Risk Mitigation with Tailored System Testing Following Subsystem Modifications

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Executive Summary

When end-to-end system testing (in the case of a defense system, a missile launch for example) is not feasible following subsystem upgrades, tailored system testing is a cost-effective alternative that can reduce the risk of system problems. Tailored system testing exercises the delivered system in an environment representative of normal operations, while operated by trained end users, and emphasizes specific areas of the system (including the interfaces between subsystems) that have been affected by the subsystem changes. Use of real-time monitoring tools during the tailored testing provides the ability to assess satisfactory test completion and supports problem investigation.

This paper demonstrates how tailored system testing, including on-board real-time evaluation of test results, enabled the Director, Strategic Systems Programs (DIRSSP), to significantly reduce the risk of system problems following subsystem changes. It also describes how this low cost concept forms DIRSSP's baseline testing concept for new systems.

Motivation

The Trident submarine-launched ballistic missile system is deployed on USS *Ohio* class ballistic missile submarines (SSBN). Weapon system development, under the cognizance of DIRSSP, focused on creating a highly reliable system with sufficient accuracy to meet specified objectives. A key strategy in meeting this development objective was to include dual redundant equipment for many of the critical system components. The Trident program managers have also, from the beginning, required the existence of a sophisticated test and evaluation program to verify that the asset will meet the design objectives and to validate that the deployed fleet continues to meet the reliability and accuracy objectives over its deployed life, even after significant weapon system and subsystem upgrades. One part of the test and evaluation program includes a fully instrumented system design. This instrumented system allows not only complete post-mission evaluation of system performance, but also the potential for real-time monitoring during system operation.

Historically, the Trident test and evaluation program has included missile ground tests, subsystem laboratory and at-sea tests, and system testing in the operational environment up to and including end-to-end testing of system capability via a missile launch. Missile launches were conducted following major system upgrades and in support of ongoing performance evaluation via random sampling.

overall 205a
2046 - passive sensor VLF
UK Survey Vessel
Uses US Data Reduced System (DRS)
VAr - sonar 2043 - active
2082 - passive inband, hydrophone
p/a tilt
Navradar - Type 1007 tactical display

As part of the continuing validation of capability, following each patrol, refit, and test launch, the Johns Hopkins University Applied Physics Laboratory (JHU/APL) evaluates weapon system performance and reports to DIRSSP. The report contains recommended corrective actions to resolve any identified individual ship or design problems. However, data delivery and evaluation can take from three to six weeks, sometimes preventing a response from getting to an SSBN before the ship departs for the next patrol. Limited scope testing is conducted by the crew and shore support during routine maintenance periods. However, this testing is designed to verify continued satisfactory operation of deployed systems; it is not designed to identify all types of potential problems that could occur after a system change. Thus, the routine ongoing system test and evaluation process cannot provide timely detection of problems incurred following equipment upgrades installed during maintenance periods or help correct these problems before the next deployment.

Because of these limitations, following major system upgrades of the past, each asset underwent a system certification process, including missile launch, to ensure that the weapon system would continue to meet its objectives. This process (shipyard upgrade, followed by certification, including launch) is very expensive both in cost and in loss of deployable asset availability. Therefore, instead of major system overhauls, the Navy has transitioned to non-synchronously upgrading subsystems of the weapon system. These upgrades are installed in the standard or slightly lengthened refit periods without use of the shipyard.

Since initial deployment in 1982, equipment aging and obsolescence have increased maintenance costs and the potential for degraded system performance. Equipment and software modernization is needed to lower life cycle costs by reducing maintenance cost with relatively small capital cost components. Modernization also alleviates the current reliance on redundant equipment, thus maintaining the safety factor provided by the dual redundant design and reducing the risk of performance degradation.

Many of the subsystem upgrades are the result of technology improvements and the transition of previously specialized technologies to commercial-off-the-shelf equipment and/or software. However, because commercial-off-the-shelf equipment typically has a shorter life and more rapidly becomes obsolete than custom-designed military equipment, equipment refreshment will be required more frequently than in the past.

Because the upgrades are conducted on smaller parts of the weapon system and there is a need to maximize deployable asset availability, system testing was not initially considered necessary or cost-effective. Instead, the Navy initially planned to rely on comprehensive subsystem testing in the laboratory and on-board an at-sea non-submarine test platform, with limited on-submarine testing. However, DIRSSP soon recognized the need for more extensive pre-deployment testing on SSBNs, including extensive testing of the subsystem interfaces with one another and the interfaces between the weapon system and other support systems. These areas are difficult to fully exercise in the laboratory environment, and simulation of some subsystems is required. The subsystem laboratory and non-submarine test facilities cannot fully replicate at-sea submarine conditions with 3-D underwater motion. And significantly, by requiring more extensive shipboard testing and evaluation, DIRSSP was able to assess many of the major

"…ilities," the ability of the SSBN crews to effectively operate, maintain, and repair the upgraded system in its deployed environment.

One historical example that illustrated how a lack of system testing resulted in undetected problems remaining until system deployment is the replacement of electromechanical gear trains with electronic circuit cards in the electromagnetic log. The electromagnetic log, external to the weapon system, provides ship's speed to the inertial navigation system, which uses it as a velocity damping reference to help control velocity errors. Without the electromagnetic log reference signal, inertial navigation system velocity errors would grow unacceptably large. Ship's speed from the electromagnetic log is provided to the strategic navigation subsystem by the command and control system. Due to obsolescence and climbing maintenance costs (in the form of frequency and difficulty of repair and replacement part cost) a form, fit, and function replacement was developed for the electromagnetic log. The interface between the command and control system and the navigation subsystem was not being changed by the electromagnetic log upgrade and therefore, there was no anticipated impact on weapon system operation due to the replacement.

However, because the command and control system to navigation subsystem interface is simulated in laboratory testing, it could not be tested in reality until the new equipment was installed on an SSBN. When the new electromagnetic logs were installed on several SSBNs, problems were discovered; some of the problems were not identified or resolved for several months. The types of problems observed included loss of data inputs under various navigation subsystem and command and control system configurations, poor calibration results, and unexpected sudden degraded performance. Tailored system testing, including evaluation of data transmitted from the electromagnetic log to the navigation subsystem under various command and control system and navigation subsystem configurations, would have identified the configuration problems. Comparisons of electromagnetic log and inertial navigation system data during testing would have identified the anomalous electromagnetic log performance and highlighted the lack of insight into the internal electromagnetic log calibration data.

Although DIRSSP was convinced that more extensive system testing was needed before other subsystem upgrades were deployed, complete end-to-end system testing following upgrades of individual subsystem components was still too expensive and time-consuming. In addition to the missile and range costs, deployable asset unavailability results in increased operational tempo for the other fleet units, which may not be permissible. Consequently, a lower cost alternative was needed to reduce the risk of deploying an asset with an underlying system problem – tailored system testing is one alternative.

Tailored System Testing Concept

The tailored system testing concept uses system level tests, limited to areas of the weapon system affected by the subsystem changes, to verify that system performance has not been degraded by the changes. Specific areas that are targeted include the changed subsystem, its interfaces with other subsystems and external systems, and any other subsystems and external systems that have cause/effect relationships with the changed subsystem. Key considerations that need to be addressed when developing the tailored system test plan include whether the test should be

conducted in the operational environment and whether the test should be conducted by trained end users with tactical procedures.

Test success includes not only correct system operation, but also appropriate system response to configuration changes and inserted casualties. Satisfactory test completion is determined by real-time observation of system indications and analysis of data acquired with onboard analysis tools. Use of onboard real-time monitoring tools supports problem investigation in addition to providing the ability to assess satisfactory test completion.

Part I: Test Design

Step 1: Know what subsystem changes are being made.

Step 2: Use system knowledge to assess potential system effects.

Sufficient system knowledge and understanding of the subsystem changes are required to identify which critical weapon system functions need to be tested and evaluated following subsystem changes; subtleties may exist. For example, missile launch is not required to verify that the navigation subsystem continues to send valid ship's position, velocity and attitude data to the fire control subsystem following a navigation subsystem upgrade. Missile and launcher system performance will not be affected by the change; however, simply verifying that the position, velocity, and attitude data are correctly passed to the fire control system may be insufficient. A weapon system test verifying that the missile guidance system can be properly initialized to the transmitted navigation data will provide a better check that no problems exist.

Step 3: Develop limited scope test plans targeting areas of potential effects.

In addition to identifying which critical functions need to be tested following a subsystem upgrade, it is important to consider how the system is operated during the system testing. Specialists, either contractors or navy personnel from the naval support commands, have an expertise that may allow them to successfully operate the system in spite of underlying faults in documentation, navy formal training, or the human-machine interface. When considering system performance as whole, these three factors are important and can only be tested by the crewmembers trained to operate the system when deployed. Observations can then be made regarding the ease or difficulty with which the sailors conduct routine and maintenance evolutions using standard operating procedures.

In addition to having trained crewmembers conduct standard operating procedures for system testing, it is also important to operate the system in the same environment that will be encountered when the asset is deployed. For the Trident Weapon System installed on-board submarines, the unique features of the operating environment include dynamic operations in three dimensions. Some problems may only be identified if the system is stressed while the ship is submerged or changing depth; moored or surfaced operations may be insufficient.

Another important aspect of tailored system testing includes verification of proper system response during and following configuration changes and inserted casualties. If system faults

never occurred, it would be sufficient to test only the primary configuration. However, faults do occur, and redundancy and reconfiguration have been designed into the system to allow maintenance of weapon system availability in spite of occasional faults. Testing for satisfactory system operation includes checking the system redundancies. A minor fault can become serious when the secondary configuration is needed but cannot support the mission. Testing the system response to inserted casualties verifies that the proper indications are available to the operator, allowing him to take the necessary corrective actions, if any.

For the Trident Weapon System, the ongoing performance evaluation process has led to the implementation of numerous weapon system tests that are conducted routinely while the ship is deployed. This suite of tests verifies proper operation of most of the system's critical functions. Consequently, during tailored system testing following subsystem upgrade, these standard operating procedures can be employed in various ways to check the critical functions relevant to the upgrade.

When the standard operating procedures do not include a test of a specific critical function relevant to a subsystem upgrade, special tests can be developed to target the specific subsystem interfaces and functions affected by the upgrade. If possible, special tests should employ the standard operating procedures or use the same format and vocabulary to simplify conduct by the crew.

The following three examples illustrate how tailored system testing, targeting the specific areas of potential impact, reduced the risk of redeploying a ship with an undetected problem. In each case, JHU/APL systems engineers used on-board real-time analysis tools during testing and identified problems. Problem identification during testing led to problem resolution before deployment.

- During a navigation subsystem change, the velocity sonar system was upgraded, including replacement of obsolete equipment and re-hosting of software on a new platform. Use of the velocity sonar system was included in system testing following upgrade installation and its output was evaluated. One advertised improvement was the capability to change the operating mode of the inertial navigation system while velocity sonar system operations were in progress. However, during system testing, evaluation of the velocity sonar system output led to the determination that the velocity sonar system did not successfully transition through an inertial navigation system operating mode change, resulting in erroneous velocity corrections being transmitted to the fire control system.

- During the same upgrade, the inertial navigation system software was also re-hosted on a new platform. Consequently, use of the inertial navigation system was also included in system testing following upgrade installation and its output was evaluated. During system testing, DIRSSP identified that an error had been introduced in the inertial navigation system reaction to changes in the timing reference signal. When the timing reference signal source was changed, the inertial navigation system would develop a large velocity output disturbance that damped to an offset in longitude output.

- Following an upgrade to navigation subsystem equipment and software, including the equipment that transmits data to and receives data from the command and control system, the test procedure directed configuration changes on both sides of the navigation to command and control system interface. When the command and control system was configured with a particular interface unit selected to transmit ship's speed, depth, and heading to the navigation subsystem, ship's speed was not provided. Although this problem would have been detected whenever this system configuration was employed, this configuration is not necessarily used when the command and control system has not been modified during a refit, as in this case. Had the interface reconfiguration not been included in the system testing following the navigation subsystem change, the problem would not likely have been detected until a later failure caused this configuration to be required. Underway, this dual failure condition would have prevented accurate inertial navigation system output.

Step 4: Conduct the test.

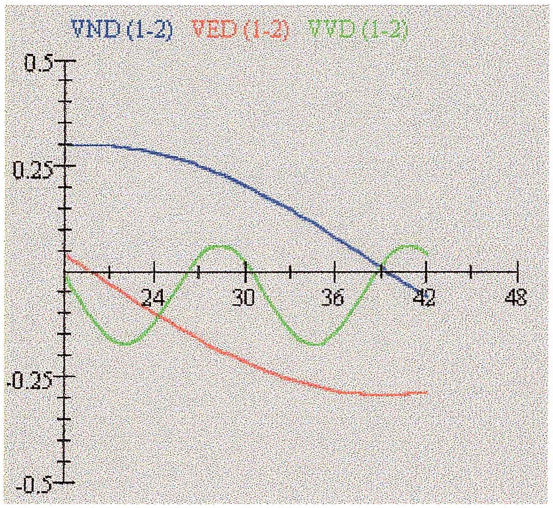
Part II: Real-Time Evaluation

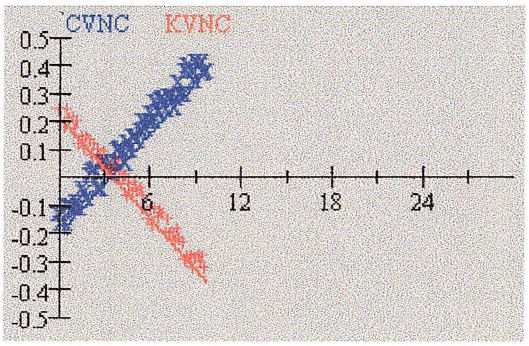
Step 5: Observe system indications and displays of onboard real-time evaluation tools to assess satisfactory test completion and test success.

Step 6: If necessary, modify test procedure and re-conduct test based on evaluation results.

Although conduct of system testing alone is sufficient to identify system problems that were introduced by subsystem changes, it may not allow problem identification and resolution within the desired response time. On-board real-time special test equipment allows insight into subsystem and interface functions to provide rapid response to detected faults. After the fault is detected, it is often possible in real time to identify the appropriate corrective action or procedural work around. If necessary, the test procedure can be modified in real time based on the evaluation results to allow continued testing in spite of identified problems. Absent this capability, a problem may not be identified until on-board data recording system data are offloaded, processed, and analyzed. Even if the critical function is visible to the operator, system testing may not be able to identify the cause of the fault and the appropriate corrective action until the data are offloaded and analyzed.

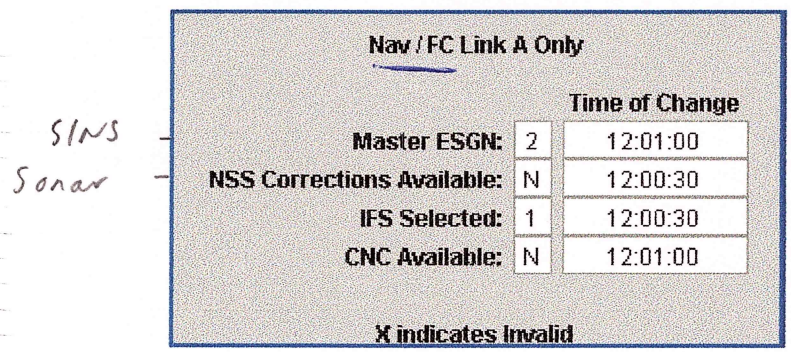
As with tailoring the system tests to target specific critical functions, the on-board real-time analysis tools must be carefully designed, targeting the same critical functions. The tools must provide sufficient information in an appropriate format such that the analyst can quickly determine whether or not the system is working as designed and, if not, sufficient analysis tools and data access to analyze the fault. Flexible data access and display capability allow the analyst to tailor the evaluation process based on test results. The following two figures illustrate monitoring displays used for real-time evaluation of five specific critical functions of the Trident navigation subsystem during tailored system testing. As the data are plotted in real-time, any anomalies in functional output are immediately identifiable by the analyst. Identification of anomalies would then lead the analyst to investigate other related functions with a common plotting software package.





Smart software design begins with existing system performance evaluation techniques, modified to provide quick answers to question about the readiness of the weapon system for deployment. As with tailored system tests, on-board evaluation tools target the critical functions with the potential to have been affected by the known subsystem changes. However, because it is cost prohibitive to redesign the evaluation software for each subsequent subsystem upgrade, it is best to include in the initial software build all the critical functions; each could be affected in future system changes. By providing the complete set of critical functions, the analyst has the flexibility to use the same software for multiple subsystem upgrades.

For real-time system evaluation, the method of displaying the critical function data is very important. Plots updated as the test progresses show not only that the function is successfully being generated and transmitted, but also that its underlying structure is as expected from system design. Displays of event data and system configuration provide real-time indications when specific events or configuration changes occurred. Event timing can then be verified against system design. The following two figures illustrate configuration displays used during real-time evaluation of the Trident navigation subsystem during tailored system testing. In addition to the real-time plots of critical functions and displays of configuration and events, it is useful to have additional non-critical functions and plotting software available to allow additional investigation should an anomaly be detected.

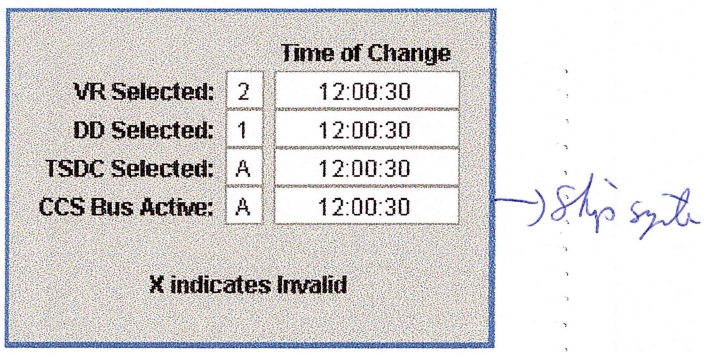


Nav / FC Link A Only

		Time of Change
Master ESGN:	2	12:01:00
NSS Corrections Available:	N	12:00:30
IFS Selected:	1	12:00:30
CNC Available:	N	12:01:00

X indicates Invalid

SINS
Sonar



		Time of Change
VR Selected:	2	12:00:30
DD Selected:	1	12:00:30
TSDC Selected:	A	12:00:30
CCS Bus Active:	A	12:00:30

X indicates Invalid

→ Ship's syste

The following three paragraphs provide examples of Trident critical functions targeted by JHU/APL on-board real-time evaluation tools.

- The primary role of the navigation subsystem is to provide accurate ship's position, velocity, and attitude to the fire control and missile guidance subsystems. Accurate inertial navigation system output and the appropriate responses by the fire control and missile guidance subsystems are vital to the successful employment of the weapon system. Consequently, inertial navigation system output is evaluated in real time during system testing to verify that the output is accurate. It is also evaluated to determine whether any fault indications received are caused by erroneous inertial navigation system output or by fire control or missile guidance subsystem response.

- Because inertial navigation system velocity accuracy generally does not meet the strict accuracy objectives of the Trident Weapon System, the velocity sonar system must provide accurate velocity corrections to the inertial navigation system velocity output. Satisfactory velocity sonar system output is evaluated to verify that weapon system accuracy is not degraded as a result of errors in the velocity sonar system, its data inputs, or its interfaces with the rest of the navigation subsystem. A secondary reason that both the inertial navigation system and the velocity sonar system outputs are checked is that during routine subsystem operations, both systems provide relatively little insight to the operator regarding whether their outputs are accurate.

part of NSS

- Because of the reasons provided above, the functions transmitted across the subsystem interfaces and between the weapon system and support systems are evaluated. Also as described above, the subsystem changes are frequently well tested; it is the inability of these system interfaces to be tested in the laboratory that provides the greatest risk of undetected problems. When these interfaces are tested, the analyst closely evaluates the critical signals passing between systems.

The following is one example that illustrates that system testing must be coupled with sufficient real-time evaluation tools. During the predeployment system test program, inertial navigation system velocity errors of a size unacceptable to the missile guidance system spin-up process resulted in spin-up failure indications at the fire control console without a problem indication at the navigation console. The problem was thoroughly investigated, the underlying cause found, and a navigation software revision was later generated, preventing this type of problem from recurring during deployed operations. However, this could not be accomplished within the allotted missile launch window. The launch had to be delayed until a temporary work-around could be identified. Had the appropriate real-time evaluation tools been on-board when the problem first occurred, system reconfiguration could have been directed and would have allowed the launch to proceed.

i.e. guidance requires vel data

Universal Applicability

Although the examples described above are taken from Trident navigation subsystem experience, the concepts described are applicable to system testing following upgrades to any subsystem of any system. This tailored system test and evaluation approach has been so successful during

upgrades to the Trident Weapon System that the approach is being applied to the system test and evaluation process used in the development of the Tomahawk Attack Weapon System of the USS *Ohio* class guided missile submarines (SSGN).

Conclusions

Reduced funding for end-to-end system testing has resulted in an increased risk that a system problem created by a subsystem upgrade may go undetected until the system is supporting its primary mission. Tailored system testing and real-time evaluation, targeting the critical functions potentially affected by the subsystem upgrade, can reduce this risk at lower cost than complete end-to-end system testing with missile launch. This process has been used successfully in the test and evaluation of the Trident Weapon System and is being applied to the SSGN Tomahawk Attack Weapon System.

Author Biography

Brant D. Palmquist received B.S. degrees in Physics and Mechanical Engineering from the University of Illinois in 1997, and a M.E. in Mechanical Engineering from The Johns Hopkins University in 2002. Since 1997, he has conducted systems engineering and analysis for The Johns Hopkins University Applied Physics Laboratory.