UGV Demo II program via the loan of target vehicles and assistance with maintenance operations.

FLIR Moving Target Detection and Tracking. A complete stand-alone system that detected and (passively) tracked moving targets in video from a stationary camera was provided by a group at Army Research Labs. The provided system ran entirely on a Datacube board and its host processor. The system integrator integrated this system into the SSV's RSTA system, and added a simple active tracking capability. Moving targets were detected in color video, and the tracker kept the hottest spot in the FLIR image actively centered. While the system worked well at Demo B, it had many limitations. It required a minimum number of pixels on a target (at least 16x24) for reliable detection. The large amount of time required to restart the system on a new sensor view, combined with the dynamics of driving a moving target in the demo scenario, required that the corresponding sensor search be constrained to use only a single field of view. The hot-spot tracker only worked on the wrecker truck because it had a large, exposed (and very hot) exhaust stack. The combined result was that detection and tracking was limited to a 100-400 meter range. For Demo C, the detection stage was switched to utilize FLIR video. The only significant impact was the smaller field of view (again, in combination with constraints on algorithm startup time and the rather short time it took for a target vehicle to move across the field of view). The significant modification was the addition of a more sophisticated active tracking technique, based on correlation of an acquired target template. The new tracker was implemented on the DAP SIMD processor, and worked well with a variety of targets. A HMMWV was the primary moving target used during development. An M2 Bradley fighting vehicle was tested in the last couple days before the demo and was detected and tracked successfully in the demo. Field testing with the Bradley was limited because the Bradley's tracks caused severe damage to the demo area.

Color Target Detection. A capability to detect targets in color imagery was the first capability integrated from a RSTA co-contractor, the team lead by Colorado State University and including the University of Massachusetts and Alliant TechSystems. This capability was available for Demo C, and the RSTA system could fuse the detection results from the FLIR and color target detection algorithms. The performance of the color detection algorithm in the highly variable field environment used in regular field work was unacceptable however, and the algorithm was not used in the integrated Demo C demonstration. See Chapter 4 for a complete description of this capability.

FLIR Target Recognition. A capability to recognize targets in FLIR imagery was provided by a team led by Nichols Research Corporation and including Loral Vought Systems and Hummel Enterprises. This capability was shown as a highly integrated tech demo at Demo C, and was fully integrated for Demo II. In addition to providing target recognition labels, this capability was also useful for pruning false alarms generated by the detection system. The RSTA co-contractor shifted a considerable amount of their research efforts to provide this integrated capability for Demo II. The system integrator also spent a large amount of time integrating the software, collecting relevant target data, and tuning the algorithm for robust performance. The target recognition capability was expected to contribute most to the Recon / Counter-recon vignette (the battlelab warfighting experiment). Unfortunately this vignette later turned out to be the vignette in which the soldiers were most pressed for search and response time. The soldiers usually opted to turn off the recognition capability in favor of faster search times. Good performance was achieved in the times when the capability was utilized at Ft. Hood. See Chapter 4 for a complete description of this capability.

Amount of Code. Table 6 shows the approximate size of the source code corresponding to each core RSTA capability. The table lists the number of lines in the source code files, including comments and blank lines. On average within the SSV system, 30-40% of the total number of lines of source code are comments and blank lines.

4.1. Integrating RSTA Co-contractor Capabilities

Recall that co-contractors in the Demo II program had the option of four different types of demos to showcase their work: a lab demo, a stand-alone tech demo (in the field, partially utilizing an SSV), an integrated tech demo (fully utilizing an SSV), and the integrated mainline demo. A co-contractor was generally expected to progress through these types of demos in one-year steps. As noted above, some RSTA co-contractors bettered this schedule and achieved fully integrated status.

Following is a typical sequence of activities necessary to accomplish an integrated tech demo for one co-contractor's work. The same general process is applicable to the creation of a stand-alone tech demo, an integrated tech demo, or the integrated mainline demo. Progressively greater amounts of effort, lead time, and visits to the integrating contractor, and time in the field are generally required for the more integrated types of demos:

- The parties define the tech demo.
- The parties agree on a delivery schedule leading up to the demo, including tasks, code deliveries, integration visits, data collections, field experiments, etc. Co-contractors integrat-ing onto the SSV for the first time are often surprised at how long before the demo date this process must begin. For example, the initial delivery of complete code is typically planned to occur around February, for an integrated demo in July.
- The parties also agree on function call inter-faces, data requirements and conventions for the code, documentation, etc.
- The co-contractor provides an "early" deliv-ery of a complete working version of their capability. One person within the integrating contractor organization typically must become very familiar with the design and implement-ation of the co-contractor's code. The main reason for this is that the co-contractors in the Demo II and RSTA programs provide research prototype code, which in almost all cases requires considerable effort to both integrate the software and get it working well within the context of the SSV system and the demo scenario. Beyond a point, most of this work must be done by the integrating contractor. In addition, some degree of modifications to the SSV and RSTA system, infrastructure, libraries, etc. are often necessary, and although much of this work can be anticipated, there are always a few details that are not obvious until software integration is well underway. An early delivery of the co-contractor code addresses all of these issues.
- Eventually, an initial working version of the co-contractor code is up and running at the integrating contractor's site. At this point the integrator and the co-contractor generally have a solid idea of the tasks required to complete the software for the demo.
- Co-contractors typically must visit the system integrator several times during the integration process. Two visits of two days each was not unusual. The first visit would often be simply to aid in the integration of the software. Depending on the amount of progress made, the system might be tested in the field on one of the SSVs. Field testing includes debugging and exercising the co-contractor capability in the context of the complete SSV system, initial debugging and

Table 6. Approximate amounts of code contained in each core RSTA capability.

Lines	Core RSTA Capability
5,328	RstaATR module alone
3,345	FLIR target detection -- C++
3,291	FLIR target detection -- DAP FORTRAN
764	Color target detection
2,176	Fuse color and FLIR target detections
20,331	FLIR target recognition
18,817	FLIR moving target detection (mostly Datacube code)
1,342	Correlation tracker -- C++
248	Correlation tracker -- DAP FORTRAN
520	DAP utilities -- DAP FORTRAN
56,162	Subtotal for core RSTA capabilities, above
246,189	**Total for entire RSTA subsystem**
1,468,860	**Grand total for entire SSV system**

testing and experimentation on live data in the field, and collection of sample imagery for the co-contractor to take back to their home location.

- Eventually the co-contractor will supply a final version of their code. The integrator will normally not accept any modified code from the co-contractor after this point.
- The co-contractor must visit again to perform final field testing of their capability within the context of the SSV system and within the variation exhibited in live imagery. Nominally this visit would conclude with a dry run of the technical elements of a tech demo, discussion of "show" elements, detailed scripting of the demonstration events, and full-dress rehearsals of the live tech demo. The final dress rehearsal may be performed during a later visit.
- In the case of a co-contractor capability that is included in the integrated mainline demo, the co-contractor would typically need to be on call during several weeks of end-to-end debug and practice runs of the integrated demo mission. The amount of such end-to-end field work and the associated amount of last-minute system debugging varied radically between the first year's integrated demonstration and the final one for Demo II.
- The process concludes with the demo day.

5. Field Work

Large amounts of field work was a general characteristic of the system integrator's work in the Demo II program, and the RSTA area was no exception. Considerable RSTA development requires running with the vehicle hardware (such as the RSTA pan/tilt and FLIR sensor), which can sometimes be achieved using the SSV inside the garage but eventually requires testing in the field environment while viewing actual target scenes. Integration requires debugging and testing within the context of the fully running SSV system, which requires executing mission runs with the SSVs in the field. Not surprisingly, field work requires considerably more man-power support than work in the lab. Accomplishments occur more slowly in the field than in a lab environment. Table 7 outlines the most significant factors effecting RSTA field work.

SSVs Available, and Their Uses. The focus of the UGV Demo II program was autonomous mobility of UGVs. Specifically the UGV Demo II sponsor and thus the integrating contractor set first priorities on completing the construction of the core vehicles, making autonomous mobility capabilities functional, and assuring the mobility functions required during each year's integrated demo work properly. The SSVs had to demonstrate new mobility capabilities each year, if nothing else. Necessarily, support for integrated RSTA capabilities and associated activities received a lower priority and commensurate resources. The lower priority for RSTA capabilities had several significant effects on the RSTA integration group:

Table 7. How characteristics of field work varied over the years.

	Demo A	Demo B	Demo C	Demo II
SSVs Available	Single vehicle (initial design)	Single vehicle (new design)	Two vehicles	Three vehicles
Program Priorities and Vehicle Uses	Working system, mobility, very simple RSTA system	Mobility, limited time for huge new RSTA system	Support large number of tech demos	No new capabilities; robust and user friendly
Weather		Hot days affect A/C	Snow & mud limit access to site in winter	Very hot and very dusty, but SSVs work well
Site Characteristics	Very close by; mostly roads	Far away; mostly off-road, benign clutter except claypit	Nearby; all off-road; high clutter and variety	No access before field trials began; high clutter and variety
Support Staff		Self-support; Everybody in field last month	Support staff; Core team in field last few weeks	Extensive support staff; Core team at Ft. Hood

- Each year, the hardware task of building an SSV vehicle had to be completed. Neither mobility nor RSTA work could begin without a vehicle, and unfortunately vehicle build schedules nearly always slipped. This problem was most acute during the Demo A and B cycles, since no other vehicle existed (that would be used in the integrated demo). Both years the vehicle hardware was completed sufficiently to begin system checkout only a month or two before the demos.
- Once a new vehicle became available each year, extensive low-level checkouts were required and new low-level system software often had to be written (for hardware that had been modified or added that year). These checkout activities typically required at least two weeks.
- Next, access to the vehicle was initially devoted to mobility. Each demo required, at the very least, that the SSV drive through the mission scenario. Schedule delays (vehicle build, low-level software, mobility software) only compounded to reduce the total amount of vehicle time available for RSTA work. This time crunch was the worst before Demo B, when a completely new RSTA system was integrated (providing effectively the same central architecture that served all the way through to Demo II). Also, during the Demo A and Demo B years most of the mobility and non-RSTA functionality was immature and required additional time to get them working reliably.
- Eventually vehicles become available for work on RSTA functions. Usually, some severely limited access was provided up to this point. But often, in the end, only a few days (leading up to Demo B) or a few weeks (leading up to Demo C) of dedicated use of an SSV were available to the RSTA integration team to work on integrated demo functionality. Working on weekends and during evenings (we *did* have a FLIR) was common for the RSTA team in the weeks / months before each year's demo.
- Similar programmatic priorities, within our resource constrained world, helped to delay the decision to construct (by a year) and then the actual construction (by months) of the new RSTA pan/tilt (built for Demo C), and also the acquisition of proper laser range finders (for Demo C and Demo II).

A considerable amount of RSTA work leading up to Demo B was performed using SSV-A, mainly to obtain access to the SSV processing architecture, pan/tilt controls, and sensors. It was not feasible to integrate with the limited SSV software system functionality that was available on SSV-A. Many surprises were encountered late when full system integration was attempted on SSV-B. The resulting lesson learned was to integrate early, and integrate often.

Limited access by the RSTA team to the SSVs due to vehicle-build issues and mobility requirements was no longer a significant issue for Demo C, since SSV-B was available for most of the preceding year. Also, overall vehicle reliability was excellent in the months leading up to Demo C. However, additional tasks to support the enormous number of mandated tech demos during Demo C placed new demands on vehicle availability. Nearly every Demo II co-contractor staged a tech demo, each of which, as described above, required several days of field work, with appropriate help from the system integrator's staff. Also, some tech demos and many parts of the integrated demo required both SSVs for cooperative functions. No SSV was available for any other work at those times. In the RSTA area, cooperative target verification was the primary task that required allocation of both SSVs during field work. Contention for vehicles was no longer a problem for Demo II, with two vehicles available from Demo C onward and the third vehicle available in February (the Demo II field exercises occurred at Ft. Hood during May and June).

The process for planning the next year's demonstration typically began shortly after recovering from the previous year's demonstration crunch. Detailed planning typically began at a community workshop held in October or December. Thus, there was time for a second workshop (December or February) to further plan details before the demo in the following summer. Unfortunately, for Demo II, the initial plans for the vignettes were developed by a number of end-user organizations in coordination with the DARPA sponsor. The complexity of this process resulted in the initial structure of the vignettes not being decided until fairly late. Specifically, the first community planning workshop was held in February. (The May-June time period for the vignettes was also not firmly decided until fairly late. Hot Texas weather and budgetary constraints were the two driving factors in the eventual decision. This also shortened the time for demo preparations.) The late schedule made it extremely difficult to put any vignette-specific hardware or software in place in a timely manner, particularly any software provided by a co-contractor. While waiting for the selection of the vignettes and thus the subsequent planning workshop, the system integrator focused on a number of tasks generic for any possible vignette, which focused on fixing known high-priority problems, making the system more friendly for the operators, and making the system more robust for the Ft. Hood and vignette style of operational environment.

Weather. The summer of Demo B was unusually hot, stressing the vehicle air condition-ing and to a lesser extent the generators (APUs). A/C and APU failures often brought work to a halt and created several hour delays before it could resume. The A/C problems were resolved the following year, mainly by a redesign of the airflow ducting. For Demo C, the huge number of tech demos consumed an enormous amount of vehicle time. While this was planned for, the effect was that field work had to begin sooner and thus could not wait until weather cleared up from the preceding winter. It rained and snowed frequently during that spring, which did not help the situation. Further, the Demo C site was less accessible after a light rain or snowfall, due to steep clay-based (slippery) dirt roads and rugged off-road terrain. Fortunately for RSTA, the Demo C site also had a highly convenient, paved, overlook area (where the tent and audience were situated), which could be used for many RSTA field activities, including two-vehicle cooperative RSTA operations. Some APU and A/C problems remained later in the year when it got warmer, resulting in downtime, but this was more of an inconvenience rather than a significant burden as in previous years. Large quantities of fine dust was the greatest weather concern for Demo II at Ft. Hood, but it was anticipated. Design changes reduced the amount of dust that could get into the hardware, and regular equipment cleaning was performed while at Ft. Hood. Ft. Hood was also extremely hot during Demo II, but the A/C and (further modified) APUs performed superbly in the heat.

Site Characteristics. Field work requires going to and from the field site more often than one might first imagine. Activities and issues include driving the SSVs between the test site and the SSV's storage and maintenance building, driving additional support people back and forth using other vehicles, driving the SSVs to the gas station or driving gas cans to the SSVs, returning the SSVs to shelter moments before the onset of rain from brief but regular afternoon thundershowers that occur in the Denver area, driving out to the target positions at the site to turn their engines on or off or to reposition them, returning to eat lunch or use the rest rooms, and sending special software and/or hardware talent to the field location to debug new problems. The Demo B site was a great distance away, requiring 5 to 20 minutes to drive to certain locations from our building. Voice radio communication between the Demo B site and our building was barely functional. The Demo C site was far more convenient. Its edge was a minute drive away, but the far north end of the site required almost 10 minutes of driving on winding dirt roads. Access to the vignette sites within Ft. Hood obviously required the longest distances and time delays.

Support Staff. In order for one software engineer to work in the field, a number of other people may be involved in support roles. For example: One of the safety procedures required two people to be in an SSV when it was driven, manually or autonomously. So generally two people were required for each SSV in the field, though during some fixed-vehicle RSTA work a person or two could sometimes return to the lab. When using the operator workstation, an additional person was needed there. A hardware person was always either on site or on call to help resolve any A/C, APU, or other hardware problems. Operations people were needed to start target vehicle engines, periodically move them to new field positions, to drive moving targets, etc.

The amount of regular field support staff, particularly hardware and operations support staff, increased every year, as it was realized how greatly this improved the productivity of field work. Early in the year leading up to Demo B, the two or more people using a vehicle in the field (during RSTA work) typically had to deal with everything by themselves, driving the vehicle back for gas (the generators required gas about every 5 hours) and driving the vehicle back to the lab when any other problems were encountered. As Demo B approached and end-to-end dry runs of the integrated demo were underway, literally all of the staff was stationed at the demo site at all times. Needless to say, the responsiveness and amount of support when any problem arose was good. In the year leading up to Demo C, the continuous presence of a hardware or operations support person at each vehicle proved to be an excellent investment. This support person would monitor the APUs, A/C, any other minor hardware problems of the moment, and maintain gas for APUs via gas cans. Operations support to reposition fixed targets and drive moving targets was plentiful. This philosophy of increased staff support was continued, and increased, during the operations at Ft. Hood, with highly beneficial results.

As an illustration, one day of field experimentation of a RSTA algorithm by the system integrator would typically include the following activities: An interval of up one to two hours would transpire from the time that personnel depart their desk to the time that a piece of code was successfully run for the first time that day in the field. This interval involved tasks such as: starting the generators, cooling down the FLIR camera, starting and verifying the system software, fixing the occasional hardware problem (which arose when the vehicles were regularly used 8-12 hours every day), fixing software configuration problems, finding all the right people to fix these problems, driving out to the demo site, etc. This startup time got progressively shorter each year. By the time of Demo C, this total startup time was as short as 30 minutes for pure RSTA (non-mobility) operations. Autonomous mobility operations required an additional checklist of tasks before executing a mobility run. Next, testing and debugging code within the context of the complete SSV / RSTA system could begin. This took much longer than debugging at a workstation in the lab. System problems took more time to trace down, and interactively restarting and running the system for debugging took a long time. Finally, returning with the vehicle from the field to the building, shutting everything down and uploading data to the lab computers could easily consume an hour.

6. Summary

A significant issue regarding the emergence of RSTA capabilities within the SSV system was that the RSTA program started one year after the core

UGV / Demo II program. Thus, construction of the RSTA architecture, infrastructure and core capabilities by the integrating contractor lagged all the mobility work by one year. The RSTA co-contractor work lagged by one year in maturity and readiness for integration, and the RSTA program did not require every co-contractor to integrate their work into the SSV system. In the end though, several capabilities from the RSTA community were integrated into the SSV system and available for use during the Demo II field exercises.

The UGV / Demo II program provided RSTA researchers the opportunity to move algorithms out of the lab and into a field environment. It also initiated work on combined mobility and RSTA issues, such as observation point planning and RSTA on the move. The RSTA community benefited greatly from interactions with the UGV end-user community, developed during the last two years of the program. An enormous volume of imagery was collected, both informally and including ground-truth data, and is available for future work. Finally, the combined functionality of the SSV / RSTA system, containing all the efforts of the system integrator and the integrated RSTA co-contractor capabilities, will endure and be available for use within future UGV programs.

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