ISAAC Advanced Composites Research Testbed

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ABSTRACT

The NASA Langley Research Center is acquiring a state-of-art composites fabrication capability to support the Center's advanced research and technology mission. The system introduced in this paper is named ISAAC (*Integrated Structural Assembly of Advanced Composites*). The initial operational capability of ISAAC is automated fiber placement, built around a commercial system from Electroimpact, Inc. that consists of a multi-degree of freedom robot platform, a tool changer mechanism, and a purpose-built fiber placement end effector. Examples are presented of the advanced materials, structures, structural concepts, fabrication processes and technology development that may be enabled using the ISAAC system. The fiber placement end effector may be used directly or with appropriate modifications for these studies, or other end effectors with different capabilities may either be bought or developed with NASA's partners in industry and academia.

INTRODUCTION

Composite structures and materials are widely recognized as state-of-art enabling technologies for modern aerospace vehicles (Figure 1). This widespread use of composites contributes to reduced vehicle weight and maintenance requirements, and also increased performance and reliability of these systems [1]. The automated manufacturing technologies now used to successfully fabricate these composite components have proven satisfactory for the current generation of vehicles. However, the more demanding weight and performance requirements for future aerospace vehicles will require further advancements in the composites state-of-art, and require development of even more advanced materials, structures, fabrication processes and manufacturing technologies that are both more affordable and more efficient. This paper describes one potential solution that can help to address many of NASA's critical needs in both advanced composite structures and materials, as well as enable future development, integration and assessment of new advanced manufacturing technologies from NASA and its partners in academia and industry.

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Figure 1. Airbus A350 XWB (Airbus).

COMPOSITES FABRICATION STATE-OF-ART

The American aerospace industry has made significant investments in composites fabrication capabilities over the past decade, with many large automated fiber placement (AFP) systems currently in service at manufacturing facilities across the country (Figure 2). Their mature nature means that they may be classified as the manufacturing equivalent of Technology Readiness Level (TRL) 9, or fully proven in operational service [2]. However, these systems are not typically used for advanced composites research and technology development (R&TD), as they are often placed in the critical path for delivering revenue-generating hardware on tight production schedules for active programs. Therefore, industry is understandably reluctant to use these high-value assets for lower-priority (for them) R&TD work, including higher-risk evaluation of new material systems and process development.

While various contractual instruments with industry have been used before to access these types of production assets, they are generally cumbersome, expensive, time-consuming, and do not result in the full attainment of knowledge by NASA. At the same time, foreign composites research organizations (e.g., the Canadian NRCC, Dutch NLR, German DLR and National Composites Centre in the UK) are aggressively developing and using in-house AFP capabilities, in conjunction with their local aerospace industries, to advance their R&TD activities with concomitant economic benefits.

At present, the NASA field centers do not have the advanced systems needed for development of critical contributions to advanced composites fabrication R&TD. Marshall Space Flight Center is currently the only NASA field center with direct access to significant advanced composites manufacturing capabilities, with two contractor-run, single-purpose AFP systems located at the Michoud Assembly Facility [3]. These older machines would each require multi-million dollar modifications to upgrade them to the state-of-art in AFP, and even then would still lack the inherent flexibility to perform operations other than AFP.

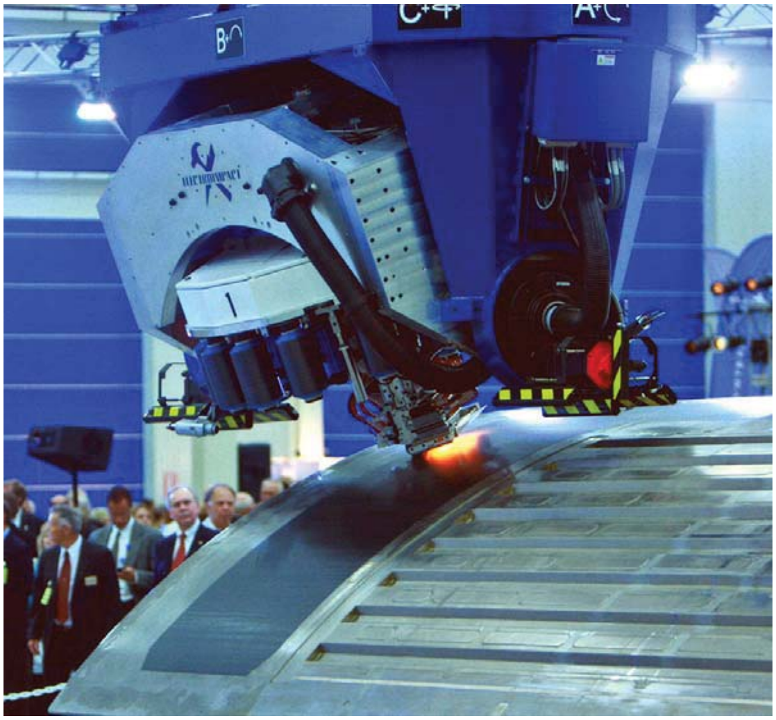

Figure 2. Large fiber placement system (Electroimpact).

While most of the other NASA field centers have some limited in-house capability to build composites, the resulting laminates – made using hand layup – are not directly traceable to the products made using industry's highly automated fabrication processes. However, the NASA field centers with responsibilities for composite materials and structures already have experienced personnel whose capabilities span the entire TRL spectrum, making them well positioned to perform advanced composites research. Acquisition of a system like the one described below will provide them an appropriate platform for this activity.

INTEGRATED STRUCTURAL ASSEMBLY OF ADVANCED COMPOSITES

Recent technology developments have increased both the affordability and utility of highly capable robotic platforms for additive manufacturing of thermoset composite structures. One such commercial system [4], produced by Electroimpact (Mukilteo, WA), combines an industrial robot having multiple degrees of freedom, a tool changer interface, and a specialized AFP end effector (Figure 3). This capability, under acquisition by the NASA Langley Research Center, is named ISAAC, or *Integrated Structural Assembly of Advanced Composites.*

The AFP end effector provides a highly mature, state-of-art, initial operating capability for ISAAC that is fully compatible with the composites manufacturing processes used throughout the aerospace industry. In fact, the same type of AFP end effector is also used on other mobility platforms (e.g., Figure 2) to manufacture large composite primary structures [5].

Figure 3. Robotic fiber placement system (Electroimpact).

The positioning accuracy and precision of the commercial robot that provides the mobility platform for ISAAC is improved by an order of magnitude through a combination of digital encoders, secondary feedback and computer numerical control. The highly modular system architecture also greatly reduces the potential for overall obsolescence, as individual hardware or software components can be replaced or upgraded over time. A digital "flight data recorder" logs all process information during AFP operations, which allows performance of post-hoc analyses of these data to understand both correlation and causal links between composite materials, manufacturing and the resulting structures.

In addition, the commercial software that is used to drive the system supports establishment of tightly integrated design, analysis and manufacturing models and databases. The feed-forward control typically used on conventional AFP systems only generates knowledge of the as-programmed fiber orientation angles for post-hoc comparison with as-designed values [6]. The secondary feedback used for control of the ISAAC system will also generate knowledge of the actual *as-manufactured* fiber orientation angles, allowing both in-process *and* post-hoc comparison with both the as-designed and as-programmed values, thus closing the loop on a more fully integrated digital environment.

At the appropriate scale, the baseline ISAAC system could also be used to build flight-quality composite structures to support NASA's diverse missions in aeronautics, science and space. Selected components of the Orion spacecraft (e.g., various doors, fairings and panels), optical benches, small test/flight entry vehicles, aeroelastically tailored wind tunnel models, wind tunnel stings, model supports and fan blades, are all likely candidates for further development.

While this baseline ISAAC system is highly capable and will enable many promising lines of composites research at NASA Langley, its functionality to rapidly change end effectors will also enable further advancements in composites processing. Thus, the extended ISAAC system becomes something akin to a multi-axis high-speed machining center, where interchangeable tools are used to perform different cutting operations during fabrication of metal parts. Implementation of the extended ISAAC system will then enable future development, integration and assessment of new advanced manufacturing technologies, such as automated tape layup (ATL), thermoplastic and out-of-autoclave cured materials, in-situ/in-process curing, in-situ/in-process non-destructive inspection and evaluation (NDI/NDE), integral stiffener fabrication [7] (Figure 4) and addition of through-thickness reinforcements to reduce laminate delaminations (e.g., stitching, [8] Figure 5).

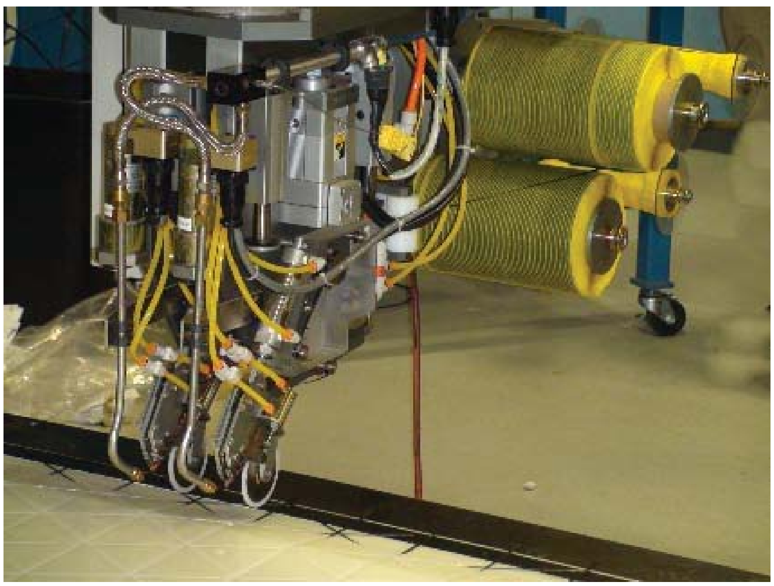

Figure 4. Composite isogrid stiffener fabrication head (ICCI).

Additional end effectors with these or other advanced fabrication capabilities may then be purchased, developed internally, or cooperatively with industry or academia, and then integrated onto the existing robotic platform to perform advanced manufacturing operations or develop new techniques and processes. This work can be performed either with or without the AFP end effector, as appropriate.

Because the baseline ISAAC system uses the same AFP end effector as many other production facilities in industry, it provides a clear scale-up path for nascent technologies to be transitioned to implementation within the broader composites industry. This traceability for technologies and processes developed using the research-oriented ISAAC capability will help these new, lower-TRL technologies to bridge the so-called TRL 4-6 “valley of death”, and more easily transition to higher-TRL applications.

Figure 5. Stitched composite structure fabrication (Boeing).

IN-SITU/IN-PROCESS NDI/NDE OF COMPOSITES

One example of how the ISAAC system can be used to enhance the capabilities of automated fiber placement is further described in this section. For fabrication of typical large components using traditional NDI/NDE processes, individual composite plies are laminated onto the tooling using an AFP system. After each ply is placed, the entire uncured part is visually inspected by trained quality personnel (a time-consuming and tedious process at best), and any identified defects repaired. After all plies are placed, the part is then cured in an autoclave and reinspected. Resolution of flaws found at this stage is problematic, as repair of a fully cured structure is even more difficult than during fabrication. Significant amounts of time are spent inspecting parts during the manufacturing process [9], sometimes requiring over twice the time required for AFP layup.

Therefore, development of reliable in-situ or in-process non-destructive inspection and evaluation techniques [10, 11] can result in tremendous savings in part inspection time during the AFP process. High-fidelity data on the tow quality can be gathered using one or more of a wide variety of electromagnetic sensors (e.g., visual and infrared cameras, laser line scanners, shearography) installed either on the AFP end effector, or on a dedicated NDI/NDE end effector. These data are then processed in real or near-real time, and finally displayed in a user-friendly format that alerts the operator to the presence of defects, which may then be corrected in a timely manner. Typical defects may include unintended tow drops, gaps, overlaps, foreign objects, fuzzballs, as well as twisted, puckered, wrinkled and buckled tows. Since the physical locations of these defects can be identified using the same virtual CAD models used to define and simulate the AFP layups, touch probes or laser placement [12] can then be employed to quickly home in on their location on the actual part. This capability can transform NDI/NDE from a post-hoc process to one that is fully integrated with the composites manufacturing process itself.

NATIONAL AND NASA MOTIVATING FACTORS

The National Science and Technology Council's 2012 report to the President [13], listed five key objectives for A National Strategic Plan for Advanced Manufacturing. These objectives are:

- *Accelerate investment in advanced manufacturing technology, especially by small- and medium-sized manufacturing enterprises, by fostering more effective use of Federal capabilities and facilities, including early procurement by Federal agencies of cutting-edge products.*
- *Expand the number of workers who have the skills needed by a growing advanced manufacturing sector and make the education and training system more responsive to the demand for skills.*
- *Create and support national and regional public-private, government-industry-academic partnerships to accelerate investment in and deployment of advanced manufacturing technologies.*
- *Increase total U.S. public and private investments in advanced manufacturing R&D.*
- *Optimize the Federal government's advanced manufacturing investment by taking a portfolio perspective across agencies and adjusting accordingly.*

The ISAAC system can directly support these key objectives. It can serve as a technology enabler for local companies (both in aerospace and other sectors) in the immediate vicinity who could utilize the system's advanced composite manufacturing capabilities, but could not afford to purchase and operate it on their own. The ISAAC system can also serve as a valuable training ground for the next generation of scientists, engineers and technicians, and allow these individuals to gain relevant hands-on experience in all aspects of advanced composites manufacturing. The ISAAC system can help to serve as a nexus for developing new partnerships between NASA and national, regional and local industries and universities, encouraging the broadest cross-pollination of concepts and ideas.

Under the aegis of NASA's Office of the Chief Technologist (OCT), Space Technology Roadmaps were prepared for fourteen advanced technology areas to describe their technical challenges, the spaceflight missions they could impact or enable, and – as a byproduct – the important terrestrial fields they could advance. The Materials, Structures, Mechanical Systems and Manufacturing (MSMM) challenges are presented in the Technology Area (TA) 12 Roadmap [14]. The ISAAC system will be able to provide broad support for precise, repeatable, fabrication of composite test coupons and structures to help achieve several of the MSMM's top ten technical challenges described in the TA 12 Roadmap, including Reliability, Advanced Materials, Multi-Functional Structures, and Advanced Manufacturing Process Technology.

To support the individual technical areas listed (Materials, Composite Structures, Manufacturing and Cross-Cutting) in the TA 12 Roadmap, the baseline ISAAC system can readily fabricate high-quality composite test hardware that is fully compatible with the state-of-art automated processes used by industry, and also use its extended capability for advanced materials, manufacturing processes and structures R&TD that would help to accelerate advancements in many of the specific technical challenges listed. For example, the baseline ISAAC system can also be used – without modification – to fabricate precise, repeatable test articles with embedded flaws and defects (e.g., a crack of specified width within a given ply), allowing generation of statistically significant experimental data for comparison with detailed analytical models.

COMPOSITE CRYOTANK

NASA's Composite Cryotank Technologies and Demonstration (CCTD) project [15, 16] is exploring advanced composite materials, processes and structures, with the goal of a 25 percent cost reduction and a 30 percent weight reduction over comparable aluminum-lithium propellant tanks. NASA contracted with The Boeing Company to design, analyze, and manufacture 2.4m-diameter (Figure 6) and 5.5m-diameter composite cryotanks for testing at NASA Marshall Space Flight Center. The selected designs incorporate highly steered tow paths, nominal thickness (0.0050 in./ply) and thin (0.0025 in./ply) ply, out-of-autoclave materials, bonded scarf- and Y-joints, and all-composite sealing surfaces. Because the primary method used to manufacture the cryotanks is a robot-based AFP system developed, owned and operated by Boeing, much of the knowledge gained from this activity cannot be widely disseminated due to contractual agreements with that company.

Figure 6. 2.4m-diameter composite cryotank.

If used to support future projects like CCTD, the ISAAC system would enable NASA to internally develop material processing parameters, establish tow-steering limitations, fabricate coupon and joint test specimens, and create manufacturing demonstration units, all prior to handing off full-scale fabrication to a contractor. Greater NASA involvement in the process development phase of a large composite program will allow exploration of the broader trade space, instead of focusing on limited point designs. In addition, any resulting material processing and fabrication procedures are then owned by the U.S. Government, thus allowing dissemination to the greater aerospace community, and simultaneously making the government a smarter buyer.

A more intimate knowledge by NASA of advanced composite manufacturing processes is also critical to establishing high-fidelity finite element models that can be digitally linked to design, manufacturing and test data, ensuring close representation of the as-manufactured hardware, as noted above. Establishment of composite materials databases that contain both the material property data, as well as the mature, repeatable processing parameters – and their sensitivities – required to achieve them should then greatly reduce the cost of future advanced composite programs.

CONCLUDING REMARKS

The recent heightened interest in advanced manufacturing offers a unique opportunity for NASA to take a national leadership role in composite structures and materials. In the mid- to late-1960s, NASA published design guidelines for shell buckling [17], which then became the de facto industry standard for the next 40 years. NASA development of modern design, analysis and manufacturing standards and databases for advanced composite structures and materials can serve a similar role today, and help to reduce the excessive conservatism present in today's methods, thus leading to higher performance systems.

Further advancements in technology and complex systems will also be made through the efforts of researchers and technologists who have the knowledge and expertise in multiple disciplines, such as the full cycle of manufacturing through the digital design, manufacturing, testing and correlation of composite structures, thus treating this technology as a fully integrated system. As noted in the TA 12 Roadmap [14], *"The manufacturing element provides the most important link between technology invention, development, and application."*

The ISAAC system will directly support advanced manufacturing and research for composite structures and materials, both by NASA field centers and for the entire aerospace industry. While an AFP end effector is selected to provide a mature initial operational capability for ISAAC, the adaptable system architecture allows advancements in new manufacturing technologies through development, integration and assessment of additional end effectors with advanced capabilities. These end effectors can either be purchased or developed, by or in cooperation with NASA, and then used to develop advanced manufacturing processes and technologies. The new discoveries and knowledge acquired using this research-oriented advanced composites manufacturing system would be then be transitioned to end users in industry for the greater benefit of all.

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