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Recent Results from the Spacecraft Fabrication and Test MODIL*

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Abstract

The Spacecraft Fabrication and Test Manufacturing Operations Development and Integration Laboratory (SF&T MODIL) is working with SDIO program offices and contractors to reduce schedule and budget risks for SDIO systems as they go into production. The concurrent engineering thrust has identified potential high payoff areas. A materials and structures demonstration project has been successfully completed in partial automated closing of matched metal molds for a continuous fiber composite. In addition to excellent accuracy, the parts demonstrated excellent predictability and repeatability of physical properties. The cryocooler thrust successfully demonstrated and inserted precision technologies into a generic cryocooler part. The precision technologies thrust outlined two potentially high payoff areas in precision alignment and miniature rocket thrust measurement. The Producing Technology Working Group (PTWG) efforts identified the need for a test and assembly thrust. Due to funding limitations, continuing efforts are limited to the cryocooler thrust.

1. Introduction

1.1 Background

The Spacecraft and Fabrication (SF&T) MODIL (Manufacturing Operations Development and Integration Laboratory) was initiated in December 1991 under funding from the Department of Defense.¹ There are now four MODILs as listed in Table 1 which are under the direction of Mr. Greg Stottlemeyer of SDIO.

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Table 1.
Current MODILs

MODIL Name	Integrator	Leader
Electronics and Sensors	Sandia National Laboratory	Peter Winokur
Optics	Oak Ridge National Laboratory	Brigham Thomas
Software	National Institute of Standards and Technology	Arnold Johnston
Spacecraft Fabrication & Test	Lawrence Livermore National Laboratory	Ted Saito

The SF&T MODIL is off to a good start to achieve its objective of establishing a producibility culture in the spacecraft fabrication community. The SF&T MODIL has been organized into five thrust areas:

- Automated Spacecraft & Assembly Project (ASAP)²
- Materials and Structures³
- Cryocoolers⁴
- Precision Technologies
- Assembly & Test.

1.2 Demonstration Projects

An early goal was set to show potential payoff and if possible feasibility at small scale through a demonstration project. Demonstration projects were designed to cost less than a few \$100K and last about a half year or less. Close coordination with the potential producer (contractor) and program office was also desirable. These projects also helped fulfill the general SDIO guideline that approximately half the MODIL funding was to be expended outside of the integrator.

This paper will describe the progress of each thrust since the last paper¹, the Producible Technology Working Group (PTWG) process, and our successful first briefing to industry. Due to a funding cut in the first

quarter of FY93, the current scope of activities are focused on the cryocooler efforts.

2.0 Automated Spacecraft & Assembly Project (ASAP)

The ASAP thrust is led by Dave Sanders. ASAP is studying the potential for leveraging "soft" (computer-based) technologies in spacecraft manufacturing, because above-the-shop-floor costs typically account for 40 to 70% of the total costs of manufacturing. Last year we reported that our preliminary survey of soft technologies of above-the-shop-floor operations identified the areas which show a significant potential benefit in cost and time savings for SDIO spacecraft fabrication and test.²

The ASAP demonstration projects were contracts with all contenders for the Brilliant Eyes Program. The contractors provided, on a proprietary basis, a snapshot of their current status of Integrated Product Development (IPD) or Concurrent Engineering (CE) in the prime contractor community. The participants in this effort are Lockheed, Martin Marietta, Rockwell, and TRW. The contracts also pay for time for contractor employees to be interviewed by the ASAP team, as well as the time necessary to prepare a final report.

Concurrent with the information gathering contracts, ASAP formed an Industrial Working Group with representatives from the previously mentioned contractors and appropriate government agencies. The response to this group was quite positive, especially at the SF&T MODIL industrial briefing.

The three areas which were being explored were a "Virtual Factory" for the manufacture of spacecraft, an "Interoperability Testing Laboratory" for design and manufacturing software, and "Infrastructure Enhancements" to facilitate the practice of IPD in SDI systems. The ASAP team made progress towards defining all three of these areas and establishing a basis to determine the cost/benefit ratio for each.

Although the specific results of the demonstration project are proprietary, several important observations resulted. There is significant interest in establishing a concurrent engineering atmosphere, both by the SDIO program offices and the contractors. The costs to establish the concurrent atmosphere hinder management decisions for investments to establish IPD, because of the major uncertainties of SDIO's future. Completion or termination of a program results in major shifts of personnel for a contractor. Departure of experienced personnel often means the loss of understanding and expertise which would have remained had an effective IPD been in place. This was another sincere reason why contractors wanted to expedite the establishment of IPD. The down sizing of the defense industries is therefore another reason to implement an IPD atmosphere, so as to minimize the loss of expertise.

After the funding cut, ASAP investigated the possibility of applying the lessons learned from the demonstration projects and earlier work to the cryocooler. It appears that notable contributions can be achieved by creating an IPD atmosphere for a cryocooler demonstration project. The IPD approach would be used for a cryocooler project in such a way as to create and demonstrate a methodology for producing moderate numbers of cryocoolers. This methodology could then be a model for other spacecraft subsystems and would serve as a building block in establishing a producibility culture in the spacecraft fabrication community.

3.0 Materials and Structures³

The Materials and Structures thrust is led by Gordon Spellman. The demonstration project was a six-month contract "Partial Automation of Matched Metal Net Shape Molding of Continuous Fiber Composites" with Sparta Corporation. This contract covered the design, construction, and demonstration of the partial automation of a novel composites fabrication process. The process allows for near net shape fabrication of complex structures from continuous fiber, organic matrix composites. The

objective was to demonstrate the key element of the automation process which was the closure of the matched metal tooling to hard stops with a fully automatic process cycle. Since this process was partially developed by SDIO's Key Technology (now IS&T), this project also gave us the opportunity to leverage previous SDIO advances.

A part was selected which would be of generic interest to the SDIO community. It was a 9" diameter, 10" high thin-wall cylinder with a high quantity of unidirectional plies oriented along the cylinder axis.

Tooling was designed to lead to automated production. The prior mode of closure used no manually operable elements. The tooling mated to a concurrently developed hydraulic closure machine which was funded through the contractors IRAD.

An iterative process was planned for the process development. The mechanical and thermal cycle times were determined from experience and experimentation. The development proceeded rapidly and, in fact, the first part produced was very successfully used in the program test phase. However, the process was not optimized for considerations beyond part performance; but even so, the production process from start to finish, including pre-consolidation, can be completed in one shift.

Twenty demonstration parts were produced. The parts are of high quality both visually and dimensionally. Some test results, discussed below, indicate that the production run is producing parts with performance virtually identical to predictions and with exceptional repeatability.

Visual inspection of the parts was very encouraging indicating high quality. Initial indications are that dimensions are all within the specification of the Statement of Work with the exception of the diameter. The diameter is small by 0.008" due to errors in tool design. This is the type of error which should be minimized by thorough process knowledge

and control. Variations in wall thickness are about 1.5 mils, and the radius varies about +/- 4 mils on a 4.5" radius.

Parts were tested to failure in tension and in compression. The moduli in tension were 15.5, 15.5 and 16.2 MSI, and in compression they were 12.9 and 13.2 MSI. Two of the tensile specimens failed in the fixturing at a point about 75% of ultimate, and the one component failed at an ultimate stress of 140,000 PSI which is essentially the same as the predicted value. The compressive failure stresses were 39 and 44 KSI and the mode was buckling. The main results to date are predictability and repeatability which are very high for these components. The MODIL believes this is a key feature of this type of automated process.

The program has resulted in a proof of concept of the automation of a process with a high potential for production of quality composite components at a reasonable cost. The MODIL hopes to demonstrate this process on an actual limited production run.

4.0 Cryocooler Thrust⁴

The Cryocooler thrust results are given in detail in the accompanying paper co-authored by the thrust leader Gill Cruz.⁵ Therefore, it will only be summarized here.

The Cryocooler Producibility Demonstration Project was established to demonstrate the need for cryocooler designers and manufacturers to concurrently interact with one another in the initial stages of the design process. The project is designed to demonstrate the cost and effect of producing components that were initially designed with minimal producibility issues taken into account.

The project focused on a generic component with a geometry which had a producibility issue common to all cryocoolers. The geometry was a thin-to-thick wall transition that required precision tolerances. The objective was to develop a production process that would be developed, in

real time, with the selected cryocooler manufacturer's suppliers. Our objective was accomplished at both LLNL and Modern Industries (with Hughes Aircraft) in Phoenix, Arizona, and at Westfield Gage (with Creare) in Westfield, Massachusetts. Contracts were established with both to pay for their efforts to cooperate with the LLNL MODIL team to define and work out production problems. In order to avoid conflicts between potential competitors, work with each contractor was handled separately to insure any proprietary information was protected.

Processes were developed at Livermore and then transferred to the contractors. Significant benefits were gained from Livermore's experience in precision fabrication. The MODIL worked with the contractors in streamlining and improving processes as well as introducing new technology and techniques. For example the MODIL introduced the Wire Electro Discharge Machining (EDM) process. Close coordination, effecting more of a concurrent engineering atmosphere, was encouraged.

In addition to the demonstration project and PTWG activities, the Cryocooler thrust had a major interaction with the USAF Cryocooler program from the Phillips Laboratory, Albuquerque, New Mexico. In addition to consulting and advising regarding producibility, the MODIL also assisted in their cryocooler contract selection.

5.0 Precision Technologies

The Precision Technologies Thrust, led by Lee Griffith, is pursuing two projects that will greatly advance the state of the art in satellite manufacturing. One project is in sensor alignment, and the other is in precision miniature rocket thrust vector measurement.

5.1 Sensor Alignment

Sensor alignment is an enormously costly and time consuming aspect of spacecraft fabrication. A one-of-a-kind spacecraft will typically allocate

eighteen months for sensor alignment. A copy of the same spacecraft will probably allocate twelve months for the same alignment task. The task can be even more involved as noted on the Hubble Space Telescope. To achieve the cost requirements for SDI elements, the sensor alignment time needs to be reduced drastically.

In conjunction with the Jet Propulsion Laboratory (JPL), the SF&T MODIL investigated ways to improve alignment. Inputs from PTWG visits were very helpful in indicating alignment issues and areas of potential improvement. JPL and the SF&T MODIL outlined a four task approach to improving alignment. The first task was completing the fact-finding initiated by the PTWG visits to pin-point critical alignment needs. Furthermore, ideas regarding methods to reduce alignment time for both assembly and on-orbit were to be sought. Secondly, procedures and software tools were to be developed and tested to address the issues found in the first task. Precision techniques, such as the "snap-together" optics techniques developed by the Optics MODIL, would be considered. This includes designing and manufacturing components with adequate accuracy to achieve alignment upon assembly. Other potential techniques included computer-aided interferometric alignment and image-based alignment. The third task, computer-aided alignment (CAA), was the most important and most powerful. The final task would be a hardware demonstration of the basic feasibility of the CAA. Preferably the final task could be demonstrated on an actual SDIO pre-production system.

JPL has extensive experience with computer-aided alignment. Images of a well known scene, or a known star, are taken after changing alignment parameters (such as focus, spacing, or tilt). Computer analysis of the images then can give information on error sources of the optical train. This method was successfully used by JPL in analyzing the Hubble Space Telescopes spherical aberration problem. The analysis of the images predicted very well the error in the primary that was later deduced by the Allen Committee which reviewed the archival data and the test set up.

Another very exciting aspect of this approach is being able to align sensors in orbit. On orbit alignment offers significant design flexibility while reducing the alignment requirements during fabrication and test. Also the alignment requirements to be held during and after launch are reduced offering system advantages.

In addition to intrasensor alignment, one must be concerned with co-alignment of the many sensor packages on a satellite. Co-alignment is essential to communications, guidance, inertial management, and sensor-to-sensor image hand-off. Malcolm Shuster of Johns Hopkins Applied Physics Laboratory describes pre-launch alignment determination as costly and difficult. The SF&T MODIL had planned to build off Shuster's experience to reduce the difficulties of co-alignment. Plans were to integrate Shuster's work with JPL's to form a thorough on-orbit sensor calibration system.

5.2 Miniature Rocket Thrust Measurement

The SF&T MODIL's effort in miniature rocket thrust vector measurement emphasizes the MODIL's role as an integrator. In this case, the MODIL planned to bring together several smaller projects to accomplish valuable research at lower cost and in less time than would have been possible without MODIL coordination. The SF&T MODIL has heard concerns about rocket thrust vector measurement from a variety of sources which include from contractors during PTWG visits and other MODIL interactions. Some applications are very sensitive to knowing both the magnitude and the direction of the thrust vector. Failure to apply the thrust through the center of mass can cause the spacecraft to roll and jeopardize the mission. The problems can range from excessive roll creating loss of orientation to misdirection requiring increased fuel consumption for compensation.

The SF&T MODIL planned work with existing SDIO contractors such as Martin Marietta, Aerojet, and LLNL's Brilliant Pebbles program to both have adequate sensitivity and accuracy of thrust measurement. The plan included a careful finite element analysis of the test stand to insure that it

would have the stability and strength for the test. Then a redesign of ancillary elements of the test stand plus a change in the calibration procedure was conceived with hopes of achieving the necessary sensitivity and accuracy.

6.0 Assembly and Test Thrust

The Assembly & Test Thrust was initiated after the Brilliant Eyes PTWG visit in March of 1992. Based on direct feedback from the contractors and discussions with Greg Stottlemeyer, of SDIO, and Mohan Aswani, of the Aerospace Corporation, the decision was made to start the Assembly & Test Thrust. One suggestion was to consider a major re-visiting of the DOD spacecraft testing requirements. This study could consider the current state-of-the-art of spacecraft fabrication, review data from current satellites, and propose a test requirement suitable for quantity production of spacecraft.

There is a need to re-evaluate the test requirements. Military Standard 1540B is not the major problem. The major question is, "What tests are necessary in order to insure spacecraft performance and lifetime?" Therefore, it is necessary to develop a good test criteria to satisfy both the program offices and contractors that their satellites will meet lifetime requirements.

Several major efforts were already in progress. The Aerospace Corporation was studying possible improvements to Military Standard 1540B. Another Aerospace initiative was the Vehicles/Satellite Environmental Test Simulation System (V/SETSS) which was evaluating large quantities of historical test/failure data. One V/SETSS interest was investigating possibly deriving cost/benefit insights from various spacecraft tests.

Unfortunately, this thrust was just in its initial stages when the funding was cut. Therefore, the MODIL was not able to follow up on keen interest from several key SDIO contractors in test and assembly.

7.0 SDIO Producibility Support: Producible Technology Working Groups

The Producible Technology Working Groups have been established to assist in assuring that the manufacturing and processing capabilities and industrial capacities are sufficient to meet the SDIO element production schedule and cost targets. The organization and leadership is the same as described last year¹ except that Arnold Johnson, the Software MODIL Leader, is the Software PTWG leader. Meetings have been held with the Brilliant Pebbles, Brilliant Eyes, Ground Based Interceptor contractors. The BE and GBI interactions were constrained due to the imminent issue of a Request for Proposal for a major program follow-on. A typical visit started with a plenary session which included an overview of the purpose of each MODILs and the PTWGs and an overview briefing of the program requirements and manufacturing needs. Then separate meetings were held with the PTWGs and the contractors' (and appropriate/available sub-contractors') personnel. Sometimes PTWGs were combined depending on the representation of the PTWG visit.

The PTWG process has been one of the major sources of the MODIL obtaining information of producibility needs of the SDIO community. Numerous detailed discussions were held ranging from information on specific materials information to potential sub-system problems. In one case separate trips were taken to potential future sub-contractors to assess current state-of-the-art and related producibility issues. Other specific discussions included topics such as outgassing, dimensional stability, repeatability of properties, maturity of processes, and software compatibility for a concurrent engineering environment. A specific design was even evaluated and suggestions made to make the design more producible. In other cases specific design philosophy errors were detected

and reported. As mentioned in section 6.0 the Test and Assembly Thrust was initiated in response to PTWG findings.

The PTWG mechanism and interaction have significant potential benefits for enhancing producibility. A key hurdle is overcoming the contractor's sensitivity in disclosing their manufacturing weaknesses. As projects proceed beyond the bidding stage (selecting fewer contractors from those currently participating) and the realities of meeting schedule and budget arise, their openness should increase. Another important element is for the MODIL and the PTWG process to provide contractors real help in solving production problems.

8.0 First Briefing to Industry

The first SF&T briefing to industry was held at the Lawrence Livermore National Laboratory in September 1992. There were two objectives of the briefing:

- Explain the mission, goals and progress of the SF&T MODIL and solicit industry's and SDIO program's participation and support.
- Demonstrate and show LLNL capabilities available to solve SDIO producibility issues.

It was extremely well attended, and the feedback was very positive from the attendees. Dr. James D. Carlson was the featured speaker at the evening banquet giving a perspective on SDIO's future. In pursuit of the second objective, tours of several major LLNL facilities were arranged as well as a half day of presentations regarding key LLNL technologies of potential use to the spacecraft fabrication community. These technologies are seeds for potential future SF&T MODIL thrusts.

9.0 Summary

The SF&T MODIL is off to a good start to achieve its objective of establishing a producibility culture in the spacecraft fabrication community. The SF&T MODIL has been organized into five thrust areas:

- Automated Spacecraft & Assembly Project (ASAP)²
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- Cryocoolers⁴
- Precision Technologies
- Assembly & Test.

Interest has been high from the SDIO contractors, and progress has been made gaining support of the SDIO program offices. Current work has been severely limited by funding cuts, and future contributions of all the MODILs will depend on future SDIO direction and funding of the MODILs.

10.0 Acknowledgments

I'm grateful to the fine leadership each thrust leader has given: ASAP - Dave Sanders, Materials and Structures - Gordon Spellman, Cryocoolers - Gill Cruz, and Precision Technologies - Lee Griffith. I also thank them for their help in preparing this manuscript. Dr. Mohan Aswani, of the Aerospace Corporation, has continued to play a key role in helping the SF&T MODIL as well as serving as a chairperson for the Materials and Structure PTWG. I thank Dr. Larry Fehrenbacher and his team from Technology Assessment and Transfer Incorporated for advice and tireless efforts in keeping all the MODIL teams coordinated.

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