Data and Event Visualization

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ABSTRACT

The increasing complexity of today's information environment is reflected in the increasing complexity of military operations. A brief look at the evening news reveals organizational and technological complexity that was unheard-of even a generation ago: Improved explosive devices detonated via cel phones; unmanned vehicles both ground and air; handheld communication devices on virtually every combatant; ubiquitous and near-instantaneous media coverage of even the smallest military actions. All of these factors, and more, can critically impact the success of military operations. Understanding this new environment to facilitate mission success is truly a challenge.

Just as with operations in the real-world tactical environment, our ability to test military equipment depends critically on our ability to rapidly understand causes and effects among numerous variables represented by extremely high-volume data of several types (such as numerical, visual, boolean, and textual). Traditional analysis methods, which often center on very efficient mining of single data sources, are increasingly inadequate to meet this challenge, and advanced means of visualization and understanding are required.

While our initial focus was on analysis—understanding data produced by test events—we have quickly come to the realization that operational test and evaluation will use visualization technologies not only for analysis, but for planning and control of test events. This control is not only of live operations, but increasingly of sophisticated federations of models and simulations that support the conduct of our tests. The ability to develop, integrate, and operate these federations directly reflects the complexity of actual military operations, and depends on our ability to understand the relationships among multiple software applications, each of which is extremely complex in its own right. Hence, technical control—such as of the simulation federation, of test and evaluation networks, or of data collection applications—becomes increasingly challenging, yet potentially tractable due to the use of visualization technologies similar to those in use in the commercial world.

Introduction

The increasing complexity of today's information environment is reflected in the increasing complexity of military operations. A brief look at the evening news reveals organizational and technological complexity that was unheard-of even a generation ago: Improved explosive devices detonated via cel phones; unmanned vehicles both ground and air; handheld communication devices on virtually every combatant; ubiquitous and near-instantaneous media coverage of even the smallest military actions. All of these factors, and more, can critically impact the success of military operations. Understanding this new environment to facilitate mission success is truly a challenge.

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It is axiomatic in software engineering that an understanding of the problem domain is an essential first step in crafting a solution[1], and this problem is no different. This paper describes the problem domain as seen by the operational tester, and our initial steps towards solutions. We first describe the problem domain (section 1), followed by an overview (section 2) of our process towards finding solutions; a brief description of our initial operational architecture (section 3); and (section IV) a presentation of a few of the promising technology solutions that we have found, using them to illustrate features of benefit to the operational tester.

I. The Problem Domain

While our initial focus was on analysis—understanding the data produced by test events—we have quickly come to the realization that operational test and evaluation can use visualization technologies for other purposes. Just as in the operational force or in the commercial world[2], visualization technologies can be used to improve our ability to control a test event—both in planning an event, and in monitoring and understanding its execution. Further, these technologies can assist in both *operational* control (that is, controlling the execution of the event by test team and test unit) and *technical* control (controlling the hosts and applications that support the event, such as by collecting data).

Our work to date indicates that the challenge of *operational and technical control* is in many ways quite similar to that faced by operational units: The operational tester has the same challenges of—

- creating, analyzing, and choosing among courses of action, while--
  - allocating forces to terrain and to missions,
  - planning networks while considering the mission, the terrain, and the weather,
- rehearsing, and
- monitoring execution such that needed changes can be made in a timely manner.

We examine each of these in turn.

In terms of *operational control*, the tester's task of creating, analyzing, and choosing among courses of action is very similar to the operational warfighter's. Two key similarities are the tasks of *allocating forces to terrain and to missions* and *planning networks while considering the mission, the terrain, and the weather.* The tester, however, must face the added complexity of performing this task both for the test unit (to determine the probable tactical execution of the test, which is needed to plan data collection and other test operations) and for the test team (to determine the best means to collect data while minimizing interference with the tactical scenario). An increasingly important point for the tester, just as for the warfighter, is the placement of sensors (in test terms, instrumentation) such that they will collect the desired data at the proper time, and are not impeded by terrain or distance. Figure 1, below, illustrates this challenge in simple terms: The tester cannot afford to place data collection sensors at every point on the test "battlefield," so must choose carefully where the action will take place, and where he places his sensors. In this scenario, the friendly unit may choose axes of advance represented by both the solid and the dashed arrows—or may choose to send forces along both. Modeling of terrain and electromagnetic energy propagation, coupled with simulation of the ground combat operations of the units in the sketch, will allow the tester the best opportunity to control both the event and his sensors to get the most good data from the event.

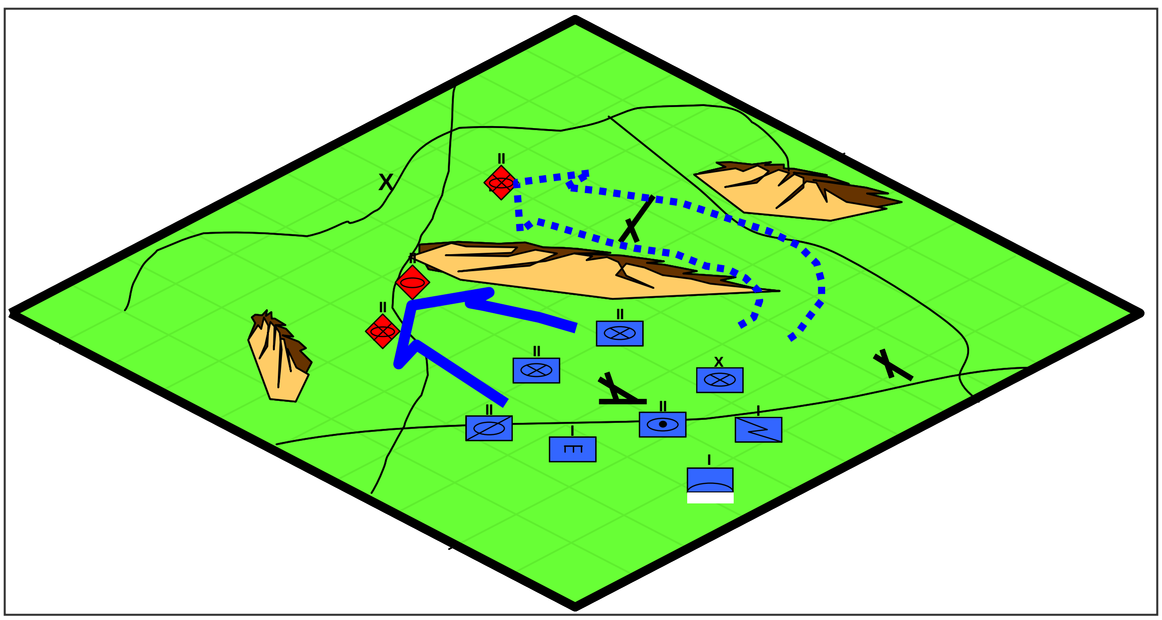

Figure 1. Test Planning Considerations.

The tester's challenge of *technical control* is again very similar to that of users in other domains. Planning networks while considering the mission, the terrain, and the weather is also a task very similar to that faced by operational warfighters. The increasingly networked nature of test instrumentation and of simulation federations[3] creates a potential requirement to establish and maintain network connectivity among all "test players" such that engagements can be simulated and weapons effects assessed rapidly. Since many of the test players may be in combat vehicles, this places a severe challenge at the feet of network planners. Similarly, networks to support test team operations—such as data collection, or data analysis—must take into account not only terrain and weather but the probable tactical execution of the test. Those readers familiar with mounted combat operations are probably familiar with the effects of a heavy vehicle running over an exposed telephone or network cable.

The test team will also in many cases face the challenge of comprehending and controlling applications exchanging extremely high volumes of critical data. For instance, many tests now use an integrated live and constructive simulation environment, where information is exchanged via protocols like the High Level Architecture (HLA) or the Test and Training Enabling Architecture (TENA): "Disconnects" in data format or content among these applications can cause execution to fail, or—almost as critical—present incorrect information to the test unit or the test team.

In all these cases, the ability to "virtually rehearse" the test operation—whether in operational or technical terms, or both—will be invaluable to the tester, in analyzing courses of action ("Did I place the instrumentation correctly?"), in ensuring test team understanding of the mission and its execution, and in ensuring the correctness of execution.

Monitoring test operations can again be understood in light of its similarity to the task of monitoring military operations. Again, the similarity is tempered by the additional complexity of monitoring both test unit and test team operations; and the latter is in terms of both operational and technical control. Increasingly[4], the tester is challenged to understand the status of his instrumentation and data collection in near real time, so that progress can be measured and execution changed—or suspended—in response to the specific conditions encountered.

Analysis of the data gathered is perhaps the most challenging of the visualization tasks: It can be thought of as consisting of—

- Authenticating data,
- Ordering data,
- Conducting extended analysis of single-factor data,
- Conducting extended analysis of multi-factor data, and
- Applying Evaluative Military Judgment[5]

Authenticating data is the task of confirming the test data, correcting it as necessary (such as by identifying and discarding invalid or redundant data points), and recording the results of the procedure in usable, agreed-to formats.[6] In operational tests, this task is the charge of the Data Authentication Group or DAG. The DAG is often confronted with enormous volumes of data[7], and usually has limited time to perform its tasks. Further, DAGs may review data of very different types (video, military messages, network traffic) but relating to the same test event. These requirements immediately result in the requirement for new visualization techniques to comprehend extremely high-volume data, and the need to comprehend this data from multiple sources. These challenges are discussed in more detail below.

Ordering data is the task of arranging data in convenient order for further processing. While this may seem simple in concept—for instance, ordering military messages by the time of their arrival at a given node—in practice it can be extremely complicated. Which of thousands of nodes, for instance, are relevant for arrival times? Given sophisticated routing topologies often found in modern military networks, are routing protocols and their implementation important to those arrival times? What were the relations of time- and location-dependent battlefield factors (such as electronic attack or "jamming") with message arrival times? These are only a few of the many conceivable challenges to comprehending data and "arranging…for further processing."

Extended analysis goes beyond primary statistical tests to (for instance) combine analytic results from different sources, to apply queuing or inventory theory or decision analysis techniques, or to use mathematical models or combat simulations.[8] The analyst may work with numerous high-volume data sources in different combinations using different tests or algorithms. The potential combinations of data could be virtually limitless: In a large combined-arms test such as of the Future Combat System or FCS, an analyst might have multiple video sources (from cameras placed on the test battlefield, or of individual system user interfaces), numerous audio sources (from test unit radio nets), several streams of military message traffic (such as for situational awareness, or for command and control, from any one of many units), application logs, and signal-strength data from the electronic spectrum collected at several or many points on the battlefield. Many factors represented by these data sources could—singly or in combination—conceivably contribute to a unit's effectiveness in the test, resulting in questions such as the following:

- What was the effect of electronic attack on the quality of information presented to a certain user?
- What was the effect of location on information quality?
- Did the quality of information available at a certain time affect a commander's decision?

These questions, and many more, will tax the analyst to comprehend very large data sets, often of disparate types, and—most crucially—comprehend their combined effect on the results of the test.

Finally, applying evaluative military judgment is perhaps the most complicated analysis task of all. The analyst must not only reach conclusions about the overall effectiveness and suitability of a given system from data that is often brutally complicated, he or she must be able to comprehend or even challenge the work of the analysts in all previous steps: Have all relevant factors been considered? What is the sensitivity of the conclusion to each factor in the test? What challenges have been raised to the analysis, and have they been fully addressed? This step emphasizes the requirement—already suggested by the earlier work—to rapidly and easily compose and comprehend queries against very large data sets, and in similar fashion to integrate the queries and their results.

II. The Solution Approach

OTC's Transformation Technology Directorate (TTD) chose to approach the data visualization problem through an integrated process team (IPT). The IPT in turn chose to approach this complex problem in multiple phases that will take place over FY09 and FY10, thereby allowing Visualization IPT members to analyze multiple problem sets (instantiated as the requirements of specific tests) while examining numerous potential solutions. The IPT chose to use as its *lingua franca* the Department of Defense Architecture Framework (DoDAF), Version 1.5, to document the processes and systems associated with visualization issues.

The IPT quickly identified the visualization needs of operational control, technical control, and data analysis described above; what was needed, however, was a more detailed view of the problem domain—down to the low-level tasks, and further down to the visualization requirements associated with those tasks. The DoDAF Operational View - 5 (OV-5, Operational Activity Mode), was used to begin this process; the team chose to depict the OV-5 as an Activity Hierarchy[9] to facilitate organizing it in a logical, easy-to-understand format. This is described further in the next section. We believe our current OV-5 is a significant advance, but obviously represents only a first step in defining the tester's requirements for visualization.

After the initial requirements determination, the IPT will verify the requirements through the target audience—OTC's test teams. This process will require the demonstration of potential solutions in order to elicit the thoughts of the user on the emerging capabilities and the feedback on how demonstrated capabilities may tie back to known requirements, enhance test capabilities, or create unnecessary overhead.

The capabilities of the potential solutions will be recorded in a DoDAF Systems View - 4 (SV-4) to allow the IPT to compare tool capabilities against known requirements. After the requirements are verified and the correlating solutions are identified, a knowledge repository containing the requirements and the corresponding possible solutions that will be accessible throughout OTC for testers, analysts and technologists will be created. The last phase of the Visualization IPT effort will be to provide an overall demonstration of visualization capabilities for key requirements, facilitating selection of the tools that best meet those requirements when the criteria of affordability, tailorability, extensibility, and usability are taken in consideration.

III. The Operational Architecture

When the IPT began assessing the requirements for visualization across a broader spectrum than data analysis, the user's "task list" of course became much larger. It appears to us that visualization capabilities may support tasks such as configuring complex system-of-systems environments, and for controlling test operations. Tasks such as these defined the components and sub-components of the operational architecture for the IPT effort. The team chose to group the sub-components in a manner roughly corresponding to major activities in a test event, as shown in Figure 2 below. This served as the first level of the activity hierarchy.

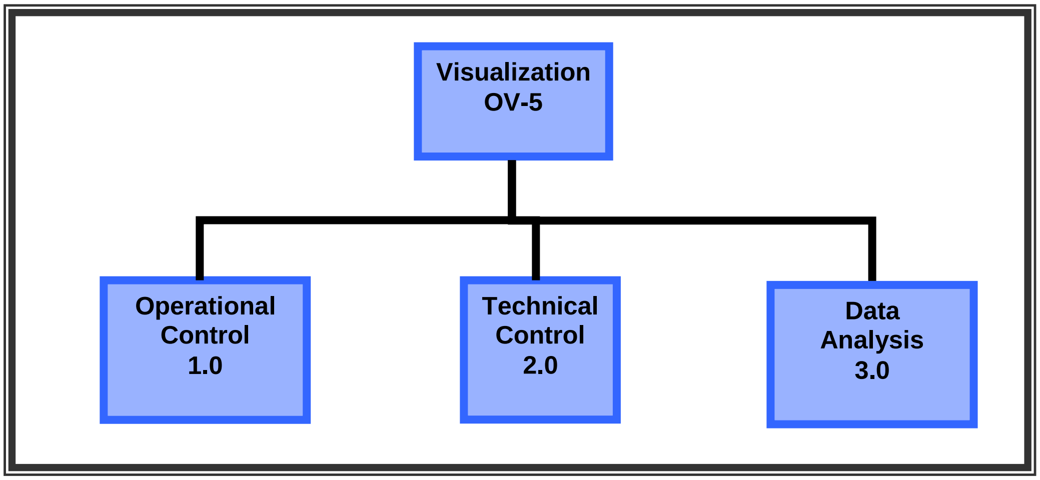

Figure 2. First Level Activity Hierarchy.

The subcomponents of the Operational Control task are shown below in Figure 3. Turning first to the Operation Planning subcomponent, we further divide the task into Scenario Generation and Comprehensive Event Rehearsal. While various simulations provide graphical means to build their scenarios—as well they should given the size and complexity of even single-simulation scenarios—we are unaware of any current capability to do this for the much more complicated case of a scenario for an integrated LVC test environment. Further, we believe the ability to “virtually rehearse” this scenario will greatly enhance the test officer’s understanding of the event, and his identification of risks to the test as was briefly mentioned in Section 1.

In the Operation Execution phase, an integrated common operational picture (Integrated COP) allows the test officer to understand the state of his “test battle space,” including both live and virtual or constructive entities. The ability to see Entity Attributes -- exactly what that entity is, whether it is live or constructive, and its state – facilitates understanding of the state of test execution and thereby supports decision-making. An immersive 3D Battle space for virtual entities can simulate actual tactical operations center (TOC) assets (such as the video from an unmanned aerial system (UAS)), or stimulate a role player to provide quick and more accurate reactions to events in the scenario.

It is common practice to conduct After Action Reviews (AARs) in the Post Operation “Wrap-up” for both the test team and the test unit. While the focus of each will be on the execution of the event, the test team will of course focus on test team activities (such as data collection, or the execution of the simulation environment) while the test unit will focus on its own execution of military tasks. In both cases, the ability to playback events in the scenario adds greater fidelity to the AAR, facilitating understanding by the unit and the test team of what happened, its effect on the operation, and why it happened.

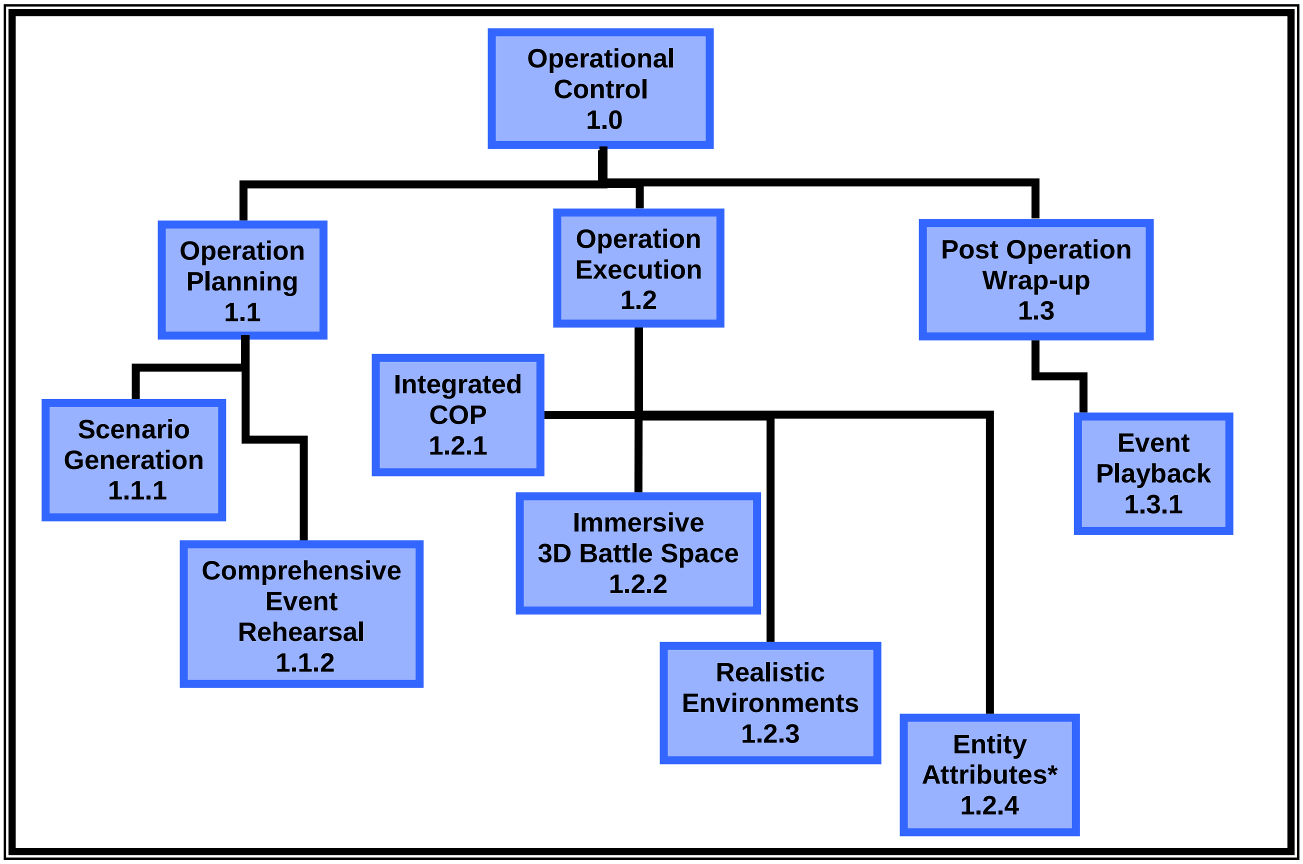

Figure 3. Operational Control Activity Hierarchy.

The Technical Control Activity Hierarchy is shown below in Figure 4. The IPT chose to structure it based on the tasks we have performed in configuring a live, virtual, and constructive (LVC) test support architecture. The key tasks we have identified include validating the interfaces among LVC components; network monitoring; and monitoring system health. While the last two tasks may appear mundane—at least to those who operate and manage systems in a production environment—the first is somewhat peculiar to system-of-systems integration such as is done in a simulation federation. In particular, we encounter the need to validate the correctness of data exchanged among the systems—both in terms of its syntax or format, and in terms of its semantics or underlying meaning. The ability to visually comprehend and analyze these exchanges could reduce configuration time, greatly expedite the Verify and Validation effort of the architectures, and in turn allow rapid response to any interoperability issues that may arise during execution.

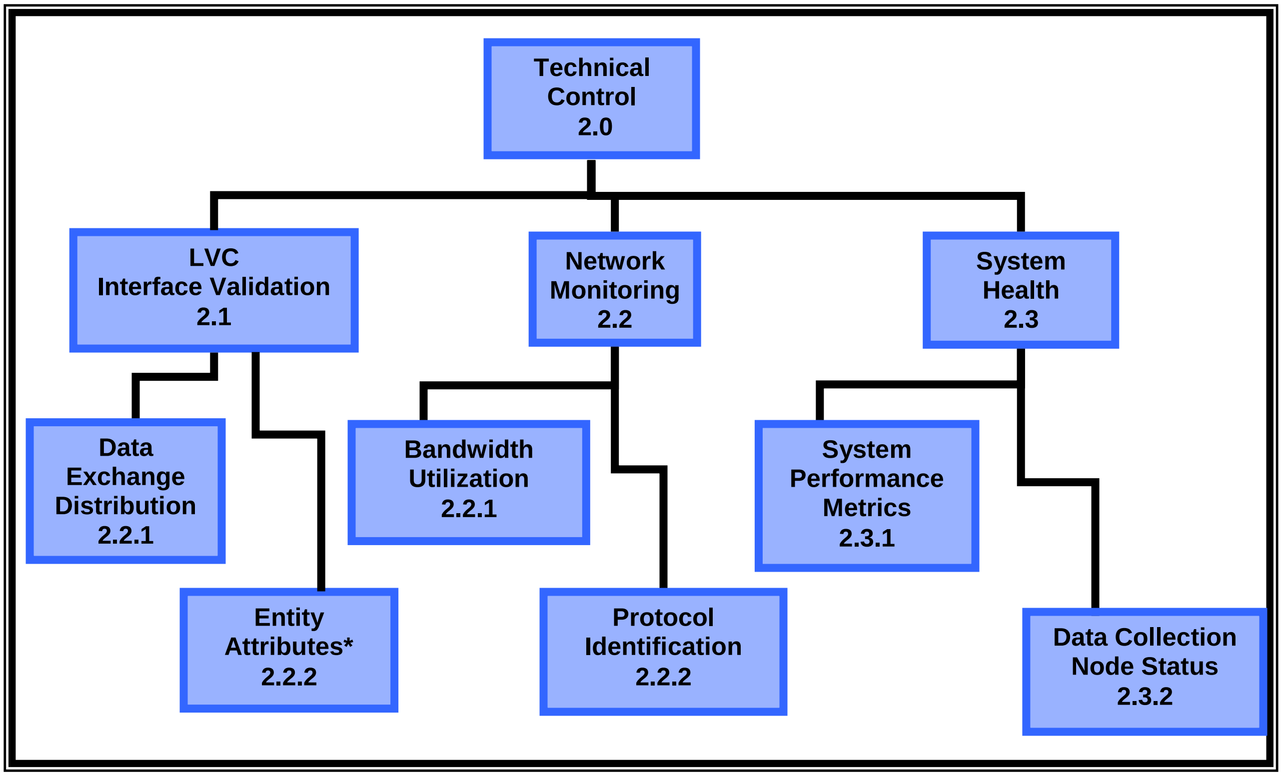

Figure 4. Technical Control Activity Hierarchy.

While perhaps mundane to many readers, the Network Monitoring and System Performance components are just as important to the control of the test support architecture. Monitoring network resources such bandwidth, and identifying the protocols used, are much more easily done graphically—such as is currently done in the commercial sector—when the network is complex and traffic volume is high. (We suspect that this subcomponent might be more finely subdivided in later versions of the architecture, but believe this initial division helps shed light on the tasks that might be performed.) These capabilities allow test teams to understand the status of its network in time to make corrections as necessary—ensuring that data reaches the processing center and simulation information reaches the unit under test. System performance metrics, such as CPU or Memory Utilization, or CPU processing queues, form key indicators of the health of critical nodes, allowing the team to shift processing loads or change collection schemes as required. Data Collection Node Status is the indication of the status (functioning, powered off, in or out of communication) of the various data collection devices in the test. Just as in the case of network monitoring, this is simple to do for a few systems, but very difficult for hundreds or thousands—and again, as is done in the commercial sector, graphical displays facilitate rapid understanding of the situation and help decision-making.

The process of data analysis, already briefly described in Section 1, is shown in Figure 5, below. The two subcomponents, Preliminary Data Analysis and Post Event Data Analysis, roughly correspond to the tasks of the test and the evaluation team in Army operational testing; but more specifically correspond to the immediate steps taken to ensure data quality (Preliminary) and to analyze the data in depth (Post Event). The Quick Look step is taken to ensure the presence of readable data on the media delivered from the test site, and depending on time available may include more in-depth quality checks of the data, such as looking for and analyzing anomalous data values.

Visualization technologies show their great value in the next two steps, Authenticating and Ordering Data. As previously mentioned, the Data Authentication Group or DAG is often confronted with enormous volumes of data, and has little time to perform its work; this challenge is exacerbated by the presence of multi-source data such as from communications logs, video cameras, radar traces, and textual data. It is here that integrated-query technologies, such as the Sensor Data and Analysis Framework described below, are particularly useful: The DAG can rapidly and easily compare data from several sources, bounded by time, position, or both; and can therefore rapidly identify and diagnose apparently anomalous values. Ordering data also shows strong potential for visualization technologies: When the data is purely and obviously only time-ordered, little assistance is necessary, but in today's sophisticated networks this simple case is extremely rare. Visualization of a network topology and its traffic, for instance, supports good decision-making in support of ordering, yielding information on (for instance) which nodes had the highest traffic volumes, which interfaces were the busiest, and so forth. Again, just as is commonly done in the commercial sector this can also assist in troubleshooting slow or otherwise problematic information exchanges—help which can be of great value to the system's project manager or development and engineering teams.

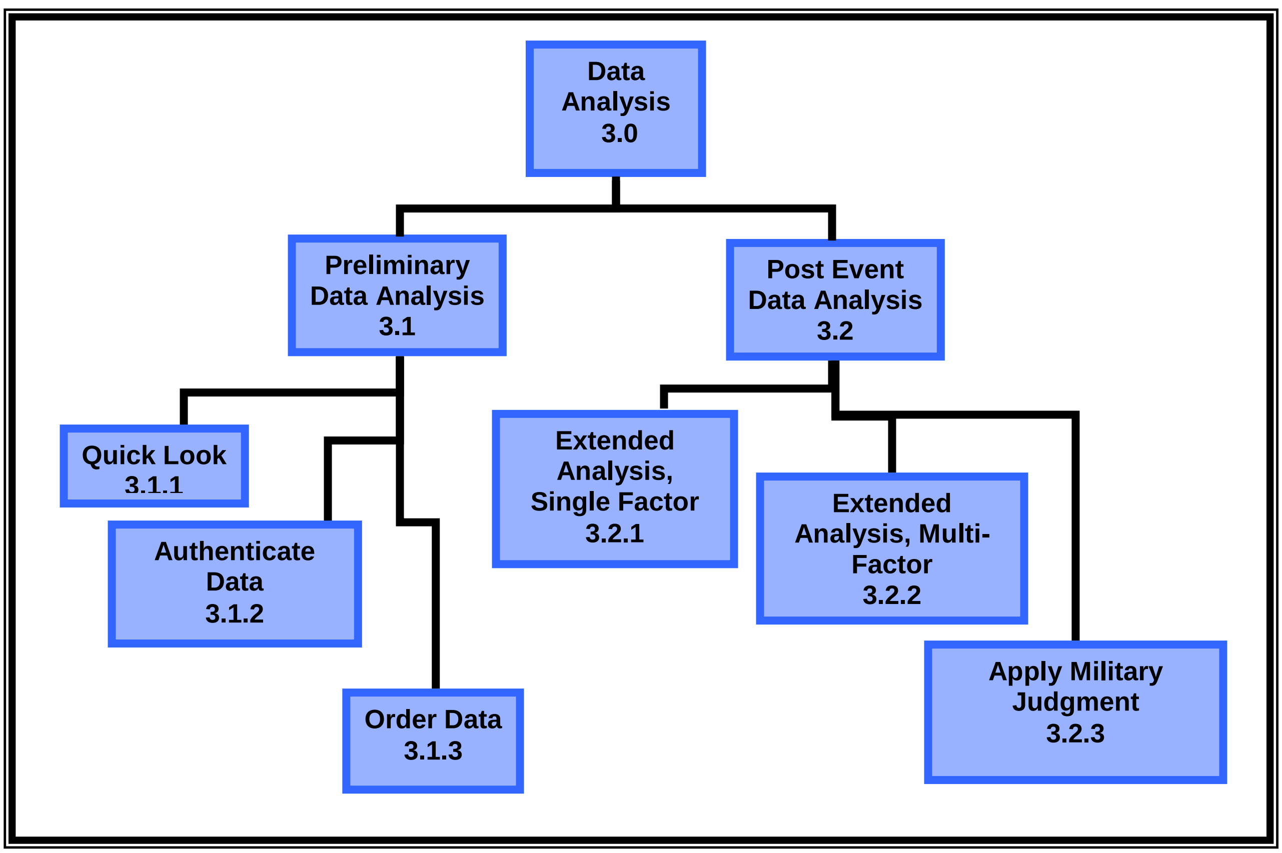

Figure 5. Data Analysis Activity Hierarchy.

Post Event Data Analysis takes an in-depth look at the test data to produce overall results and to arrive at conclusions, such as on the effectiveness or suitability of a given weapons system. Broadly speaking, it can be decomposed into the basic tasks of single- and multi-factor analysis[10], plus the heterogeneous task of applying evaluative military judgment to the analysis results. In all these cases, visualization can assist what would otherwise be a daunting task.

Single-factor analysis, as its name implies, focuses on the effects of a single causative battlefield factor, such as the presence or absence or electronic attack ("jamming"), or the strength of the jamming signal. "Single factor," however, does not mean "simple": This analysis may need to comprehend the effect of that single factor over thousands of battlefield entities, each of which may encounter numerous environmental or potentially confounding factors. Here again, advanced visualization technologies can help the analyst by displaying, for instance, color codes for ranges of attribute values, allowing the analyst to quickly discern patterns in the data which may be related to time, location, or distance from a given emitter.

The presence of other factors of course leads to multi-factor analysis, which extends the task to examine the combined effect of multiple factors, such as weather plus electronic attack, or weather plus electronic attack plus emitter location. Given the great proliferation of potential data sources, and the amount of data they may generate, the analyst is clearly challenged to come to terms with the data he is examining, to say nothing of arriving at and defending his conclusions. Visualization solutions for this process must allow rapid and tailorable queries, facilitating many different explorations of the data and many tests of the analyst's conclusions.

Finally, applying evaluative military judgment may apply the techniques of all the preceding analysis steps as the evaluator checks his analysts' tests and conclusions, and asks for or performs sensitivity analyses. This will place a premium on the ability of visualization solutions to store queries and query results, both within single sources and across multiple sources.

IV. Promising Potential Solutions

Because we are at a very early stage in our journey, it is clear to us that both our requirements and our potential solutions will change significantly over time. Nevertheless, the similarities described above between testing and other problem domains have greatly facilitated our search for promising potential solutions to these challenges. A few of these, chosen for their feature sets which illustrate key parts of the problem and solution domains, are described below.

The Sensor Data and Analysis Framework (SDAF), developed by a team at the MITRE Corporation, offers the unique feature of performing *integrated queries* on both streaming (such as sensor data) and persistent (such as RDBMS) data sources. Based on a service oriented architecture (SOA), SDAF allows the flexible combination of data sources, data operators (such as stream mining algorithms), and various visualization clients. A sketch of the SDAF architecture is shown below at Figure 6.

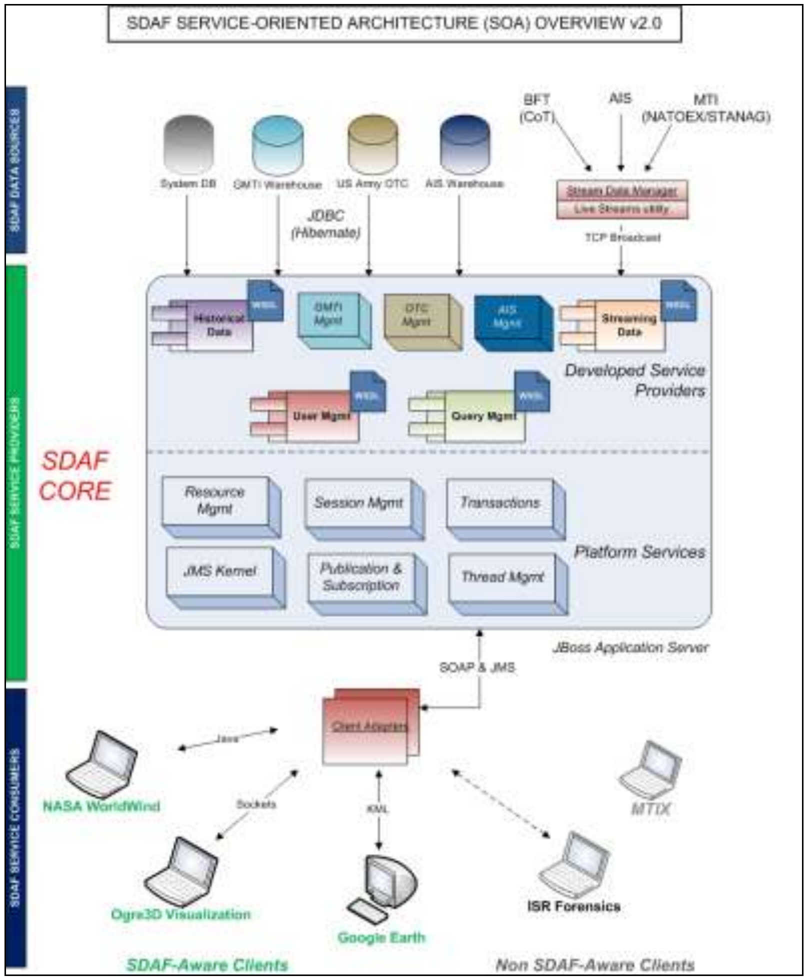

Figure 6. SDAF Architecture.

Notably, SDAF was not developed in response to the needs of testers, but rather in response to the needs of operational intelligence analysts confronted with extremely high-volume data from multiple sources such as ground moving-target indication (GMTI), video, textual reports, and photographs. The Air Force is currently using SDAF for data characterization; OTC is studying its use in both test control and in data analysis functions.

A sample SDAF display, integrating position-location data with real-time casualty assessment (RTCA) data is shown at Figure 7. In this implementation, the analyst can choose any vehicle location from a "snail trail" of its locations over time and be immediately shown all position-location attributes for it (northing and easting grid locations, altitude, and exact time); he or she can then query the RTCA database to find, for instance, all shots taken by or at this vehicle in a tailorable time period, including shooter, target, weapon and ammunition, and engagement result.

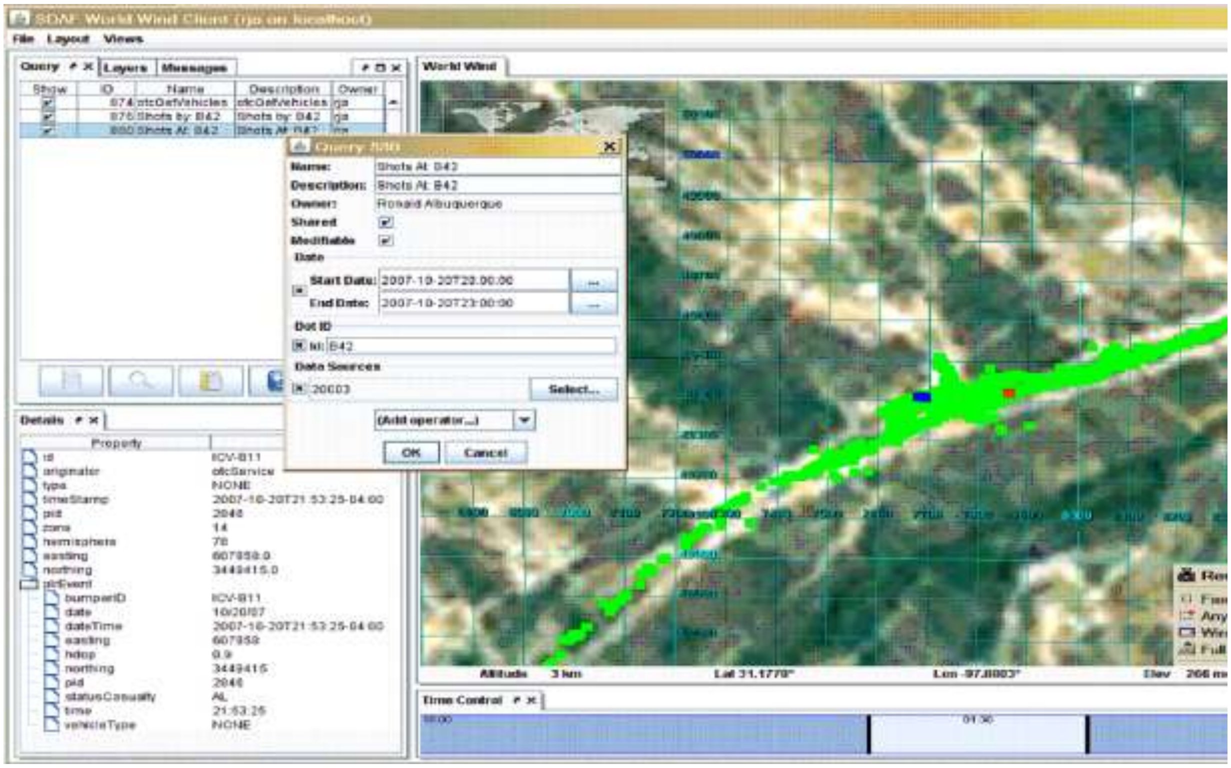

Figure 7. Example SDAF Display.

While the use of SDAF in data analysis would seem fairly obvious, with many possible uses similar to the example above, its potential use as a test control tool requires elaboration. Interviews with test officers[11] indicate that—in addition to the basic requirement to monitor vehicle or personnel locations on a map display—the operational test officer is challenged to monitor and comprehend the detailed status of his data collection, and to compare it against that which the test and evaluation team expects for the event: Are all collection devices working? Are they collecting the desired kinds of data, and are they collecting *enough* data to meet sample size requirements? Given the constantly-increasing costs of military operations, the answers to these last two questions may mean the difference between success and failure for an extremely expensive trial—or may offer the opportunity to terminate the trial early and "give back" valuable time to the test unit commander.

Another tool of note, developed by Texas A&M University under the Army's University XXI research program, emphasizes the development of *visual analytics:*

> …the science of analytical reasoning facilitated by interactive visual interfaces. People use visual analytics tools and techniques to synthesize information and derive insight from massive, dynamic, ambiguous, and often conflicting data; detect the expected and discover the unexpected; provide timely, defensible, and understandable assessments; and communicate assessment effectively for action.[12]

The University XXI visualization tool is based on an interactive software framework capable of interfacing with a variety of data sources, such as relational databases or text files. A sketch of the tool's architecture is shown in Figure . As Figure 8 implies, the tool provides an extensible set of data operators and processing modules, which produce cached intermediate data that can then be interactively explored using various visualization techniques.

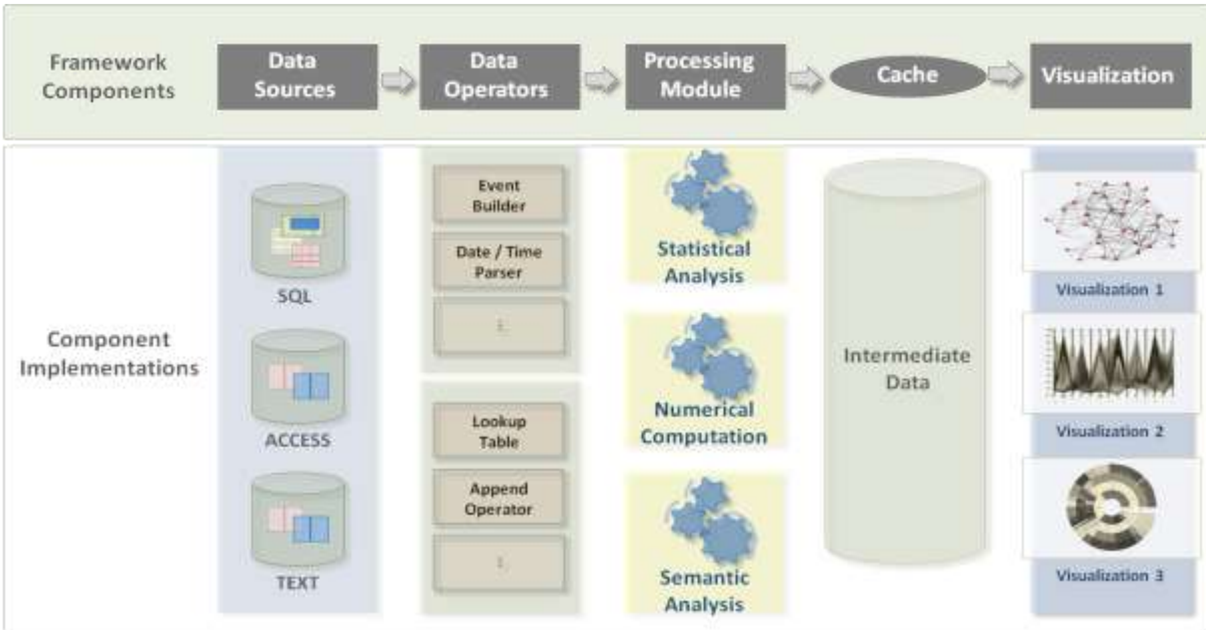

Figure 8. University XXI Data Visualization Architecture.

Of particular note in this effort is the emphasis on a large and growing set of linked visual representations of the data set: As of October 2008, the set included various bar, line, radial axis, parallel axis, frequency, availability, event timeline, and geospatial displays.[13] University XXI researchers are using these and other techniques to explore analysts' comprehension of very large data sets, such as the terabyte-sized database from a recent communications system test, or the results of ground-combat tests involving large numbers of direct-fire engagements. A sample multi-view visualization of a series of information exchanges is shown at Figure 9.

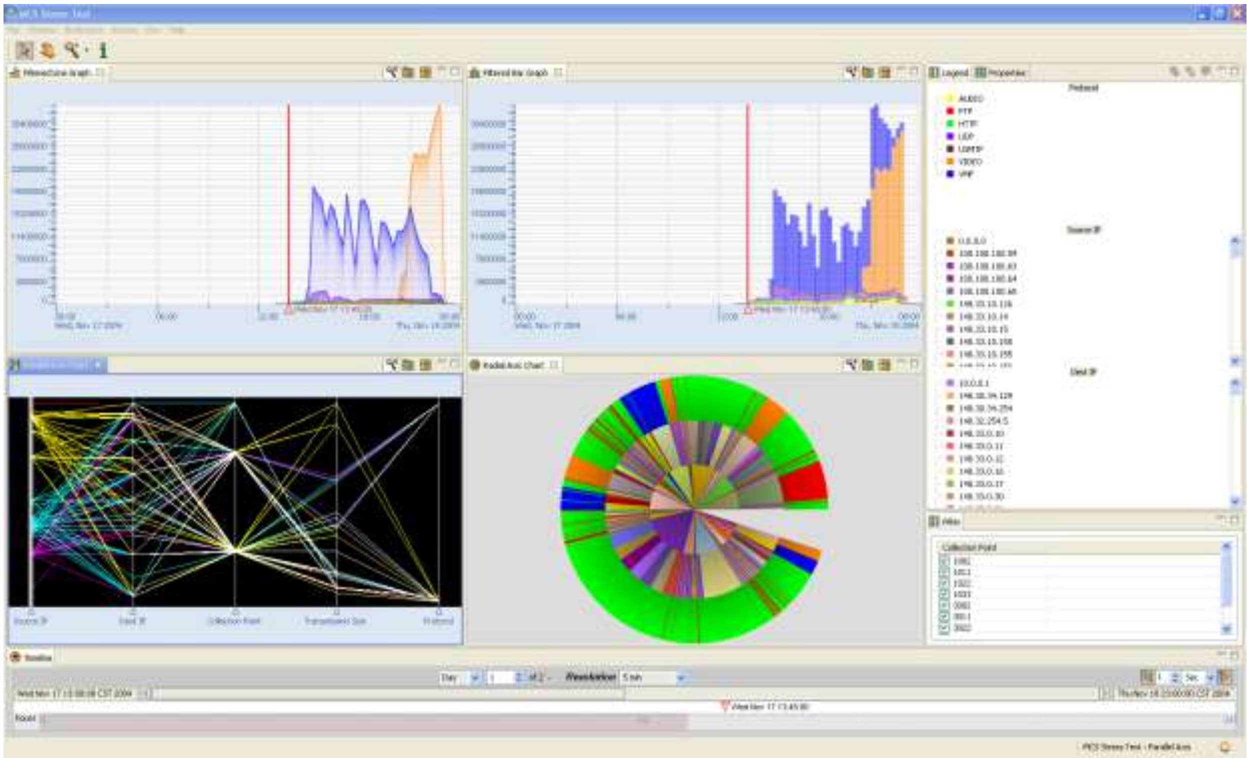

Figure 9. Multi-View Visualization of Communications.

Of particular note in each of these potential solutions is not only the rich visual display of information, but the thoughtful arrangement of features in the user interface so that the analyst can quickly "drill down" on an item of interest to reveal the data underneath.[14] The SDAF team, for instance, built a visualization of a ground-combat test integrating position-location data, RTCA data, reliability, availability, and maintainability (RAM) data, and textual observations; all data was accessible in seconds via a few computer mouse clicks that tailored queries by data type, by location, and by time window. By contrast, analysts are rightfully dissatisfied with solutions that provide only a bare visual representation of, say, entity locations over time with no access to the huge volume of relevant data associated with them.[15]

V. Conclusion.

We have seen how the great complexity of today's military operations is reflected in the increasing complexity of the operational testing environment, where the tester is confronted with extremely high-volume data of numerous and disparate types. Visualization technologies and techniques are not merely interesting – they are crucial for the rapid comprehension of this new environment of extreme complexity. While traditional analysis methods appear to have reached the limits of their effectiveness in this new regime, technologies developed both within and outside of the operational test domain offer great promise, and illustrate feature sets that inform the issue. We believe our beginnings of an operational architecture, and the initial requirements we are developing from it, are necessary initial steps to choosing the right solutions—and we invite comments and input from other practitioners! The conclusion is just the beginning of the

Visualization IPT effort and while our IPT has taken some important initial steps, they are just that—initial steps. We have a long yet fascinating journey ahead.

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[1] Dean Leffingwell and Don Widrig, *Managing Software Requirements: A Unified Approach*, Boston: Addison-Wesley, 2000, p. 32.
[2] Many readers will easily recognize the visualization techniques and technologies in use by operational units through such systems as Force XXI Battle Command Brigade and Below (FBCB2), which shows a map display of friendly and reported enemy locations; Command Post of the Future (CPOF), which can show highly detailed, three-dimensional geospatial intelligence data; or the network topology displays of commercial monitoring tools such as WhatsUpGold™.
[3] The OTC simulation federation has demonstrated, for instance, the ability to perform engagements between "test players" in live and constructive simulations, enforcing a requirement for network connectivity among all the players—hence a requirement to establish and maintain radio links with the live players.
[4] Conversation between the authors and the Future Combat System (FCS) OTC Test Officer, Mr. Joseph Lucidi, February 26, 2008. Mr. Lucidi emphasized the challenge of being able to monitor data collection in near real time, such that the tester can understand his progress towards collecting the data required for any given test. Hereinafter cited as "Lucidi interview."
[5] US Army Operational Test Command Test Officers' Procedures Manual (TOPM) 73-301, Data Authentication Group, November 2003, Appendix B, Figure B-1, page B-2, describes the "levels" of data from a test ranging from Level 1 (raw data) to Level 7 (Conclusions), and the procedures (such as "applying evaluative military judgment") to arrive at them. The tasks shown here are those that the authors estimate are most amenable to visualization support. Hereinafter referred to as "TOPM 73-301."
[6] Ibid.
[7] For instance, the Joint Network Node (JNN) Initial Operational Test in 2006 produced over 5 terabytes (TB) of network traffic data.
[8] TOPM 73-301.
[9] DoD Architecture Framework, Version 1.5, 23 April 2007, Volume II, page 4-40 describes the OV-5, its possible formats, and the benefits and drawbacks of each.
[10] TOPM 73-301 briefly describes possible methods of single- and multi-factor analysis—but having been written before the advent of extremely high data volumes, and before sophisticated visualization means were available, it is silent on any detailed methods for performing these steps under current conditions.
[11] Lucidi interview.
[12] J. J. Thomas and K. A. Cook. *Illuminating the Path: The Research and Development Agenda for Visual Analytics*: IEEE, 2005.
[13] University XXI Data Visualization Tool Information Briefing, Texas A&M University, October 22, 2008.
[14] Edward Tufte, in his classic *Visual Explanations* (Graphics Press, Cheshire, CT, 1997) makes the point (p. 45) that all information ("all observations for all variables…") should be available to the analytical audience. This of course becomes extremely difficult as data volumes explode, and sources and formats proliferate. Hence, the ability to rapidly query all available data with differing query parameters becomes indispensible to the analyst of today's extremely large data sets.
[15] Interview by the authors with Mr. Sid Fincher and Mr. John Fuller of the OTC FCS test team, April 8, 2008.