Appendix D

Environmental Scans in support of the Manitoba Aerospace TRM Thrust Reports

NRC - Knowledge Management

The following compilation contains sixteen Scientific and Technical Information documents which were prepared by the NRC Knowledge Management team as part of supporting the Manitoba Aerospace Technology Road Map.

Appendix D – Environmental Scans

Reports In Support Of

The entirety of the Manitoba Aerospace Technology Road Map reports are available through the Manitoba Aerospace Association and EnviroTREC websites:

Manitoba Aerospace Association

EnviroTREC

STI Assessment

Title	**Aerospace Environmental Scan - Adaptive Machining**
Project Numbers	STI Footprint project number
Date	June 5th, 2013
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC
Prepared by	Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca) Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca) Mike Culhane, Strategic Information Analyst (mike.culhane@nrc-cnrc.gc.ca) Jean Kneale, Information Specialist (jean.kneale@nrc-cnrc.gc.ca)

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1 ADAPTIVE MACHINING

Adaptive machining refers to "systems that adapt manufacturing data to suit changing conditions, such as on demand manufacturing systems, are typically used when individual components in a batch have slight geometric differences".[1] It can also be used when the exact position of the workpiece is unknown. Adaptive machining control involves monitoring fabrication to identify any mistake during the process.

1.1 Drivers and barriers

Very little commercial information was found on the topic and the scientific and technical literature mostly discusses very specific applications and usages, which don't address the key questions identified by the client. Companies like Delcam are active publishers and many documents found were published by corporate players.

Some drivers and barriers have been identified from the scientific and commercial literature. The drivers are mostly related to the benefits that adaptive machining processes can bring to the fabrication operations. Other drivers include the increasing cost of labor around the world, need for increased productivity and increased commercialization.

However, some sources indicate that the technology has been slow to be widely adopted; while specific barriers are rarely discussed, some reports point to higher costs and complexity.

The drivers and barriers found are listed in Table 1.

Table 1. Drivers and barriers to the adoption of adaptive machining technologies

Drivers	Barriers
• Increased accuracy and repeatability • High volume/high productivity requirements • High R&D interest and funding • Reduced cycle times • Extended tool life and reduced tool breakage	• High development and implementation costs • Need for higher processing power • High overhead requirements and complexity with regards to CAD/CAM integration

[1] Source: Advanced Manufacturing Technology Alert. Sustainable Printed Circuit Boards; Next Generation Feeding System for Small Parts; Numerical Tools Support Adaptive Machining (Frost & Sullivan, 2011)

Drivers	Barriers
• Reduced maintenance and downtime (by reducing the time spent on tool changes) • Reduced scrap • Health and security concerns, especially in grinding or polishing applications	

1.2 Commercial availability

Adaptive control systems have been in use since the 1960s but the advance of sensors, faster microprocessors and the lower costs of memory have contributed to making the technology more accessible.

Many companies claim to use adaptive machining in the aerospace sector. TTL (UK) uses them on compressors and turbine aerofoils, blisks and impellers, fan blades and nozzle guide vanes; one company based in Montreal, AV&R Vision & Robotiques, also uses them on turbine blades while Honeywell uses adaptive machining technologies on airfoil repairs. These are just a few examples, but the interest is visible by looking at the literature published on the topic.

Applications found include the remanufacturing of turbine blades and machining of composites. According to the literature found, adaptive controls are primarily used in applications where finish is not a concern, but it can also be used for finishing.

Many products supporting the use of adaptive machining technologies have also been found; companies in the area mostly focus on robotics, on inspection and on software. Machine vision systems are also a key enabler to the technology. Table 2 lists the adaptive machining and control products found during the search.

Table 2. Companies offering products supporting adaptive machining

Company	Products
BCT GmbH (Germany)	Software for automating repair processes; the product is called OpenARMS.

Company	Products
Caron Engineering (USA) http://www.caron-eng.com/	The company offers the Tool Monitor Adaptive Control (TMAC) product, which can measure tool wear in real time.
Delcam Consulting (UK) http://www.delcamconsulting.com/	Software solutions to support adaptive manufacturing operations, including PowerSHAPE, PowerMILL and PowerInspect OMV.
FANUC Factory Automation http://www.fanucfa.com/	iAdapt adaptive control solution is built into their CNC systems.
Heidenhain (Germany) http://www.heidenhain.com/	Adaptive control functions are built into the iTNC 530 controller family.
OMATIVE (many locations, headquarters unidentified) (http://www.omative.com/)	The OMATIVE Adaptive Control Monitor monitor cutting operations in real time and adjusts the feed rate during operations.
Renishaw (UK) http://www.renishaw.com/	Productivity+, adapted to adaptive machining operations.

Sources

Reports and articles

- Adaptive Robotics for Flexible Manufacturing (Frost & Sullivan, 2012)
- Advanced Manufacturing Technology Alert. Sustainable Printed Circuit Boards; Next Generation Feeding System for Small Parts; Numerical Tools Support Adaptive Machining (Frost & Sullivan, 2011)
- Aerospace automation: interview with Eric Beauregard of AV&R Vision & Robotics, Robotics Tomorrow, nd. (http://www.roboticstomorrow.com/emagazine/2013/04/aerospace-automation/1846)
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- Dickin, Peter. The Adaptive Approach, Control Engineering Asia, 2008. (ftp://tawe.delcam.com/pub/pdf/ext_news/CEA-NOV-DEC08.pdf)
- Haftl, Larry. Adaptive controls save tools and time, American Machinist, 2007. (http://americanmachinist.com/machining-cutting/adaptive-controls-save-tools-and-time)
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- http://www.aero-mag.com/features/19/20116/908/
- Robotics, Technology Map. Strategic Business Insights, 2012.
- Walton, Paul. Adaptive machining shows its mettle in manufacture and repair, Modern Power Systems, 2002. (http://www.modernpowersystems.com/features/featureadaptive-machining-shows-its-mettle-in-manufacture-and-repair)

Databases

- Aerospace Database (Proquest)
- Business & Industry
- Business Source Complete
- Compendex
- Inspec
- OneSource
- SBI
- Scopus
- Techniques de l'ingénieur

STI Assessment

Title	**3D Printing, Near Net or Net Shape (Metals)**
Project Numbers	STI 17174
Date	2013.06.25
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, Envirotrec
Prepared by	Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca) Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca) Mike Culhane, Strategic Information Analyst (mike.culhane@nrc-cnrc.gc.ca) Jean Kneale, Information Specialist (jean.kneale@nrc-cnrc.gc.ca)
Contact	C Jean Kneale, 613-998-3327

Contents

1 3-D PRINTING, NEAR-NET OR NET SHAPE (METALS)

1.1 3-D Printing or Additive Manufacturing (AM)

The ASTM F42 Technical Committee defines additive manufacturing (AM) as the "process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" . It is also known as additive fabrication, additive processes, direct digital manufacturing, rapid prototyping, rapid manufacturing, layer manufacturing and solid freeform fabrication. The term AM describes additive fabrication processes in the broadest way that includes AM of prototypes (for design verification, form and fit checking), tools, patterns, and concept parts, as well as functional parts with required properties for direct industrial applications and services.[1]

When describing additive manufacturing processes, Guo and Leu identify the following processes for metals.[2]

Table 1: Additive Manufacturing Processes

Process	Description	Top Players
Selective Laser Sintering (SLS)	Uses a laser beam to selectively fuse and sinter polymer particles by scanning cross-sections on the surface of a powder bed layer-by-layer into an object that has a desired 3-dimensional shape based on a CAD model. After each cross-section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is spread on top, and the process is repeated until the part building is complete. SLS can produce parts from a relatively wide range of powder materials, including wax, polymers, polymer/glass composites, polymer/metal powders, metals, and ceramics. The binding mechanisms include solid state sintering, chemically induced binding, liquid phase sintering, and partial melting. For metal and ceramic parts, the metal or ceramic particles are coated with polymer or mixed with polymer particles serving as the binder. Post processing is required to remove the binder and fully sinter the part. Unlike some other AM processes such as SLA and FDM, SLS does not require support structures because the	Major commercial manufacturers of SLS equipment include 3D System and EOS.

[1] Guo, N., Leu, M.C. (2013, in press) Additive manufacturing: technology, applications and research needs. Frontiers of Mechanical Engineering , pp. 1-29 [p. 1].
[2] Guo, N., Leu, M.C. (2013, in press) Additive manufacturing: technology, applications and research needs. Frontiers of Mechanical Engineering , pp. 1-29 [p. 4-5].

Process	Description	Top Players
	part being fabricated is surrounded by unsintered powder.	
Selective Laser Melting (SLM)	Completely melts the metal powder with a high-power laser beam to form a metallic part that is almost completely dense and does not require post processing. This results in mechanical properties equal to or even better than those of rolled metal sheets. The SLM process is more difficult to control due to the large energy input to melt metal particles, which causes problems such as balling, residual stress development, and part deformation. Currently available alloys used in this process include stainless steel, cobalt chromium, inconel, and titanium.	The manufacturers of commercial SLM equipment include the MCP Realizer, EOS and SLM Solutions.
Electron Beam Melting (EBM)	Has emerged very recently, is similar to the SLM process in some sense because it also uses a power bed. The major difference is that the EBM process uses an electron beam rather than a laser beam as its energy source. EBM builds parts by melting metal powder layer by layer with an electron beam in a high vacuum chamber. The fabricated parts are fully dense, free of voids, and extremely strong. Compared to SLM, EBM generally has a superior build rate because of its higher energy density and higher scanning speed; however, the part's surface finish is not as good.	The EBM process is developed and commercialized by Arcam in Sweden.
Laser Metal Deposition (LMD)	Also known as Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), or laser cladding, is an AM process in which, as in SLM, the powder is completely melted by a laser beam, resulting in fully dense parts without the need for post processing. The major difference between LMD and SLM is in the provision of the powder material. In LMD, the powder material is locally supplied by a powder feeding nozzle (coaxial or off-axial), while in SLM, the part is fabricated in a powder bed. LMD can build very thin walls because of the very small heat-effect zone generated during the process. LMD also can build up material layers directly on the surfaces of a 3D part and thus can be used for repair and wear/corrosion protection applications.	Commercial vendors of the LMD process include Optomec (LENSTM), AeroMet (LasformTM) and Precision Optical Manufacturing (DMDTM).
Three-Dimensional Printing (3DP)	Where the part is built in a powder bed. An inkjet printing head is used to spray a liquid binder into a layer of powder, and the binder solidifies to form a solid layer. Then, the piston holding the part descends by one layer thickness, and a new layer of powder is applied. The 3DP process is quite flexible in terms of the types of materials that can be used. Any combination of a powdered material with a binder that has low enough viscosity to form droplets could be used. Plastic, ceramic, metal, and metal ceramic composite parts can be produced using 3DP. The disadvantage is that the parts are porous because of density limitations on the distribution of dry powder. Post processing steps including sintering and/or infiltration are applied in order to make fully functional parts.	The system is commercialized by 3D Systems and Z Corporation (which was acquired by 3D Systems in 2012).
Laminated Object Manufacturing	Solid material is supplied in sheet form. Process steps involve cutting a cross-section in the sheet and attaching the cross-section to the part being built. A sheet of material is spread across a movable substrate,	The major commercial LOM system is from Helisys Inc. (USA),

Process	Description	Top Players
(LOM)	and a laser cuts it along the contours of the part's geometry determined by the CAD model. The layers bond when a hot roller compresses the sheet and activates a heat sensitive adhesive. The materials used in this process can be layers of adhesive-coated paper, plastic, or laminated metal. The main advantage of this method lies in its high fabrication speed, which is achieved because the laser only has to scan through the contour of the part and not the whole cross-section. Because the quality of the surface finish depends upon the thickness of the sheet, achieving a very good surface finish is difficult.	which later went out of business and was succeeded by Cubic Technologies (USA).

According to Ross Friel from the Additive Manufacturing Research Group at the Loughborough University, "One of the main application areas for laser melting at the moment will be in aerospace. I can see lots of different parts that will be produced for aerospace applications and other highly specialized low-volume application areas." Aerospace is one of the areas where the most intensive research is being conducted and new technologies for 3D printing are being developed.[3]

1.2 Additive Manufacturing in the Aerospace Industry

The stringent requirements such as need for weight reduction and accurate designs of airplanes parts drive AM over traditional manufacturing methods in the aerospace industry. In the aerospace industry, AM is mainly used to manufacture critical parts of airplanes or for low-scale production associated with high performance and quality. It has a significant impact on production timelines of the industry, as prototypes and direct products are created with proper fit and design in less time, and at lower costs, than other traditional techniques. In some cases, the aerospace models themselves have been used in the production unit to avoid tooling costs. AM is used in fabrication of on-demand replacement parts, creation of new tools, and repair of damaged components. For long-term usage, it is used to recycle broken parts to provide feedstock for fabrication of replacement parts. AM proves to be advantageous for aerospace industry in terms of both improvement in process and better material control for manufacturing.

[3] Frost.com. Process Control Technology Alert. 3D Printing--Building the Future of Manufacturing
Published: 24 May 2013 [available via NRC subscription]

The probable application for AM technologies in the aerospace industry in the future will have a large effect on aircraft production. This is characterized by customization of aircraft and aircraft parts; Europe is gaining pace and fostering AM technologies in this field. With several manufacturers increasing their investment, the ratio of functionality and costs of AM technologies has improved. Functional-driven design is the key to success for the aerospace industry, and this can be achieved quickly through AM technologies. However, a problem associated with application of AM in this industry is the necessity to build general ground rules for the design and implementation of secondary aircraft structures and systems.

To further research in this field, the European Aeronautic Defence and Space Company N.V. (EADS) and GKN, PLC, an aerospace component company, have collaborated to examine industrializing the additive layer manufacturing process. According to EADS researchers, the additive manufactured parts produced by European Aerospace Consortium (the parent of Airbus industry) are as strong as a machined part, with the exception that the process uses less raw materials than traditional manufacturing.

The two main techniques used for AM in the aerospace industry are Selective Laser Sintering (SLS) and Electron Beam Melting (EBM). The SLS technique can produce components with complex designs and less weight, which would be extremely complicated and expensive to produce by other processes. The EBM technique, too, offers large cost savings in production, and enables designers to create new and innovative lightweight products using advanced lattice structures. Boeing uses the SLS technique of AM to produce parts for commercial and military aircraft.
The major players of aerospace industry in AM are GE (U.K.), Stratasys, Airbus (France), and Arcam (Sweden).[4]

1.3 Expected market size

[4] MarketsAndMarkets. Global Additive Manufacturing Market (2012-2017). Section 4.7 Aerospace. Published: 29/10/2012.

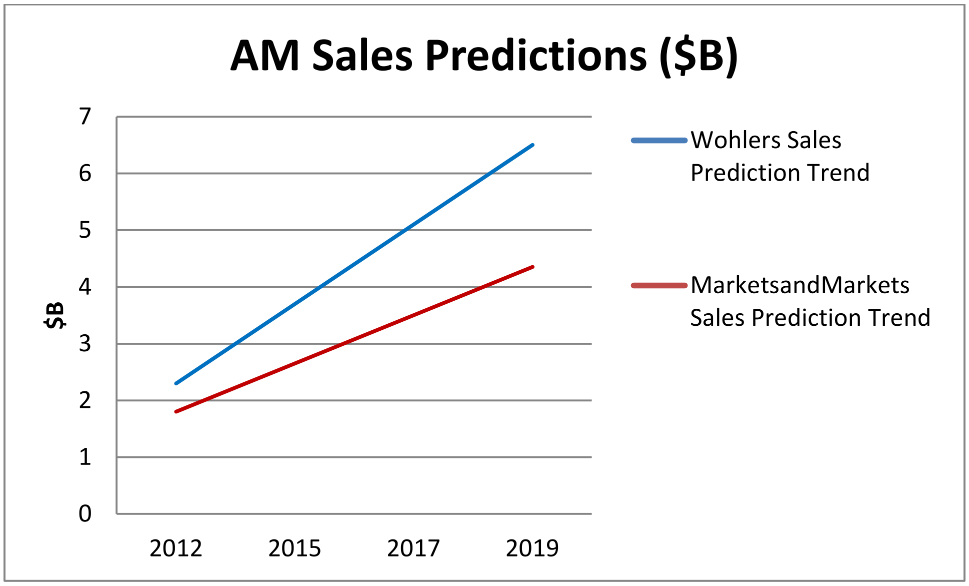

Figure #1: Additive Manufacturing Sales Predictions

The compound annual growth rate of additive manufacturing was 29.4 per cent in 2011, as compared with a 26.4-per-cent average over its 24-year history, according to a recent study by Colorado-based Wohlers Associates Inc. The report forecasts sales of additive manufacturing products and services to reach $3.7-billion worldwide by 2015 and up to $6.5-billion by 2019.[5]

Additive manufacturing is a growing revolutionary technology. The market is estimated to be $1,843.2 million in 2012, and is expected to grow at a CAGR 13.5% to reach $3,471.9 million by 2017. It has vast areas of application in every industry manufacturing sector. Based on industry types, the market is classified in eight segments, namely, motor vehicles, consumer products, business machines, medical, academic, aerospace, government/military, and others (architecture, paleontology, and forensic pathology).[6]

[5] Bouw, B. The 3-D printing revolution has begun. Globe and Mail, Published Friday, Feb. 01 2013, 5:00 AM EST, Last updated Monday, Feb. 04 2013, 8:28 AM EST http://www.theglobeandmail.com/report-on-business/small-business/sb-digital/innovation/the-3-d-printing-revolution-has-begun/article8043259/ [Last consulted: 2012.06.17]

[6] MarketsAndMarkets. Global Additive Manufacturing Market (2012-2017). Section 3.2.1 Global Additive Manufacturing Market, by Industry Type. Published: 29/10/2012.

The following figure illustrates the near future demand for additive manufacturing devices by the Aerospace sector as compared to other sectors. It does not however estimate the revenue generated for the Aerospace sector as a result of the use of this technology. [7]

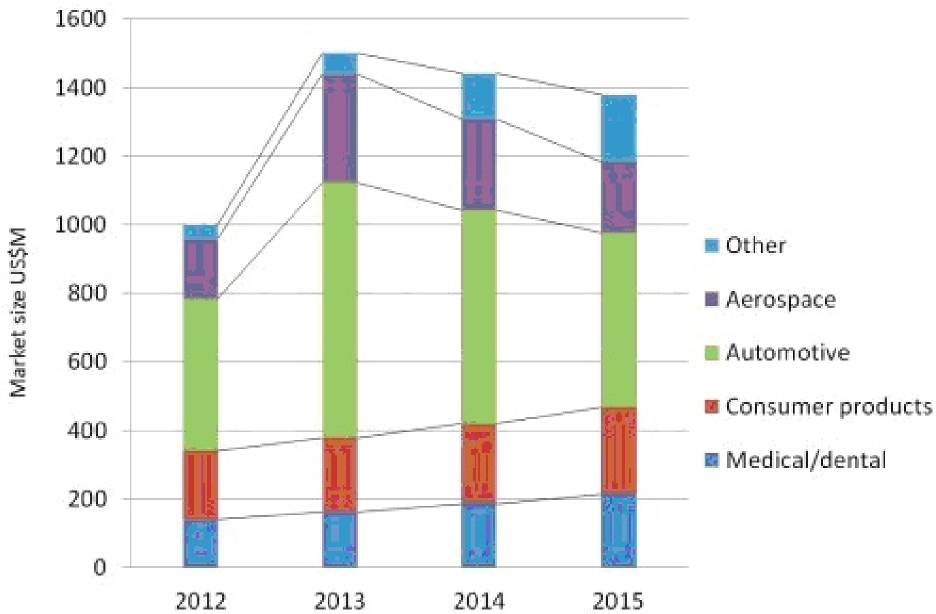

Figure #2: Market Size by Application Sector in US$ Millions

[7] IDTechEx. 3D Printing: Industrial Revolution or Renovation?, Date Added: Jun 13, 2013 | Updated: Jun 13, 2013. Date Added: Jun 13, 2013 | Updated: Jun 13, 2013. http://www.azom.com/article.aspx?ArticleID=9204 [Last consulted: 2013.06.18

1.4 Drivers and barriers

A Frost and Sullivan report lists the following drivers and barriers to the adoption of additive manufacturing. [8]

Drivers	Barriers
• Reduced time to market • Product life cycle management (increased flaw detection, reduced prototype development time) • Mass customization (parts designed to client need and printed to their requirements) • Extended tool life and reduced tool breakage	• Not suitable for large structures • High initial costs of 3d printers • CAD software limitations

In a recent white paper Carol Hauser of TWO Ltd. listed the following drivers for the use of Additive Manufacturing in Aerospace. [9]

- Freedom of design: new or optimized lightweight complex shaped structures e.g. lattice structures
- Processing of lightweight materials e.g. titanium alloys
- Materials processing is easier. Ni and Ti super alloys which work hardens making it difficult to machine and difficult to weld due to solidification cracking
- Low production volumes
- Low cost ? high material utilization of expensive materials, powder recycling validation to reduce further waste
- Environmental impact ? no toxic chemicals, reduced materials waste

[8] Fotedar, S. Top Technologies in Advanced Manufacturing and Automation--2013 (Technical Insights). Frost.com. 2013.04.15 (15 Apr. 2013)

[9] Hauser, C. Laser Additive Manufacturing as a Key Enabler for the Manufacture of Next Generation Jet Engine Components - Technology Push, EU Project Merlin, New Challenges and Perspectives for LAM Processes. TWI Ltd. 2012. http://fabricationmecanique.files.wordpress.com/2012/10/eu_hauser_carl.pdf

1.3 Latest investments / projects

Key Industrial Participant and Research Organizations

In general, additive manufacturing has become increasingly visible across the globe due to its tangible advantages. According to Frost & Sullivan research, intensive research on 3D printing is being carried out in the US. One of the research institutions pushing the limits of this technology is the University of Texas in Austin, which has been extremely active in these areas. On the other hand, in the US, the number of active companies is significant and these include the large market participants, such as 3D Systems, Z Corporation, Stratasys and so on. An analysis of the market shows that it will continue expanding at a steady pace. For instance, the 2012 annual report of 3D Systems indicates a growth of approximately 90 percent in sales in professional 3D printers over 2011 though the company announced even higher sales across all revenue categories. High growth is also noticeable in other market participants.

In Europe, the growth is not slowing down either and companies, such as EOS experience high growth underscored by increasing sales. Examples of the research institutions in Europe that are undertaking intensive work on these technologies include the Loughborough University in UK, University of Leeds in UK and the globally-recognized Fraunhofer Institute for Laser Technology, which has been working on diverse selective laser melting technologies.

Finally, there is a lot of research emanating from Asia. China has the opportunity to be a big participant in this domain globally. Today, numerous smaller scale machines are being manufactured in China and there is a keen interest in China to develop these technologies. Japan has also been involved in additive manufacturing for a long time. Moreover, according to the Loughborough University sources, there is ongoing research in India in the field of 3D printing.

According to Ross Friel from the Additive Manufacturing Research Group at the Loughborough University, "It is obvious that the technology is expanding and finding more and more opportunities in various applications and therefore its global presence is increasing."[10]

[10] Frost.com. Process Control Technology Alert. 3D Printing--Building the Future of Manufacturing
Published: 24 May 2013

Approximately 3200 patents regarding AM have been issued dating back to 1971, according to records held by Derwent Innovations Index. Of these patents, 26% are US patents, 21% Japanese and 16% World patents. Other patents are listed to Germany (10%), China (8%), Europe (7%), South Korea (5%) and Great Britain (2%).[11]

The U.S. continues to lead the world with the largest installed base of AM users. When Wohlers Report 2013 becomes available soon, it will report that 38% of all industrial AM installations are in the U.S. Japan is second with 9.7%, followed by Germany with 9.4% and China with 8.7%. With such a large number of systems, one could argue that the U.S. has the most experience, expertise, and know-how in AM.[12]

Searches of the CORDIS database, scientific and technical databases and the internet have revealed the following investments in additive manufacturing relating to aerospace manufacturing.

[11] Additive Manufacturing. DSTL Science & Technology Briefing Paper. Dstl/PUB64249, Issue 1.1, December 2012. https://www.dstl.gov.uk/downloads/Additive%20Manufacturing.pdf Last consulted: 2013.06.18
[12] Wohlers, T. Losing Another Industry. Filed under: 3D printing, Additive Manufacturing — Terry Wohlers @ 14:49, May 12, 2013 http://wohlersassociates.com/blog/2013/05/losing-another-industry/ Last consulted: 2013.06.18

Table #2 : Global Research Investments

Country / Research	Investment	Description and website for further information
CRIAQ MANU-604 0 Additive Manufacturing (Canada)	n.a.	An agreement between CRIAQ, Pratt & Whitney Canada, Bell Helicopter Textron Canada, Bombardier Aerospace, Polytechnique Montréal, McGill University and Université Laval was signed for a collaborative research project on additive manufacturing. http://www.criaq.aero/Actualites/Detail_Nouvelles/11464039464/10457886888/signature_of_an_agreement_on_an_innovative_additive_manufacturing_project.html The purpose of the project is to bring together various partners (OEMs, suppliers, universities, certification authorities, etc.) to collaborate on a common project for the development of the capability to design, produce, inspect and certify parts using additive manufacturing process. http://www.criaq.aero/Actualites/Detail_Nouvelles/11464039464/10457886888/signature_of_an_agreement_on_an_innovative_additive_manufacturing_project.html http://www.mitacs.ca/o/2013/06/criaq-manu-604-additive-manufacturing
SMART program (Canada)	$18.9 M	Funded by Canada's Federal Economic Development Agency for Southern Ontario (FedDev) and administered by CME, includes support for companies working to advance the technology.
Centre for Rapid Prototyping and Additive Manufacturing (Canada)	$0.7M	The Canada Foundation for Innovation (CFI) announced a $720,760 College Industry Innovation Fund Award to help establish The Centre for Rapid Prototyping and Additive Manufacturing at Mohawk's Fennell Campus. In addition to the Canada Foundation for Innovation, Mohawk's Centre for Rapid Prototyping and Additive Manufacturing is also supported by industry partners, including Com Dev International Products, Pratt & Whitney Canada, Wescast Industries Inc., Wescam, Canadian Manufacturers & Exporters and Canadian Foundry Association. http://www.softwarehamilton.com/2013/04/18/mohawk-college-to-become-industry-test-site-for-3d-printing/
US		
National Additive Manufacturing Innovation Institute (NAMII) http://namii.org/ (US)	$30M US gov't investment (NNMI) + $40M industry investment (5 years, 2012-2017)	•"Rapid Qualification Methods for Powder Bed Direct Metal Additive Manufacturing Processes" (Case Western Reserve University) •"Maturation of High-Temperature Selective Laser Sintering (SLS) Technologies and Infrastructure" (Northrop Grumman Aerospace Systems) •"Fused Depositing Modeling (FDM) for Complex Composites

Country / Research	Investment	Description and website for further information
		Tooling" (Northrop Grumman Aerospace Systems) •"Maturation of Fused Depositing Modeling (FDM) Component Manufacturing" (Rapid Prototype + Manufacturing LLC (RP+M)) Out of 7 projects approved March 20, 2013 NAMII announced the awardees of its initial call for additive manufacturing (AM) applied research and development projects from NAMII members.[13]
Pratt & Whitney / University of Connecticut (US)	$8 million USD (5 years 2013-2018)	The Pratt & Whitney Additive Manufacturing Innovation Center will be used to further additive manufacturing research and development and is the first of its kind in the northeast US to work with metals rather than plastics. We are currently using additive manufacturing to build complex components with extreme precision for the flight-proven PurePower commercial jet engine http://www.tctmagazine.com/additive-manufacturing/pratt-%26-whitney-celebrates-new-additive-manufacturing-lab-opening/ Pratt & Whitney moves additive manufacturing into production http://www.sae.org/mags/aem/12061?PC=130624NWAM
DARPA Open Manufacturing Program (US)	n.a.	Funded a Manufacturing Demonstration Facility (MDF) and several AM modeling proposals http://www.darpa.mil/Our_Work/DSO/Programs/Open_Manufacturing.aspx
MANsys: MANufacturing decision and supply chain management SYStem for additive manufacturing (Europe)	Total cost: € 4.4M EU contribution: € 2.9M (2013-07-01 - 2016-06-30)	ManSYS aims to develop and demonstrate a set of e-supply chain tools; to enable the mass adoption of Additive Manufacturing (AM). This will allow businesses to identify and determine the suitability of AM for metal products, and subsequently manage the associated supply-chain issues and facilitating open product evolution TWI LIMITED (coordinating organization) http://cordis.europa.eu/projects/rcn/108896_en.html
OXIGEN: Oxide Dispersion Strengthened Materials for the Additive Manufacture of High Temperature Components in Power Generation	Total cost: € 5.7M EU contribution: € 3.99 M (2013-02-01 - 2017-01-31)	TWI LIMITED (coordinating organization) http://cordis.europa.eu/projects/rcn/106325_en.html

[13] NAMII Selects Project Call Awardees. Posted on Mar 20, 2013 http://namii.org/namii-selects-project-call-awardees/ Last consulted: 2013.06.25

Country / Research	Investment	Description and website for further information
(Europe)		
TIALCHARGER: Titanium Aluminide Turbochargers Improved Fuel Economy, Reduced Emissions (Europe)	Total cost: € 1.5M EU contribution: € 1.1M (2013-02-01 - 2015-01-31)	The technologies behind this innovation are Electron Beam Melting (EBM) and Electron Beam Welding (EBW). The EBM process has the potential to fabricate a turbine wheel from successive layers of powder allowing a hollow, lightweight, low-inertia rotor-wheel to be formed. The TiAl wheel will be joined to the steel shaft using the EBW process, the challenge being to create a weld between dissimilar materials that is robust enough to withstand the vibrations, high temperatures and rotational speeds present in a turbocharger. This fabrication method provides the possibility to manufacture turbocharger wheels from TiAl, which (if of the required quality) retains its strength at high temperatures, expanding the usage of turbochargers to a broad range of engine types. http://cordis.europa.eu/projects/rcn/106663_en.html TWI LIMITED (coordinating organization)
AMAZE: Additive Manufacturing Aiming Towards Zero Waste & Efficient Production of High-Tech Metal Products (Europe)	Total cost: € 18.7M EU contribution: € 10.1M (2013-01-01 - 2017-06-30)	The overarching goal of AMAZE is to rapidly produce large defect-free additively-manufactured (AM) metallic components up to 2 metres in size, ideally with close to zero waste, for use in the following high-tech sectors namely: aeronautics, space, automotive, nuclear fusion and tooling. http://cordis.europa.eu/projects/rcn/105484_en.html
HI-STA-PART: High Strength Aluminium Alloy parts by Selective Laser Melting (Europe)	Total cost: € 0.1M EU contribution: € 0.09M (2013-02-01 - 2014-07-31)	The Hi-StA-Part project aims to demonstrate the viability to produce aerospace grade aluminium parts using Direct Manufacture (DM) specifically the process of Selective Laser Melting (SLM). The project will demonstrate that components and parts can be manufactured with a significant weight reduction, to the required mechanical properties for aerospace applications http://cordis.europa.eu/projects/rcn/108903_en.html
AEROBEAM : Direct Manufacturing of stator vanes through electron beam melting (Europe)	Total cost: € 0.1M EU contribution: €0.1M (2012-10-01 - 2013-09-30)	ASOCIACION DE INVESTIGACION DE LAS INDUSTRIAS METALMECANICAS, AFINES Y CONEXAS (Spain; project lead) http://www.aimme.es/english/aimme/presentacion/
SASAM: Support Action for Standardisation in Additive	Total cost: € 0.68M EU contribution: €0.495 M (2012-09-01 - 2014-02-28)	SASAM's mission is to drive the growth of AM to efficient and sustainable industrial processes by integrating and coordinating Standardisation activities for Europe by creating and supporting a Standardisation organisation in the field of

Country / Research	Investment	Description and website for further information
Manufacturing (Europe)		AM. http://cordis.europa.eu/projects/rcn/104749_en.html
AEROSIM: Development of a Selective Laser Melting (SLM) Simulation tool for Aero Engine applications (Europe)	Total cost: € 0.9 M EU contribution: € 0.7M (2012-05-01 - 2015-04-30)	The main objective of this proposal is to develop a simulation tool that is based on an integrated finite element model by considering the material properties and process parameters of the manufacturing process for a realistic mapping of aerospace parts of the GTF. http://cordis.europa.eu/projects/rcn/106153_en.html
MERLIN: Development of Aero Engine Component Manufacture using Laser Additive Manufacturing (Europe)	Total cost: € 7.1M EU contribution: € 4.9M (2011-01-01 - 2014-12-31)	Rolls Royce PLC UK (project lead) http://cordis.europa.eu/projects/rcn/97209_en.html
INLADE: Integrated numerical modelling of laser additive processes (Europe)	Total cost: € 0.3M EU contribution: € 0.3M (2009-02-01 - 2013-01-31)	This project will link the Laser Processing Research Centre at The University of Manchester, which is one of the largest laser groups in the UK with expertise in experimental investigation and analytical modelling of these processes, with ESI GmbH based in Germany, a commercial engineering simulation and software development group with headquarters in Paris, France and with expertise in many areas of numerical engineering and thermodynamic simulation. Its aim is to develop integrated software packages to simulate all stages of the processes, including powder conveyance, powder dispersion in the melt pool, melt pool dynamics and track formation and heat flow and stress formation in the substrate. http://cordis.europa.eu/projects/rcn/89961_en.html
IMPALA: Intelligent Manufacture from Powder by Advanced Laser Assimilation (Europe)	Total cost: € 6.4M EU contribution: € 4.6M (2008-09-01 - 2012-08-31)	http://cordis.europa.eu/projects/rcn/89918_en.html http://cordis.europa.eu/fetch?CALLER=NEW_RESU_TM&ACTION=D&RCN=45402
COMPOLIGHT: Rapid manufacturing of lightweight metal components	Total cost: € 4.6M EU contribution: € 3.5M (2008-11-01 - 2011-10-31)	The project proposes to solve identified shortcomings of Rapid Manufacturing (RM) by addressing five areas, all of which are related to design and production of lightweight metal parts. These deficiencies are: 1) lack of design rules for RM, which could guide the designer, 2) lack of guidelines and

Country / Research	Investment	Description and website for further information
(Europe)		simulation software to support to the user in the work preparation prior to RM processing and predict quality features and mechanical properties of the part, 3) CAD application software to augment & partly automate the design of internal structures of a part, 4) research in the effective use of RM integrated in a process chain jointly with conventional processes, and 5) lack of ways to define and effectively control surfaces quality http://cordis.europa.eu/projects/rcn/89909_en.html
RAPOLAC: Rapid Production of Large Aerospace Components (Europe)	Project cost: €2.7M Project Funding: €2.1M (2007-2010)	http://www.rapolac.eu/pdfs/RAPOLAC_Final_PR.pdf http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=9595563&CFID=26552980&CFTOKEN=66557607&jsessionid=FC80A513ED82A3965C9D42427D8F68E4.APP1-PEB-D_900
UK Technology Strategy Board (TSB), is to invest in the development of "3D printing" (UK)	£7 M	UK to invest £7M in additive manufacturing : Funding competition designed to help UK become "a world leader in 3D printing". 22 Oct 2012. http://optics.org/news/3/10/29 [Last consulted: 2013.06.17] The UK has spent close to £96 million on the development of AM since 2007, with a recent TSB report highlighting that the vast majority of that money (£80 million) had been spent on research, with the remainder on technology transfer and business support. The Conservative-Liberal Democrat coalition has earmarked £14.7 million especially for developing 3D printing. June 10, 2013 http://www.tctmagazine.com/additive-manufacturing-research-to-benefit-from-290m-cash-i/
EPSRC Centre for Innovative Manufacturing in Laser-based Production Processes (UK)	Grant value £5.6 million.	Led by Professor Duncan Hand at Heriot-Watt University starting October 2013. Five UK academic Centres of Excellence, Heriot-Watt University (School of Engineering and Physical Sciences), Cranfield University (School of Applied Sciences), University of Cambridge (Institute for Manufacturing), University of Liverpool (Centre for Materials and Structures), University of Manchester (School of Materials) and 31 UK companies http://www.3dp-research.com/Current-Projects http://www.themanufacturer.com/articles/ready-to-use-additive-manufacturing/
Fraunhofer Additive Manufacturing Alliance (Germany)	n.a.	The Fraunhofer Additive Manufacturing Alliance encompasses eleven institutes which are based throughout Germany to form the entire additive manufacturing process chain, comprising the development, application and

Country / Research	Investment	Description and website for further information
		implementation of additive manufacturing methods and processes. http://www.generativ.fraunhofer.de/en/profile.html
Singapore	$500 M (assumed USD) (5 years)	Just last month the Singapore government announced that it is heavily investing in 3D Printing http://www.manufacturelink.com.au/news/view/a-new-paradigm-11198.aspx
China	$300M+ (assumed USD)	China is poised to spend a significant amount of money on AM ($300M+) http://www.firpa.fi/Stucker_presentation_FIRPA_seminar_2013-05-22.pdf "use of laser metal deposition to produce what is claimed to be the world's largest 3D printed titanium component—a four meter long primary load-bearing structure that will be used in the C919.1" http://igcc.ucsd.edu/assets/001/504640.pdf
Monash Centre for Additive Manufacturing (M-CAM) (Australia)	n.a.	M-CAM will first focus on titanium and nickel high-performance alloys to boost Australia's aerospace industry while value-adding to the country's titanium production Feb 26, 2013 http://www.australianmanufacturing.com.au/6734/monash-centre-for-additive-manufacturing-opens-in-melbourne-today

Other aerospace OEM and aero-engine manufacturers involved in this field that were encountered during the search included:

Table #3: Company Involvement

Company	Description and Website for further information
Boeing Company	Wohlers wrote: "Boeing is flying more than 100,000 3-D-printed parts" Source: Adler, E. 3-D printing expected to mould our tomorrows, Waterloo Region Record, Jun 07, 2013 http://www.therecord.com/living-story/3413787-3-d-printing-expected-to-mould-our-tomorrows/ In May 2012, Boeing unveiled its experiment of applying new 3D technology on the 747 line in its Everett plant. According to WSJ, Boeing is using 3D printing to make 300 parts for its aircraft, including ducts that carry cool air to electronic equipment. http://www.3ders.org/articles/20120916-3d-printing-coming-to-boeing.html In the UK Boeing is involved in supporting research programs in additive manufacturing at the University of Nottingham and the University of Sheffield. http://www.3d-printing-technologies.com/boeing.html
EADS	EADS, Leeds U build drone aircraft with additive manufacturing. 07/12/2012 http://www.industrial-lasers.com/articles/2012/07/eads-leeds-u-build-drone-aircraft-with-additive-manufacturing.html
GE Aviation	GE and Sigma Labs to improve AM jet engine parts [in-process inspection technologies for additive manufactured (AM) jet engine components] 05 June 2013 http://www.metal-powder.net/view/32771/ge-and-sigma-labs-to-improve-am-jet-engine-parts/ GE aims to print an advanced fuel nozzle tip that can withstand temperatures of 3,000 degrees inside the CFM International LEAP engine by the time the engine enters service in 2016 on the Airbus A320. It also will power Boeing's rival 737MAX. CFM, a joint venture of GE and Safran of France , says this will be the first production use of so-called additive manufacturing technology in commercial aviation. http://www.reuters.com/article/2013/06/18/airshow-production-idUSL2N0EU01420130618
Northrop Grumman Aerospace Systems	"Maturation of High-Temperature Selective Laser Sintering (SLS) Technologies and Infrastructure" Led by Northrop Grumman Aerospace Systems, in partnership with several industry team members, this project will develop a selective laser sintering (SLS) process for a lower-cost, high-temperature thermoplastic for making air and space vehicle components and other commercial applications. In addition, recyclability and reuse of materials will also be explored to maximize cost savings and promote sustainability. "Fused Depositing Modeling (FDM) for Complex Composites Tooling" These projects address a key near-term opportunity for additive manufacturing: the ability to rapidly and cost-effectively produce tooling for composite manufacturing. NAMII Selects Project Call Awardees Posted on Mar 20, 2013 http://namii.org/namii-selects-project-call-awardees/
Pratt & Whitney	Pratt & Whitney celebrates new additive manufacturing lab opening by Rose Brooke, April 8, 2013

Company	Description and Website for further information
(UTC)	http://www.tctmagazine.com/additive-manufacturing/pratt-%26-whitney-celebrates-new-additive-manufacturing-lab-opening/ http://www.sae.org/mags/sve/12061/
Rolls-Royce	TWI worked closely with Rolls-Royce to manufacture nickel alloy seal segments for the Intermediate Pressure stage of a Trent engine, This involved TWI taking the technology from a laboratory stage (TRL 3) through process development to successful engine testing (TRL 6/7). http://www.twi.co.uk/industries/aerospace/welding-of-aircraft-engines/laser-additive-manufacture/ Rolls-Royce PLC is coordinator of the MERLIN project (see above Europe) http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=11693721 An Investigation into the Comparative Costs of Additive Manufacture vs. Machine from Solid for Aero Engine Parts. 2006 http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA521730
Spirit AeroSystems Inc / Norsk Titanium Components AS	Partners Achieve Milestone for Near-Net Shape Titanium: Spirit AeroSystems, Norsk Titanum use plasma arc technology to produce titanium structural parts Jun. 20, 2013 [direct metal deposition] http://americanmachinist.com/news/partners-achieve-milestone-near-net-shape-titanium

1.4 Sources

Besides those in the footnotes of this report, the following references were consulted.

Allen, J. (2006) An Investigation into the Comparative Costs of Additive Manufacture vs. Machine from Solid for Aero Engine Parts. In *Cost Effective Manufacture via Net-Shape Processing* (pp. 17-1 – 17-10). Meeting Proceedings RTO-MP-AVT-139, Paper 17. Neuilly-sur-Seine, France: RTO. http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA521730 [Last consulted: 2012.06.17]

Anderson, E. Additive Manufacturing in China: Aviation and Aerospace Applications (Part 2). *SITC Bulletin Analysis*, May 2013. http://igcc.ucsd.edu/assets/001/504640.pdf

Freedman, D.H. Layer by Layer : With 3-D printing, manufacturers can make existing products more efficiently—and create ones that weren't possible before. *MIT Technology Review*, December 19, 2011. http://www.technologyreview.com/featuredstory/426391/layer-by-layer/ [Last consulted: 2013.06.17]

Gu, D. D. et al. Laser additive manufacturing of metallic components: materials, processes and mechanisms. *International Materials Reviews*, v. 57, no. 3, May 2012, p. 133-164.

Maxey, K. U.S. Losing its Edge in Additive Manufacturing? Posted on May 15, 2013 http://www.engineering.com/3DPrinting/3DPrintingArticles/ArticleID/5716/US-Losing-its-Edge-in-Additive-Manufacturing.aspx [Last consulted: 2013.06.18]

Vayre, B. et al. Metallic additive manufacturing: state-of-the-art review and prospects. *Mechanics & Industry*, v. 13, no. 2, p. 89-96.

Databases:

- CORDIS database (Community Research and Development Information Service) European Commission. http://cordis.europa.eu/newsearch/index.cfm?page=advSearch
- Frost.com
- Profound
- SCOPUS
- Strategic Business Insights

Automated Scanning Technologies

Title	**Aerospace Environmental Scan (WG1) : Automated Scanning Technologies**
Project Numbers	STI 17174
Date	July 29th, 2013
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC
Prepared by	Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca)

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1 AUTOMATED SCANNING TECHNOLOGIES

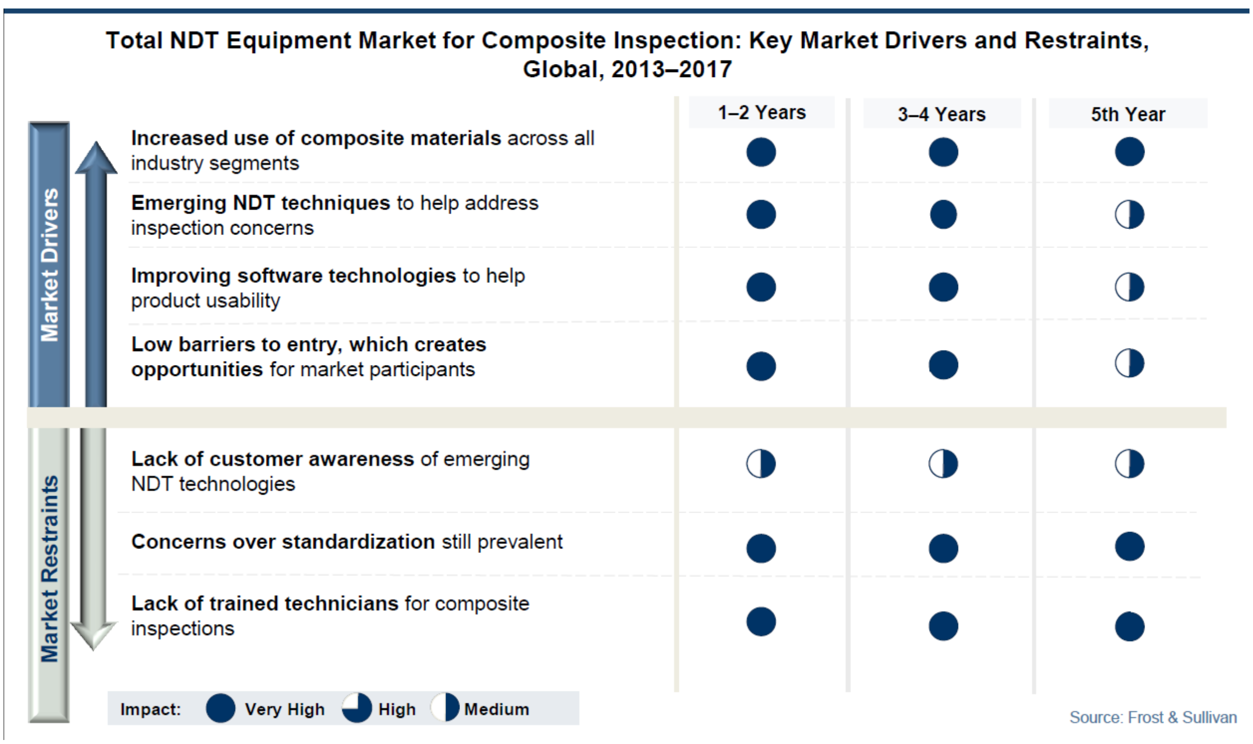
This scan covers the area of automated scanning technologies of finished parts including non-destructive testing (NDT) equipment for composite inspection.

The scan focuses on answering the following questions:

1. Drivers and barriers to the advancement/adoption of this technology;
2. Latest investments and projects;
3. Commercially available products;
4. Future of the technology

1.1 Drivers & Barriers

Figure 1: Drivers and barriers to NDT equipment market[1]



[1] Global NDT Equipment Market for Composite Inspection, Frost & Sullivan2013

Although composites constitute a multi-billion dollar industry and the NDT equipment market for composite inspection is relatively nascent. Research indicates that the NDT equipment market for composite inspection generated approximately $115 to $125 million in 2012. The CAGR for this market segment is expected to remain at approximately 6 to 8% from 2012 to 2017. Reservations regarding the capabilities of the commercial NDT equipment for composite inspection that is currently available are still prevalent. So end users prefer in-house repair and service inspection procedures.

Today, the majority of demand for NDT equipment for composite inspection comes from the aerospace industry. Strong potential exists for the future growth of this equipment type because of the market's current lack of reliable and cost-effective solutions. Globally, about 25 to 30 companies provide NDT solutions for composite inspection. Recognized companies, such as GE Measurement & Control Solutions, Olympus NDT, Sonatest, Vidisco Ltd., Technology Design Ltd, YXLON International GmbH, and Imperium, Inc., are actively involved in this market. However, research indicates that currently only approximately 5 to 8% of the total revenues of these companies are derived from equipment for composite inspection.

1.1.1 Specific Technologies

Although, currently, ultrasonic inspection is the most widely used technology for composite inspection, infrared thermography, laser ultrasonics, laser shearography, and digital radiography are making significant inroads, despite their higher costs. Progress in the establishment of NDT standards and the development of portable, user-friendly versions of the listed techniques is accelerating their adoption. There are a number of emerging and specialized NDT technologies for composite inspection, and each have their own sets of challenges and advantages. Techniques such as ultrasonic back scatter, acoustography, acousto-ultrasonics, spectroscopy, and microwave-based inspection are promising solutions. However, a lack of both standards and trained inspectors to implement these newly introduced solutions means that more traditional NDT technologies are expected to be the mainstay for composite inspection through the foreseeable future. Still, companies continue to make technological advances this market. For example, LSP Technologies, Inc., recently won a research grant from the US

Department of Defense's Advanced Research Projects Agency (DARPA) to develop its laser bond inspection system, which uses laser-induced stress waves to inspect the strength of adhesively bonded composite structures.

Table 1: Drivers and Barriers for the Adoption of Specific NDT Technologies

Technology	Drivers	Barriers
Laser Scanning	• Reduced costs of design and overall production cycle • Easier measurement, control and monitoring • High flexibility combined with decreasing cost of these solutions complemented by market potential in diverse industries	• Need for effective software for processing of large amount of data • Need for solutions enabling scanning specular (mirror and shiny) objects and surfaces • Need for simplified systems
3D Machine Vision	• Precision unachievable by human operators • Decreasing price of the 3D machine vision systems • Increased quality control across the entire manufacturing value chain	• Need for specialized software solutions • High computing power required for analysis of input data • The market is dominated by 2D solutions and professionals are not aware of capabilities of this technology
X-ray Scanning	• CT offer very high information density • Ability to scan inner structures of the measured objects	• There is a need from industry for the high flexibility unachievable with the currently available technology • Metals and other high density materials are challenging for CT scanning

The 3D (three-dimensional) non-contact measurement technologies are a group of technologies that include passive and active techniques, such as machine vision (stereovision based on two 2D cameras, 3D machine vision based on a single camera), industrial X-ray inspection, and laser scanning (laser triangulation, ToF).

The 3D non-contact measurement technologies are considered as the most promising techniques in manufacturing, process control, and in industrial automation because they have capabilities that go beyond the features of the conventional approaches based on the contact measurements. When compared to the 2D contact-free techniques, 3D non-contact measurement provides the user with the extended amount of data that can be used for more precise control over the process and for quality control and assurance.

The non-contact approach ensures that the measured surfaces/objects are not being damaged during the measurements.   These technologies ensure high level of automation of the measurements With the use of these technologies, it is possible to measure virtually any dimension of the object The techniques are flexible and are suitable for varied applications including manufacturing. [2]

Although the cost of the systems and solutions for the 3D non-contact measurement technologies is continuously decreasing, in the case of the advanced systems the cost is still a prohibitive factor. For instance, the cost of the X-ray inspection systems (for example CT) is more than € 250k (about US$332.5K) and the cost of the average scanner can vary from €25k (US$32.25K) up to €250k (US$332.5K) with the average price at $68k (about US$87.72K). The cost is a hindering factor, and typically the customers are interested in implementation of such systems when the ROI occurs relatively quickly or if the added value is significant.

Wide scale adoption/maturity of 3D non-contact measurement technologies is expected between 20018 – 2022.

1.2 Latest Investments and Projects

There was lack of market research reports, news coverage, or websites with research listings. A CORDIS database search identified the following European research programs.

Table 2: European Research Investments

Project (Country)	Investment	Description and website for further information
ADVICE : Autonomous Damage Detection and Vibration	Start date: 2006-10-01 End date: 2010-06-30 Total cost: €3.07M EU contribution: €1.76M	The objective of ADVICE is to design, model, develop and validate a smart wireless network of self-powered devices that can be used for simultaneous damping of structural vibrations and detection of damage in airplane and

[2] Advances in 3D Non-Contact Measurement Technologies for Manufacturing, Frost & Sullivan, 2013

Project (Country)	Investment	Description and website for further information
Control Systems	Project status: Completed	helicopter structures. ADVICE introduces both technological and methodological breakthroughs while addressing some of the main issues of "distributed measurement systems" Organization name: CENTRE DE RECHERCHE EN AÉRONAUTIQUE, ASBL (Europe) http://cordis.europa.eu/projects/rcn/79966_en.html
ARTIMA : Aircraft Reliability through Intelligent Materials Application	Start date: 2004-12-01 End date: 2007-11-30 Total cost: €4.9M EU contribution: €2.7M Project status: Completed	The objective of the proposed research is to achieve a leap improvement in aircraft reliability through the application of smart materials. There exists an acute need to develop the capability to monitor aircraft structural health in real-time, in a reliable manner. Real-time structural health monitoring will not only improve the overall safety but will also made it possible to replace Corrective or Preventive maintenance modes with much more efficient Predictive or Proactive maintenance procedures- thus reducing the associated cost. Organization name: AERNNOVA ENGINEERING SOLUTIONS S.A. (Europe) http://cordis.europa.eu/projects/rcn/72783_en.html
OPTIJECT : A novel NIR-based instrument for in-line monitoring during injection moulding	Start date: 2011-01-01 to End date: 2012-12-31 Total cost: €1.5M EU contribution: €1.1M	Defect detection and quality improvements are mostly carried out on the basis of quality control of finished parts, using visual inspection, weighing the moulded parts or using off-line analytical and mechanical measurements. To date, the optimisation of certain parameters of the injection moulding has been carried out using off-line analysis of the finished products. This project will build on the results of past research that has demonstrated the feasibility of using near infrared spectroscopy as a quality control tool in an injection-moulding machine. Organization neme: INNOVACIO I RECERCA INDUSTRIAL I SOSTENIBLE SL (Europe) http://cordis.europa.eu/projects/rcn/97201_en.html
AISHA II : Aircraft integrated structural health assessment II	From 2008-05-01 to 2011-10-31 Project cost: €5.7M Project Funding: €4.1M	The safe use of complex engineering structures such as aircrafts can only be guaranteed when efficient means of damage assessment are in place. Whereas the design of civil structures is nowadays based on a damage tolerance approach and time based inspection cycles, it is envisaged that the large cost associated with this approach can be drastically reduced by switching to a condition based maintenance schedule. Structural health monitoring is a technology where integrated sensors are used to enable continuous monitoring of the structural integrity. This project wants to continue the project "Aircraft Integrated Structural Health Assessment (AISHA) EU-FP6, priority 4 - STREP project nr. 502907) which was dedicated to the establishment of the

Project (Country)	Investment	Description and website for further information
		basic elements of a health monitoring systems based on ultrasonic Lamb waves. Organization name: KATHOLIEKE UNIVERSITEIT LEUVEN (Europe) http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=10422782

1.3 Commercially Available Products

About 25 to 30 prominent global vendors compete in the NDT equipment market for composite inspection. The market is still very nascent, with the primary sources of opportunity coming from the aerospace and automotive end-user industries. The competitive landscape is comprised of a combination of multinational companies with broad product lines for NDT technology and mid-sized companies with very specific regional and technological focuses.

Industry leaders such as GE Measurement & Control Solutions, Olympus NDT, and Sonatest offer a range of standard off-the-shelf NDT solutions, such as the Phasor series, Omniscan, and the Rapidscan Series, respectively. Thermography companies such as Thermal Wave Imaging, Inc. and MoviTHERM, Inc. are also active in this market.

While off-the-shelf NDT solutions are widely available, they do not meet the stringent and challenging requirements of the composite industry. A key trend is the use of robotics and automated advanced NDT devices to inspect composites of varying sizes and shapes. In 2012, EADS, in partnership with Airbus, Tecnatom SA, and iPhoton Solutions LLC, was awarded the prestigious JEC Innovation Award for the development of a new NDT system. Tecnatom and its North American technological partner, iPhoton Solutions, fine-tuned the concept for the laser-ultrasonic inspection system (LUIS), which was previously considered expensive and unreliable, to make it more accessible and cost-effective.
The iPlus series from iPhoton Solutions LLC, PaR Systems' Laser UT System, Tecnar's LUIS, and C-Check IR from Automation Technology GmbH are examples of other automated systems.

End users want devices that are easy to operate and test settings that do not require a high degree of technical knowledge. EADS Innovation Works, the global leader in aerospace, defence, and related services and the Norwegian company DolphiTech AS announced an agreement in 2011 to develop an ultrasonic 3D camera for composite inspection. In a similar vein, Imperium's Acoustocam i600 ultrasound imaging camera has generated considerable interest due to its cost-effectiveness and simplicity. In addition, Tier II participants such as SONOTEC Ultraschallsensorik Halle GmbH, Santec Systems, Inc., and Dantec Dynamics are also active in this market. [3]

Below is a non-exhaustive list of companies offering products supporting 3D non-contact measurement technologies for Aerospace applications.

Table 3: Companies offering products supporting 3D Non-Contact Measurement Technologies for Aerospace Applications

Company/Organization	Products
Faro Technologies http://www.faro.com/en-gb/products	FARO's portfolio of portable coordinate measuring machines (CMMs) includes measuring arms, laser trackers, 3D laser scanners and 3D imagers. These portable CMMs can be used for both contact and non-contact measurement
Nikon Metrology http://www.nikonmetrology.com/en_EU/Products	With the acquisition of Metris in 2009, Nikon enlarged its portfolio with optical 3D measuring instruments. The new division "Nikon Metrology" today offers the broadest range of metrology solutions for applications ranging from miniature electronics to the largest aircrafts.
Neptec http://neptectechnologies.com/our-products/	Neptec is an industry leader in developing innovative sensor, software and robotics technologies for the space market, develops and sells innovative 3D machine vision products for machine automation and robotics applications in harsh environments.

[3] Advances in 3D Non-Contact Measurement Technologies for Manufacturing, Frost & Sullivan, 2013

Company/Organization	Products
Nvision http://www.nvision3d.com/nvision-products.html	established in 1990 with one goal in mind: to provide customers with the highest accuracy non-contact optical measurement systems and services for Reverse Engineering and Inspection
Creaform http://www.creaform3d.com/en/applications/aerospace/3d-modelling-phased-array-inspection	
ShapeGrabber http://28189.vws.magma.ca/solutions-products.shtml http://blog.shapegrabber.com/2012/07/3d-laser-scanning-in-the-aerospace-industry.html	ShapeGrabber 3D laser scanners can be used to accurately measure or model any aerospace part. They help aerospace companies ensure stringent dimensional specifications for cast and machined parts.
Inus Technology http://www.rapidform.com/home/	Developer of 3D scan data processing software for reverse engineering and inspection of 3D scan data; rapidformXO Verifier (XOV), which is designed to automate the verification of part geometry using 3D digitizing/scanning technology.
Hexagon Metrology http://www.hexagonmetrology.fr/eng/Products_98.htm	Products include CMMs, laser scanners, CT scanners, etc.
Carl Zeiss Industrial Metrology http://metrology.zeiss.com/industrial-metrology/en_us/metrology-solutions/aerospace.html	Solutions include CMMs, software, sensors and accessories

1.4 Future of the Technology

Frost & Sullivan predicts that the industry will continue to push for simple NDT inspection and analysis techniques. Tthe design and manufacturing processes for composite components are constantly evolving. This will continue to pose considerable challenges to standardizing NDT procedures. The demand for NDT equipment that will inspect large areas during composite manufacturing will drive demand for non-contact solutions. [4]

According to Frost & Sullivan, currently there is lack of appropriate software tools for the 3D measurement technologies. 3D non-contact measurements have varied challenges with respect to software tools and there is a need for the industrial community to focus on this aspect.

Opportunities exist for start-ups and companies operating in the machine vision industry. 3D scanner manufacturers rely on the providers of the optical components' manufacturers and also on computing power. By increasing the speed, especially in the case of the 3D scanners, the amount of data that is needed to be computed is increased exponentially. This data must be visualized on the computer, processed and the results have to be analysed. This requires optimization of both the algorithms and data management capability.

One of the significant innovations in the field of the laser scanners is ToF (time of flight) technology. It is an emerging technology but it is not yet well developed for high resolution scans. The resolution achieved with this technology is in the range of few hundred points. With this increase in resolution, there is scope for diversification of applications.

The prices of 3D sensors are decreasing and, hence, these systems are becoming highly attractive to the customers. According to industry sources, the price of some of the 3D sensors is slowly reaching the price of the conventional 2D sensors.

[4] Global NDT Equipment Market for Composite Inspection, Frost & Sullivan2013

The market for the 3D non contact measurement technologies is in the phase of significant growth; and the investment opportunity is constantly growing. Demand for 3D non-contact technologies is high. Growth was high after the economic down turn, but the CAGR for all of the 3D non-contact measurement technologies (2013-2018) is above 5 percent. Asia appears to be one of the emerging markets for the 3D non-contact measurement technologies. However, the solutions are supplied to Asian companies from global corporations headquartered in the Europe and US. The growth of conventional measurement technologies is less dynamic compared to emerging technologies. [5]

1.5 Sources

Databases

- Frost & Sullivan
- MarketResearch.com
- Freedonia
- OneSource
- Cordis
- Internet

[5] Advances in 3D Non-Contact Measurement Technologies for Manufacturing, Frost & Sullivan, 2013

Machining Strategies/Technologies & Residual Stress

Title	**Aerospace Environmental Scan (WG1) : Machining Strategies/Technologies to Avoid Residual Stress**
Project Numbers	STI 17174
Date	July 29th, 2013
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC
Prepared by	Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca) Jean Kneale, Information Specialist (jean.kneale@nrc-cnrc.gc.ca)

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1 MACHINING STRATEGIES/TECHNOLOGIES TO AVOID RESIDUAL STRESS

Residual Stress Engineering (RSE) is becoming an increasingly important aspect in the design and manufacture of large monolithic aero-structures, more so under the environmental and aircraft weight challenges. Residual stresses not only affect structural performance during its service life cycle, but they also affect the part quality during manufacture and assembly. The inherent residual stresses are induced into the materials from various upstream manufacturing processes, such as quenching, stretching, compression, forming, machining, etc.[1]

This scan covers the area of machining strategies/technologies to avoid residual stress in metal parts. It hoped to answer the following questions:

1. Drivers and barriers to adoption of a particular technology;
2. Latest investments and projects;
3. Applications for these technologies.

No applicable market research reports were found specifically on this topic. We have had to rely on review and research articles in order to attempt to answer the questions.

As a result this report is comprised of a list of machining strategies or technologies used to avoid residual stress in metal parts. The machining strategies highlighted in this report were selected because avoiding or reducing residual stress was linked to the technology in the literature. We were only able to identify one source[1] that identified three technologies for distortion correction through residual stress engineering – shot peening, laser peening and age forming.

1.1 Drivers / Barriers

At a very high level, the drivers for developing processes that deal effectively with residual stress in aero-structures are the same as those for increasing the life of components.

[1] Sim, Wei-Ming (2012) Residual Stress in Engineering in Manufacture of Aerospace Structural Parts. http://www.transport-research.info/Upload/Documents/201211/20121115_114058_91510_Paper_IDE_2011.pdf

- Reduced material costs
- Reduced manufacturing costs
- Reduced downtime
- Reduced labor costs
- Improved reputation
- Increased future sales
- Increased safety
- Increased readiness/capability[2]

Ultimately, manufacturers are looking for technologies that will allow them to replace traditional parts with lighter ones having the same or better physical, mechanical or chemical properties.

Although no sources outlined the barriers to the adoption of all these technologies, LSP Technologies, Inc. lists the barriers for laser peening adoption as:

- relative high cost compared to traditional machining methods
- slow throughput[3]

A 2009 Bachelor of Technology thesis[4] lists the disadvantages of ultrasonic machining as:

- Ultrasonic machines have a relatively low MRR. Material removal rates are quite low, usually less than 50 mm3/min.
- The abrasive slurry also "machines" the tool itself, thus causing high rate of tool wear , which in turn makes it very difficult to hold close tolerances.
- The slurry may wear the wall of the machined hole as it passes back towards the surface, which limits the accuracy, particularly for small holes.
- The machining area and the depth of cut are quite restricted

[2] LSP Technologies, Inc. (2013) http://www.lsptechnologies.com/laser-peening-vs-shot-peening
[3] LSP Technologies, Inc. (2013) Preventing Fatigue Failures with Laser Peening. http://www.slideshare.net/laserpeening/preventing-fatigue-failors
[4] Samal, S.K. (2009) Study of Parameters of Ultrasonic machining. Bachelor of Technology Degree in Mechanical Engineering at the National Institute of Technology, Rourkela (Deemed University) http://ethesis.nitrkl.ac.in/1013/1/sumit_thesis.pdf

1.2 Investments & Projects

In a 1999 review on shot peening, David Kirk, the then Chairman of the International Scientific Committee on Shot Peening, stated, "It is worth noting that a very large number of published papers relate to the improvement of some aspect of service performance. This, of itself, has meant that there is a rapidly-accumulating knowledge base. Academic-based research is largely confined to the UK, France, Germany and Japan. Industry-based research appears largely as accounts of isolated examples of component improvement or equipment development. Current areas of study include attempts to quantify the improvement of stress-corrosion behaviour brought about by shot peening."[5]

A search of the CORDIS database was conducted and produced the following European projects. The US Army research program and other research programs in China and the UK were encountered during the internet research.

Table 1. Investments & Projects

Project titles	Description
AEROSIM http://cordis.europa.eu/projects/rcn/106153_en.html	Development of a Selective Laser Melting (SLM) Simulation tool for Aero Engine applications **From** 2012-05-01 **to** 2015-04-30 **Total cost**: EUR 966 476 **EU contribution**: EUR 700 290 Hence, the main objective of this proposal is to develop a simulation tool that is based on an integrated finite element model by considering the material properties and process parameters of the manufacturing process for a realistic mapping of aerospace parts of the GTF. Thus, for every part that has to be manufactured, the virtual process qualification of SLM increases the quality objectives high density", reduced distortion and residual stresses and specified microstructure characteristics.

[5] Kirk, D. (1999) Shot Peening : A Contributed Paper. http://www.shotpeener.com/library/pdf/1999003.pdf

Project titles	Description
OPTOCOM http://cordis.europa.eu/projects/rcn/108818_en.html	Optimal tooling system design for large composite parts **From** 2012-12-01 **to** 2013-11-30 **Total cost**: EUR 287 740 **EU contribution**: EUR 215 805 The general objective of the project is to smartly handle the overall process of the composite integrated parts production reducing costs in two ways. First, by adequately simulating the spring back produced after the curing process and providing solutions in order to reduce the costs of reworking or assembly. Secondly, by simulating the thermal model of the set tooling/compositepart/vacuum bag and auxiliary parts under autoclave conditions to optimize the cure cycle temperatures distribution creating more uniformity in the composite part, lower residual stress, lower energy costs and better environmental friendliness. Given the large number of parts produced and their growth, the importance of the target is large.
HITNIFO http://cordis.europa.eu/projects/rcn/102667_en.html	Development of an advanced design and production process of High Temperature Ni-based Alloy Forgings **From** 2011-10-01 **to** 2013-09-30 **Total cost**: EUR 455 000 **EU contribution**: EUR 260 875 High temperature strength means in most cases bad forgeability and weldability as well as combined with high toughness challenging machinability. Thus, beside of new designs the production processes have to be altered to get high quality parts. The overall goal of this project is an improved understanding of thermomechanical processing and its effect on residual stresses and distortion as well as microstructure and mechanical properties of forgings used for improved temperature exhaust cases.
AFSIAL http://cordis.europa.eu/projects/rcn/106997_en.html	Advanced fuselage and wing structure based on innovative Al-Li alloys **From** 2012-10-01 **to** 2013-08-31 **Total cost**: EUR 587 900 **EU contribution**: EUR 339 425

Project titles	Description
	The project aims at the development and demonstration of a metallic solution combining innovative aluminium alloys of the Al-Cu-Li family and advanced assembling technologies such as Laser Beam Welding and hybrid welding. Laser beam welding had demonstrated in the past to be the best suitable welding technology for flat panel production, especially for fuselage. The main advantages are the very low distortion, the absence of defects and reduced postweld re-work. Hybrid laser welding combines the advantages of laser processes with arc welding resulting in high joint quality and completion rates with increased tolerances to fit up and without compromising joint quality and distortion control.
COMPACT http://cordis.europa.eu/projects/rcn/78733_en.html	A concurrent approach to manufacturing induced part distortion in aerospace components **From** 2005-10-01 **to** 2009-09-30 **Total cost**: EUR 5 485 265 **EU contribution**: EUR 3 734 110 COMPACT is to look at manufacturing induced part distortion of aerospace alloy components. It is estimated that tens of millions of Euros are spent every year in an attempt to either avoid or remedy distortion in components. Consequently this is an expens ive problem for the aerospace sector that offers a significant business and intellectual challenge. Part distortion is a function of residual stress and is caused by the complex relationships between material processing, component design and manufacture.
FASTEBM http://cordis.europa.eu/projects/rcn/100826_en.html	High Productivity Electron Beam Melting Additive Manufacturing Development for the Part Production Systems Market **From** 2011-12-01 **to** 2013-11-30 **Total cost**: EUR 1 488 264

Project titles	Description
	EU contribution: EUR 1 145 600 Electron beam melting additive manufacture is used to produce successive layers of a part in a powder bed and offers the ability to produce components closest to their final dimensions, with good surface finish. At this time the process is faster than any other technique of comparable quality, however the parts are not produced at sufficient rate to make them economically viable for any but very high value specific applications. It has been identified that airframe production requires a large number of brackets of many different designs (>1200 in an Airbus A380). These are currently machined from aluminium and titanium billet, plate or forgings with extremely high wastage of material, which in the case of titanium alloys is expensive and contains scarce elements such as vanadium.
AEROBEAM http://cordis.europa.eu/projects/rcn/105870_en.html	Direct Manufacturing of stator vanes through electron beam melting **From** 2012-10-01 **to** 2013-09-30 **Total cost**: EUR 134 601 **EU contribution**: EUR 100 950 New aeronautical engine designs strive the manufacturers to use new processes which permit to add specific features such as stiffeners, often leading to weight or lead time saving. Electron Beam Melting (EBM) process is potential candidate but is not yet fully understood and controlled because of its lack of maturity.
Third Wave Awarded $500,000 to Develop CAE Technologies for Predicting and Modeling Distortion Minneapolis, MN USA http://www.thirdwavesys.com/news/press_ releases/2012/AATD_Award_Announcement.html	December 10, 2012 The Aviation Applied Technology Directorate (AATD) of the U.S. Army has awarded Third Wave Systems an approximately $500,000 contract to continue efforts to model machining, laser peening, and forming effects on final part stresses and distortions. The twelve-month initiative will focus on developing modeling capabilities for a variety of machining effects, including clamping, fixturing, and toolpath dependencies. Metal Improvement Company will serve as a

Project titles	Description
	collaborator on the project, providing expertise on laser peening and forming mechanics that produce engineered stresses. This is the second project at Third Wave to be funded by the AATD with a focus on residual stress and distortion prediction and management.
Effects of Laser Peening on Residual Stress Distributions and Deformation Microstructure of TiAl Studied by Blisk Laser Peening Device http://english.sia.cas.cn/rh/rp/201307/ t20130718_106597.html	Update time： 2013-07-18 Shengyang Institute of Automation, Chinese Academy of Sciences

1.3 List of Machining Strategies/Technologies

1.3.1 Shot Peening

Shot peening is a process by which several small spherical pellets bombard the surface of the part. This process is similar to sand blasting, but is not abrasive to the surface. During shot peening, the spherical pellets hit the surface of the metal with just enough force to cause plastic deformation. This deformation creates a dimple of the surface of the metal, which causes compressive stress. This type of stress is beneficial to the surface as compared to the tensile stresses, which are created while grinding and other operations during the manufacturing stages.

Nearly all fatigue and stress corrosion failures originate at the surface of a part, but cracks will not initiate or propagate in a compressively stressed zone created during shot peening. This is because of the overlapping dimples, which create a uniform layer of compressive stress at metal surfaces. In short, the process provides considerable increases in part life. Depending on process parameters, materials used, and part geometry shot peening can increase fatigue life from 0 to 1000%

Shot peening is the most economical and practical method of ensuring surface residual compressive stresses. This is because the process does not depend on heating the surface or altering the surface characteristics in modified conditions. By increasing layer depth of the surface, shot peening has the ability to prevent crack formation. However, to prevent cracks at a higher depth, techniques such as laser peening are used. However, laser peening is more energy-intensive, and hence less economical.

Apart from preventing cracks and fatigue-related failure, shot peening can also induce aerodynamic curvature in metallic wing skins used in advanced aircraft designs. Additional advantages of shot peening include, improvement of corrosion and wear characteristics of the sheet metal surface. Shot peening techniques are mostly applied on parts such as connecting rods, camshafts, turbine blades, and so on. [6]

1.3.2 Laser Peening

The website, LaserAge, states that Laser Shock Processing (LSP) or Laser Peening (LP) is consolidating as an effective surface technology to increase the resistance of metallic components to high-cycle fatigue (HCF), stress corrosion cracking (SCC), wear, etc. through imparting compressive residual stress fields to metallic structures or components from the surface level.[7]

According to the Shengyang Institute of Automation, laser peening technology has matured into a fully qualified production process designed to improve the performance and fatigue life of work-pieces, and will enable designers to consider higher stress levels in life limited designs. Laser peening can be used to prolong the fatigue life of aerospace, automotive, power generation, nuclear waste disposal, petroleum drilling, medical implants and recreational sports. In the aerospace industry, this surface technology starts to be applied to the tip of fan blades inside aircraft engines with the aim of saving the fatigue failure by foreign object damage.[8]

LSP Technologies, Inc. states that, laser peening exists today primarily due to one fact: shot peening generates insufficient residual stress profiles to prevent some critical parts from failing. Sometimes the shot peening intensity is insufficient to generate high enough compressive stresses and other times the

[6] Advanced Coatings Technology Alert, Frost & Sullivan, April 2011
[7] LaserAge website. (2013) http://www.laserage.ie/Technology_Development.html
[8] Shengyang Institute of Automation, Chinese Academy of Sciences. (2013) Effects of Laser Peening on Residual Stress Distributions and Deformation Microstructure of TiAl Studied by Blisk Laser Peening Device. http://english.sia.cas.cn/rh/rp/201307/t20130718_106597.html

depth of the compressive residual stress is simply too shallow. Laser peening bests shot peening in both of these categories.

In addition LSP Technologies, Inc. claims that laser peening has been shown to increase material performance in more ways than just by extending cyclic fatigue life. Laser peening also provides better results than shot peening in the following ways:

- Retains compressive residual stresses to higher temperatures
- Reduces crack growth rates (da/dN)
- Improves life of welded components
- Improves fretting damage resistance
- Improves galling resistance
- Improves spallation resistance
- Improves stress corrosion (SCC) resistance[9]

LSP Technologies, Inc. lists the barriers for laser peening adoption as:

- Its relative high cost compared to traditional machining methods
- Its slow throughput[10]

1.3.3 Electronic Beam Melting

An Electronic Beam Machine reads data from a CAD file, and deposits layers of powdered metal, which are subsequently diffused via a laser. Minimal post-production finishing is required. High-strength, void-free, residue-free, thermal stress-free parts can be manufactured. This process is mainly used for working titanium and other hard alloys, which are tough and difficult to work with. The cost to invest in this technology is high. Arcam AB (Sweden), holds several key patents in the technology.

[9] LSP Technologies, Inc. (2013) Laser Peening vs. Shot Peening. http://www.lsptechnologies.com/laser-peening-vs-shot-peening
[10] LSP Technologies, Inc. (2013) Preventing Fatigue Failures with Laser Peening. http://www.slideshare.net/laserpeening/preventing-fatigue-failors

EBM has been a pioneering concept. Production of cranial implants, high-accuracy production of parts and systems for defence sector has reached a new standard with this technology. It is now the de facto prototyping solution for working with titanium, titanium-based alloys, and other extremely hard materials. Areas of application include defense, aeronautical, biomedical, and automobiles--particularly in motorsports. [11]

1.3.4 Ultrasonic Machining

Ultrasonic machining (USM) is a new method used in metal cutting. This process does not involve heating or any electrochemical effects, causes low surface damage, has small residual stress, and does not rely on the conductivity of the work piece. [12]

Table 1: Advantages / Disadvantages of Ultrasonic Machining[13]

Advantages	Disadvantages
• Can be used to machine hard, brittle, fragile and non- conductive material • No heat is generated in work, therefore no significant changes in physical structure of work material • Alternative to EDM and ECM for non-metal materials (because of the poor electrical conductivity) • Is a burr-less and distortion-less process • Can be used in conjunction with other new technologies like EDM, ECG, and ECM	• Low Metal removal rate • Difficult to drill deep holes, as slurry movement is restricted. • Tool wear rate is high due to abrasive particles. • Can only be used when the hardness of work is more than 45 HRC

Ultrasonic machining is a mechanical type non-traditional machining process. It is employed to machine hard and brittle materials (both electrically conductive and non conductive material) having hardness

[11] Advances in Rapid Manufacturing – Technology Market Penetration & Roadmapping, Frost & Sullivan, Nov. 201

[12] Study of Optimal Machining Conditions of Ultrasonic Machining by Taguchi's Method, Wei Liu et al., Transactions of the Korean Society of Mechanical Engineers A, 37(2): 213-218, 2013

[13] National Institute of Technology Calicut, Jagadeesha T, Assistant Professor, Chapter 3 – Ultrasonic Machining

usually greater than 40 HRC. The process was first developed in 1950s and was originally used for finishing EDM (electro discharge machining) surfaces.

In ultrasonic machining, a tool of the desired shape vibrates at ultrasonic frequency (19 to 25 kHz.) with an amplitude of 15-50 microns over a work piece. Generally the tool is pressed down with a feed force F. The machining zone, between the tool and work piece, is flooded with hard abrasive particles generally in the form of a water-based slurry. Ultrasonic machining is a method of grinding that uses an abrasive liquid rather than direct tool contact. Most grinding processes involve a work tool making direct contact with a work piece in order to gouge material away. In ultrasonic machining, a liquid filled with abrasive material flows through over the work piece, and the work tool vibrates against the abrasives. The abrasive materials affect the work piece and remove material. Since the tool doesn't directly touch the work piece, the pressure and tool materials used in ultrasonic machining are often very different from those used in more common machining techniques.

The key to an ultrasonic machining process is the abrasive liquid. This material, called slurry, is a mixture of a free-flowing liquid and one or more types of solid abrasive. The liquid part of the slurry is generally water. For some jobs benzene, glycerol or oil may be used instead, but increasing the viscosity of the liquid will often lead to a slower process.

Since the abrasive used in ultrasonic machining slurry needs to be harder than the machined material, a wide range of abrasives are common. The basic abrasives are often silicon carbide or boron carbide, mostly due to their hardness and low cost. Occasionally, diamond dust is due to work the hardest materials. [14]

Applications

- Machining of cavities in electrically non-conductive ceramics
- Used to machine fragile components in which otherwise the scrap rate is high
- Used for multistep processing for fabricating silicon nitride (Si3N4) turbine blades
- Large number of holes of small diameter. 930 holes with 0.32mm has been reported (Benedict, 1973) using hypodermic needles

[14] http://www.wisegeek.com/what-is-ultrasonic-machining.htm

- Used for machining hard, brittle metallic alloys, semiconductors, glass, ceramics, carbides etc.
- Used for machining round, square, irregular shaped holes and surface impressions.
- Used in machining of dies for wire drawing, punching and blanking operations
- USM can perform machining operations like drilling, grinding and milling operations on all materials which can be treated suitably with abrasives.
- USM has been used for piercing of dies and for parting off and blanking operations.
- USM enables a dentist to drill a hole of any shape on teeth without any pain
- Ferrites and steel parts, precision mineral stones can be machined using USM
- USM can be used to cut industrial diamonds
- USM is used for grinding Quartz, Glass, and ceramics
- Cutting holes with curved or spiral centre lines and cutting threads in glass and mineral or metallo-ceramics

1.3.5 Age Forming

The following information has been taken from Ribero's 2010 review article on creep age forming.[15] Creep Age forming (CAF), also known as Age forming or Creep forming, is a process in which a part, usually an aluminium machined plate, is forming by creep on a tool at the same time that an ageing precipitation heat treatment is conducted . CAF is generally carried out within an autoclave. Vacuum is formed between the plate and the tool through of a vacuum bags assembly. When the autoclave pressure is raised, stage 1, the part is moulded on the tool and, if necessary, an extra pressure can be imposed by mechanical equipment. For the second stage, the residence time and temperature used in autoclaves are optimized for the ageing heat treatment. Therefore, the part reaches the best mechanical performance, hardening and strength. Later, creep is interrupted and the stress relaxation is not the maximum possible. Thus, after the part is removed from tooling, stage 3, the plate undergoes about 70% springback.

[15] Ribeiro, F.C., et al. (2010) Creep age forming: a short review of fundaments and applications. Journal of Achievements in Materials and Manufacturing Engineering, v. 43, issue 1, November 2010. http://www.journalamme.org/papers_vol43_1/43139.pdf

This process is relatively recent. CAF started to be studied in the 1980s by Textron, aiming large aluminium panels of about 15 m, to attain airfoil sections and complex curvatures. Textron developed a closed equation for beam and cylindrical CAF mold as well. The first aircraft to receive CAF parts was the USAF B-1B Long Range Combat Aircraft. Both the upper and lower wing skins were manufactured using CAF. The Gulfstream G-IV project marks the first time a double curvature wing panel was made using CAF techniques. CAF was applied in Airbus 330 and 340 imparting twist and curvature to extruded stringers. In the UK, QinetiQ developed the wings manufacturing process for Airbus 380. Both skins and strings were made using the CAF process .

More recently (as part of European Framework 5, 1998-2002), a consortium was formed by Alcan as an aluminium supplier, the University of Manchester focused on of the metallurgical interactions in the age forming process, Dassault Aviation representing executive aviation, Airbus representing commercial aviation, Sabca concerned with space structures for the Ariane program and Alenia, interested in studying new methods for fuselage.

One of the desires of the aviation industry is to manufacture structures with higher stiffness and strength, and low weight. In the context, to use creep age forming implies that the manufacture of the wing, skins and stringers, can be made entirely from the machining of a single aluminium block. Therefore, at the same time that this desire becomes possible, there is no need to have built-up steps with rivets or welding, therefore decreasing the manufacturing cost. Moreover, unlike all concurrent process, peen forming, stretching and roll forming, CAF is not carried out in plastic regime and, therefore, the residual stress level is significantly lower.

According to a report published in 2008 by the Argonne National Laboratory, age forming cannot generally be used on alloys in the damage tolerant condition (e.g. AA2024-T351)76. Therefore, one challenge for age forming is to obtain the best balance between operating creep and resulting part damage tolerance characteristics such as fatigue crack growth. To overcome this challenge, there is a need to introduce new alloys that can be used in artificially aged tempers. AA6056 and AA7475 have been shown to be less sensitive to the age forming process compared to the AA2XXX series alloy77.

1.4 Sources

Databases

- Frost & Sullivan
- OneSource
- Freedonia
- CORDIS
- Scopus
- Internet

STI Assessment

Title	**Human-Machine Interaction in Robotics**
Project Numbers	STI 17174
Date	2013.07.29
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC
Prepared by	Tamara McLaughlin, Information Specialist
Contact	Tamara McLaughlin 778-410-2356

Contents

1 HUMAN MACHINE INTERACTION IN ROBOTICS

The current standard perception of human-robot collaboration envisions a shared workspace between humans and robots in which the two can work safely in a collaborative manner. This technology is still only in the early stages or research, but already we are beginning to see significant advancements in the areas of voice controlled robotics, exoskeletons, haptic control (control by touch) and even neural control that will allow robots to become integrated into many industries, and even everyday life. As human machine interaction is in the very early research stage, both collaborative robotics (as it stands today) and human robotic interfaces (as they are envisioned to replace collaborative robotics) will be discussed in the following report. Where possible, we will focus on the programming aspects of touch, voice, gesture and neural controlled robots.

This report attempts to address the following four questions:

1. Where is this technology currently being used?
2. Where is it likely to be used in 5, 10 and 15 years?
3. Who is the world leader (company, university, research institute) in the development of the technology?
4. Has this technology been identified for applicability in the aerospace industry?

Please note that this report does not discuss remote controlled robotics systems unless they utilize haptic, voice, or neural control mechanisms.

1.1 Industries using the technology

Conventional industrial robots have traditionally been enclosed behind fences away from human workers, for safety reasons, and engaged in autonomous activities, for technological reasons. The push towards more automation and the increase in robotics sensing capabilities has allowed robots to work un-fenced, on the same floor with humans in a co-operative, assistive, capacity. Force sensing robots with the capacity to work safely with humans are becoming more commonplace in industrial manufacturing facilities, though they are largely still in the research and development phase[1]. Industrial robots are also being equipped with voice recognition capacity to further enhance human-robot collaboration. The obvious next stage in development is fully human-controlled robotics that can

[1] 2012. Frost and Sullivan. Advances in Collaborative Robotic Systems.

respond to mind, thought, voice, gesture, touch, etc controls. While we're beginning to see some progress in this area, even the newest designs are still in the early research stages[2 3].

According to Frost and Sullivan, the main application areas for collaborative robots (robots designed to work alongside humans) both now and in the future are automotive, aerospace, and job shops for custom parts. Collaborative robotics is currently being used in a service capacity in military applications, pipeline inspections, and logistics control [4].

1.1.1 Voice recognition

According to Frost and Sullivan, the key challenge in voice recognition in robots is the elimination of high environmental noise that interferes with the robots ability to follow human voice. "Language understanding and dialog systems between human users and robots continue to remain as an open research challenge which in turn hinders its adoption in consumer applications." Frost and Sullivan suggest that voice recognition robots will largely be used in home automation applications, rather than industrial manufacturing[5].

1.1.2 Gesture recognition

What was very recently strictly a research and development area, has become a hot trend in consumer electronics. Consumer-grade gesture recognition has been driven by Microsoft's Kinect for the Xbox gaming system. With the introduction of Kinect, gesture recognition quickly migrated from gaming systems to smartphones and televisions, and while not yet integrated into robotics systems, Microsoft released a Kinect software development kit in 2011 that was specifically intended to encourage developers to use the Kinect system in robotics applications[6]. Outside of the gaming industry, gesture controlled robotics systems are being looked at as assistive devices in operating rooms where they would respond to gestures from the surgeon and perform the desired function accordingly[7].

[2] 2010. Frost and Sullivan. Robotics for Maintenance and Safety.
[3] 2012. Strategic Business Insights. Viewpoints August 2012: Robotics.
[4] 2012. Frost and Sullivan. Advances in Collaborative Robotic Systems.
[5] 2010. Frost and Sullivan. Robotics for Maintenance and Safety.
[6] 2012. Innovaro. Technology Foresight: Machine Vision and Robotics. TF-2012-12.
[7] http://www.sciencedaily.com/releases/2011/02/110203152548.htm

1.1.3 Haptic control and wearable robotics

In terms of robotics that respond to touch or other tactile stimulations, the vast majority of current development is taking place in medicine (limb replacement or enhancement), and defense (exoskeletons, enhanced vision, etc) and these fields are likely to remain at the forefront of exoskeleton development for the foreseeable future[8]. Wearable robotics can facilitate the regaining of limb function in people with disabilities, and can also be used to increase the strength and endurance of workers. Existing full body exoskeletons are hampered by weight and bulk issues as well as issues related to power capacity and lack of flexibility or manual dexterity. Research is still ongoing in this area, particularly for military applications. To circumvent some of the issues present with current exoskeleton technologies, some researchers are focussing on certain physical component technologies that robotize only the body part necessary. As an example, General Motors and NASA are jointly developing slim-fitting robotic gloves intended to reduce repetitive strain injuries in both astronauts and autoworkers[9].

1.1.4 Neural control

Haptic feedback and physical mirroring are useful for augmenting or mapping an individual's movements, but more sophisticated means are necessary if researchers are going to be able to use robotics to enhance human bodies. Many prosthetic limbs must repurpose existing muscles to function, causing a strain on the user. In order to ameliorate this strain, a great deal of research is being done on using neural interfaces for prosthetic control. Despite the relative newness of the technology, significant advances have been made recently in both monkey and human subjects. BrainGate's recent research has shown great promise in allowing people to control prosthetics with their minds, and rather than utilizing sophisticated software to enable normal movement, they've created a control software program that can essentially write itself for each user by identifying "unique patterns of brain activation when each patient thinks about a specific movement. By learning each user's unique pattern, the software can relatively accurately assign the appropriate motions to the robotic arm.[10]" The United States Defense Advanced Research Projects Agency (DARPA) is another proponent of this research, and in addition to supporting BrainGate's research, they announced their own program last year, entitled *Avatar*, that should "enable a soldier to effectively partner with a semi-autonomous bipedal machine

8 2012. Innovaro. Technology Foresight: Human Enhancement and Work. TF-2012-40.
9 2012. Strategic Business Insights. Viewpoints August 2012: Robotics.
10 2012. Strategic Business Insights. Viewpoints August 2012: Robotics.

and allow it to act as the soldier's surrogate.[11]" There are numerous other attempts at producing thought controlled robotics[12] [13], but these are largely in the research and development stage with no clear timeline to deployment. While it seems logical that such technologies could be utilized in multiple industries, currently the only industries strongly present in this area are medical devices and defense.

1.2 Future of the technology

Frost and Sullivan expects a breakthrough in artificial intelligence sometime in the next 10 years that will lead to significant improvements in human robot interfaces (gesture control, biometrics, haptics, etc) and interaction[14]. They anticipate early adoption of collaborative robots in the automotive industry between 2015 and 2019 with mainstream adoption of collaborative robots in automotive, aerospace, consumer goods manufacturing, and apparel manufacturing taking place between 2020 and 2025[15]. Innovaro expects cooperative robots to expand to distributed control and team-based tasks through 2015, and to full cooperation and learning by 2020. They anticipate human machine interfaces to move from text-based interfaces in 2010 to human communication channels like touch by 2015 and direct brain interfaces through 2020[16]. Innovaro anticipates that the increased safety features inherent in collaborative robotics, and the responsiveness of voice control will encourage the adoption of robotics into the non-manufacturing sectors including foodservice, retail, logistics, healthcare, personal and professional services, education and entertainment. They will, of course, remain highly valuable to the manufacturing industry, oil and gas, military, security, automotive, aerospace, and space exploration.[17].

[11] 2012. Strategic Business Insights. Viewpoints August 2012: Robotics.
[12] http://www.reuters.com/article/2012/12/17/us-science-prosthetics-mindcontrol-idUSBRE8BG01H20121217
[13] http://www.newscientist.com/article/mg21528725.900-robot-avatar-body-controlled-by-thought-alone.html?full=true
[14] 2010. Frost and Sullivan. Robotics for Maintenance and Safety.
[15] 2012. Frost and Sullivan. Advances in Collaborative Robotic Systems.
[16] 2009. Innovaro. Robotic Visions. TF-2009-39.
[17] 2009. Innovaro. Robotic Visions. TF-2009-39.

1.3 Technology leaders

The lists of technology leaders below have been compiled from market research, and web sources.

These are not comprehensive, but rather represent the major companies.

Table 1: Collaborative robotics

Company	Technology
ABB	Software for facilitating safe robot human interaction - SafeMove[18]
Fanuc	Software for facilitating safe robot human interaction - Dual Check Safety[19]
Fraunhofer IFF	Workplace monitoring software for facilitating safe robot human interaction - ViERforES[20]
Harvest Automation Inc	Developing a cooperative robot for material handling[21]
Kawada Robotics	Nextage – collaborative robot
KUKA	Software for facilitating safe robot human interaction - Safe Operation[22]
Pilz GmbH	SafetyEYE – safety camera system[23]
Redwood Robotics	
Sick Inc	Software for facilitating safe robot human interaction[24]
Universal Robotics	Software and force sensors for facilitating safe robot human interaction.[25]

[18] Ibid.
[19] Ibid.
[20] 2012. Frost and Sullivan. Advances in Collaborative Robotic Systems.
[21] 2010. Frost and Sullivan. Robotics for Maintenance and Safety.
[22] Ibid.
[23] Ibid.
[24] Ibid.
[25] 2012. Frost and Sullivan. Advances in Collaborative Robotic Systems.

Table 2: Human-interfaced robotics

Company	Technology
Argo Medical Technologies	ReWalk – bionic walking assistance exoskeleton.
BeBionic	Myoelectric prosthetic hand with 14 different grips.
BrainGate Company	Neurologically controlled robotics for medical applications.
Delcam	Collaborative robotics software
DARPA	Neurologically controlled robotics for defense applications.
Festo	ExoHand – robotic exoskeleton glove and controller. Human augmentation device or glove that provides haptic feedback to an individual controlling a robot arm.
General Motors and NASA	Robo-Glove – reduces force exertion for heavy lifting.
Lockheed Martin	Human Universal Load Carrier – exoskeleton designed to help humans carry heavy loads.
NASA, The Florida Institute for Human and Machine Cognition (IHMC) of Pensacola, Fla. And Oceaneering Space Systems of Houston, TX.	X1 robotic exoskeleton used to assist or inhibit movement of leg joints. Inhibiting leg movement would be used in space to exercise the legs. Assisting leg movement would be used on the ground to facilitate walking for people with mobility issues.
Rethink Robotics	A semi-humanoid robot named Baxter. The robot can be trained by having a person manipulate its arms in a sequence to perform a task. The robot will record the sequence and be able to replicate it on demand[26].
RobotMaster	Collaborative robotics software
TIGAL, Austria	Developing a low cost voice recognition module to provide robots with voice command capability[27].
Tokyo University of Agriculture and Technology	Robotic suit to assist elderly farmers performing laborious tasks. Field tested. Commercialization expected soon.[28]

[26] 2012. Frost and Sullivan. Advances in Collaborative Robotic Systems.
[27] 2010. Frost and Sullivan. Robotics for Maintenance and Safety.
[28] Ibid.

Company	Technology
Tsukuba University and the robotics company CYBERDYNE	Hybrid assistive limb (HAL) – powered exoskeleton designed to support and enhance the physical abilities of the user. Mostly used as an assistive device for people with disabilities.
United States Naval Research Lab	Shipboard Autonomous Firefighting Robot (SAFFiR), is being designed to move autonomously throughout a ship, interact with people, and fight fires. The robot is being designed to work in a team environment, with interfaces to visually track the team, to monitor and respond to gestural commands, and understanding and follow voice commands[29].

1.4 Aerospace applications

While I was not able to find a listing of specific applications for collaborative robotics in the market research, aerospace was listed by Frost and Sullivan as one of the industries where the technology will be heavily used in the future[30]. Two examples of collaborative robotics in the aerospace sector come from MIT; the first is a new algorithm developed by MIT that enables a robot to learn human workers' preferences and adapt to their work style accordingly. The algorithm is being used to train robots to work closely with humans in aerospace factory conditions[31]. The second example from MIT is a navigation system with speech recognition that may one day be used in personal aircraft, and is currently being designed for use in conventional vehicles. The technology would ask the driver what he/she needs to accomplish in an allotted amount of time and then use digital maps to plan the most time and energy efficient route, suggest alternatives, and identify impossibilities[32].

For more advanced human-controlled robotics systems, it seems that the research is too preliminary to have clearly defined application areas outside of medical devices and defense, though some mention

[29] http://www.nrl.navy.mil/media/news-releases/2012/nrl-designs-robot-for-shipboard-firefighting
[30] 2012. Frost and Sullivan. Advances in Collaborative Robotic Systems.
[31] http://web.mit.edu/newsoffice/2012/robot-manufacturing-0612.html
[32] http://www.mit.edu/newsoffice/2013/vehicle-robot-human-collaboration-0503.html

has been made of utilizing haptic control interfaces for tele-operation of aerial robots[33], and human-interfaced robotics will likely figure in the future of un-manned space exploration.

1.5 Sources

Resources consulted during this search include:

IDC

Business Source Complete

Innovaro

Freedonia

OneSource

Frost.com

Profound

SCOPUS

Strategic Business Insights

[33] http://eprints.eemcs.utwente.nl/20019/

STI Assessment

Title	**Multi-use End of Arm Tooling**
Project Numbers	STI 17174
Date	2013.07.26
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC
Prepared by	Tamara McLaughlin, Information Specialist (Tamara.mclaughlin@nrc-cnrc.gc.ca)
Contact	Tamara McLaughlin 778-410-2356

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1 MULTI-USE END OF ARM TOOLING

End-of-arm tooling (EaOT), or end effector, is the term used for the tools attached to a robot arm that the robot uses to perform a value-added function. Most EoAT are constructed for a specific purpose such as drilling a hole. This request focuses on providing a robot with the ability to modify or assemble its own end-of-arm tool specifically to complete the desired function. A robot that is equipped to modify or construct its own end-of-arm tools will have a significant advantage over those that must wait for a human operator to design, built and install a new custom tool.

While quick-change EoAT's have been in place in the robotics industry (allowing robots to select from a set of existing tools and replace the current tool independently) since the 70's, the notion of a robot creating/modifying its own custom tools in largely unheard of. Searches of market research, scientific and technical literature, industry websites, and general Google searches did not turn up any useful information on robots capable of designing their own end-effectors. There is, however, an intermediary technology in place; multi-function end effectors. Multi-function end effectors allow the robot to select from a suite of tools built-in to the end effector without having to switch to a new end-of-arm tool. Due to the lack of information on robots that can construct their own tools, this report will focus solely on multi-use end effectors.

This report attempts to address the following four questions:

1. Where is this technology currently being used?
2. Where is it likely to be used in 5, 10 and 15 years?
3. Who is the world leader (company, university, research institute) in the development of the technology?
4. Has this technology been identified for applicability in the aerospace industry?

1.1 Industries using the technology

In the absence of existing market research on multi-use end-of-arm tooling, the listing of industries likely to utilize, or currently testing, this technology has been compiled from robotics manufacturers' websites.

Table 1: Industries using multi-use end of arm tooling

Industry	Use
Aerospace	Automated drilling and fastening of complex aircraft structures[1], fuselage assembly.[2]
Automotive	Tire manufacturing[3], painting[4], handling of small parts, removal of die-locked parts, injection mold extraction.[5]
Medical	Adaptable robotic surgery tools.
Food	De-panning baked goods, packaging, palletizing, bag handling.[6]
Palletizing	Bag gripping, palletizing plastic, woven cloth or paper bags containing grains, chemicals, dog food, minerals.[7]
Plastics	Packing bottle blanks and decorated bottles into trays, service cases, re-shipper cases, gondolas, as well as bulk packing – including the ability to fill out case headers with rows of lay down bottles.[8]

1.2 Future of the technology

No information on the future of this technology was identified during the search. Future applications are likely similar to those listed in the Self-reconfiguring Robotic Systems report.

[1] http://www.kuka-systems.com/NR/rdonlyres/879A9DC9-C921-489F-98E7-A6D83CE79A38/0/KUKA_MFEE_web.pdf
[2] http://www.alemaauto.fr/index.php/en/solutions-dautomatisation/effecteur-multifonction.html
[3] Applied Kinetics
[4] http://www.abb.com/cawp/seitp202/efff3baf6803681cc1257142004fc46b.aspx
[5] http://shop.sas-automation.com/en/industries/industries_automotive.htm
[6] http://shop.sas-automation.com/en/industries/industries_food.htm
[7] http://shop.sas-automation.com/en/industries/industries_palletizing.htm
[8] http://www.robots.com/articles/viewing/motoman-offers-robotic-bottle-handling-solutions

1.3 Technology leaders

Table 2: Industry leaders

Company	Technology
ABB	Cartridge bell system for automotive painting
Alema automation	Multiple mutli-function end effectors for fuselage assembly
Applied Kinetics	High performance, multi-function gripper end effector for the Tire Manufacturing Industry.
Columbia Okura	Multi-function end effectors for bagging and palletizing.
Comau	Multi-function end effector for drilling and fastener insertion.
Electroimpact	Aerospace industry - All process functions are carried out by a single multi-function end effector. Processes can include one-sided pressure to the work piece, auto-normalization, Boelube and/or flood coolant delivery, thru-tool coolant delivery, vacuum swarf extraction, automated vision, automated touch probing, precision drilling and countersinking, hole inspection, sealant application, fastener insertion, and milling.
Inventek	A specially designed multi purpose end of arm tool was designed and installed along with a large palletizing robot for a high volume plastic bottle manufacturer. The tooling not only picks and places the bottles, but also handles pallets, pallet frames and is able to place slip sheets in between layers of finished goods.
KUKA	Multi-functional robot end-effector designed specifically for the automated drilling and fastening of complex aircraft structures. Multi-functional end-effector - The unit is of a modular design, capable of being adapted to individual application requirements, and features both orbital and conventional (axial) drilling capability, in mixed materials (aluminium, titanium, carbonfibre).[9]
Motion Controls Robotics	Multifunction end effectors that can handle pallet, bottom sheet, top sheet and top frame with no need to change tools
Motoman	Multi-function gripper
SAS Automation	Programmable EOAT can be easily programmed to automatically relocate four separate component holders within the cycle of the robot, all within the same end-of-arm tooling (EOAT)[10].

[9] www.kuka-systems.com/NR/rdonlyres/.../0/KUKA_MFEE_web.pdf
[10] http://www.automation.com/automation-news/industry/sas-automation-introduces-programmable-robotic-end-of-arm-tooling

1.4 Aerospace applications

Multi-use end of arm tooling is already in use in the aerospace industry for aircraft assembly including fuselage assembly, auto-normalization, Boelube and/or flood coolant delivery, thru-tool coolant delivery, vacuum swarf extraction, automated vision, automated touch probing, precision drilling and countersinking, hole inspection, sealant application, fastener insertion, and milling[11]. As an example, OC Robotics is working with Airbus UK and KUKA to develop aerospace robots to deliver end effector packages capable of inspection, drilling, sealing and swaging[12].

No information was identified that discussed the use of robot constructed end effectors in the aerospace (or any other) industry. It is, however, clear that the aerospace industry is actively pursuing advanced robotics technology in all its forms, and is benefitting from the adoption of robotics in terms of accuracy and efficiency.

1.5 Sources

The following sources were consulted during the course of this search:

IDC

Business Source Complete

Innovaro

Freedonia

OneSource

Frost.com

Profound

SCOPUS

Strategic Business Insights

[11] http://www.electroimpact.com/Robotics/overview.asp
[12] http://www.ocrobotics.com/applications--solutions/aerospace/aerospace-case-study/

STI Assessment

Title	**Intelligent Sensing Robots**
Project Numbers	STI 17174
Date	2013.07.26
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC
Prepared by	Tamara McLaughlin, Information Specialist (tamara.mclaughlin@nrc.gc.ca)
Contact	Tamara McLaughlin 778-410-2356

Contents

1 INTELLIGENT SENSING ROBOTS

Robotics technology has come a long way since its inception. Robots are now able to handle a variety of tasks with minimal human intervention. Advancements in sensor integration such as vision sensing, force sensing and tactile sensing have imbued robots with the ability to sense and respond to their environments thus allowing them further autonomy and making them more useful tools for industry and other sectors. Intelligent robots have safety features built in that allow them the freedom to work in close proximity to humans rather than being segregated to prevent accidental injury. Their limbs are more flexible and adaptable, as are the tools they are equipped with, allowing them to perform an increasing array of functions. This request is specifically interested in those intelligent sensors that enable robots to perceive the working environment. Typically, simple sensors provide a signal to the robot's main program in which the information is compared, resulting in the possible execution of code. The term intelligent, refers here to sensors that have in-built processing capabilities and are self-learning. Once the processing is complete a signal may or may not be sent to the main robot program for evaluation. For example, the signal may contain a command and co-ordinates to move out of a "dangerous" situation. This technology is an enhancement to a robotic system which is intended to increase accuracy, speed, and safety.

This report attempts to address the following four questions for intelligent sensing robotics:

1. Where is this technology currently being used?
2. Where is it likely to be used in 5, 10 and 15 years?
3. Who is the world leader (company, university, research institute) in the development of the technology?
4. Has this technology been identified for applicability in the aerospace industry?

1.1 Industries using the technology

According to the International Federation of Robotics, intelligent sensing robots come in two main flavours, industrial robots and consumer/service robots[1]. A service robot operates with at least some degree of autonomy to perform services useful to humans and equipment (excluding manufacturing operations). They are able to make decisions and act autonomously in real-time and in unpredictable environments. The majority of applications for service robots currently fall in the defense, rescue and security sectors, though service robots also include agricultural robots (milking robots), construction and demolition robots, laboratory, rehabilitation, medical, and surgical robots, cleaning robots, logistics systems, educational and public outreach robots, and inspection robots[2].

Industrial robots are automatically controlled, programmable, multipurpose manipulators that may be fixed or mobile and are programmable in three or more axes. The automotive industry was the early adopter for industrial robots, but this uptake is now diminishing and there is an overall trend toward adoption of automation technologies in the non-automotive industries. The newer application sectors for intelligent sensing industrial robots include the food and beverage, glass, pharmaceutical, medical devices, metals, mining, processing, assembly, discrete parts manufacturing, logistics, defense, healthcare, consumer electronics and photovoltaic industries[3].

For the purposes of this report, since the main interest is aerospace manufacturing, we will be focussing on industrial robots.

1.1.1 Adaptive robots in flexible manufacturing

The only market information available on intelligent robotics was in regards to their use in flexible manufacturing. According to Frost and Sullivan, flexible manufacturing uses the same manufacturing facility to manufacture a high-volume, high variety product mix. Flexible manufacturing is becoming widely accepted across the manufacturing sectors including aerospace, automotive, consumer goods,

[1] http://www.ifr.org/industrial-robots/
[2] Frost and Sullivan. (2011). Advances in Sensors for Robotics Automation –Technology Market Penetration and Roadmapping (Technical Insights).
[3] Frost and Sullivan. (2011). Advances in Sensors for Robotics Automation –Technology Market Penetration and Roadmapping (Technical Insights).

food and beverages, warehousing, and architecture. Adaptive robotics are extremely useful in flexible manufacturing as they are able to perform enhanced functions in terms of changing part dimensions and variety with the aid of their component technologies which may include force/torque sensors, tactile sensors, vision sensors, advanced gripper systems, etc. Adaptive robotics is increasingly seen as an efficient and effective replacement for humans in hazardous or repetitive industrial tasks[4].

The key technologies which make a robot more adaptive are primarily:

1. Visual Guidance
2. Force/Torque/Tactile Sensors
3. Manipulators(end of arm tooling)
4. Software (for robot movement, guidance, and simulation).

A given intelligent robot may contain one or more of these technologies. A combination of these technologies enables the robot to make decisions in real time and thus increase manufacturing efficiency. Not all of these technologies are at the same stage of development though, and the integration of these technologies into truly intelligent robots is still in its early stages[5].

The major sectors interested in adaptive robotics are automotive, aerospace, packaging, consumer electronics, food and beverages, warehouse management, naval engineering, and architecture. Frost and Sullivan identifies five major application areas for flexible robotics: bin picking, flexible feeding, robot palletizing, robot assisted machining and mobile robots[6].

Bin picking uses vision guided robotics to select the correct part from a bin containing a random collection of parts. Given the time savings and lower labour costs, bin picking is increasingly being adopted across the manufacturing industry. The sectors primarily interested in bin picking currently include: automotive (sorting of the power train, stamping, final collection of parts), electronic devices (picking small electronic parts for processing), food and beverages (sorting of food)[7].

[4] Frost and Sullivan. (2012). Adaptive Robotics for Flexible Manufacturing (Technical Insights).
[5] Ibid.
[6] Ibid.
[7] Ibid.

Flexible feeding is an efficient and effective alternative to traditional parts feeding. Flexible feeding is most commonly used in the electronics industry (printed circuit board assembly, solar cell assembly, orientating display screens), but it also has some applications in the food and beverage (picking and transfer of food, visual line tracking, product alignment), automotive (feeding machined parts onto conveyors, part transfer), consumer goods (product alignment or selection) and aerospace industries[8].

Palletizing refers to the loading and unloading of parts from pallets in manufacturing industries. Automated palletizing robots offer cheap, flexible, easily maintained, efficient options over human-controlled devices. Palletizing robots are most commonly used in the distribution, food and beverages, and fast-moving consumer goods industries[9].

Robot-assisted machining makes use of robots to machine metal, and is cheaper and more flexible when compared to traditional machining methods. Currently robots cannot be used for high-precision machining, and most useful on soft materials like plastic or fibreglass. Robot-assisted machining is used in aerospace, architecture (stone milling, sculpting), and the automotive industry (wheel handling and machining, boring for part fixturing, and de-burring engine components)[10].

Mobile robots are used to transport materials from one point to another. This technology is increasingly being adopted by e-retailers as it allows easy tracking and retrieval of items from large warehouses. Retail and manufacturing industries are also adopting mobile robotics for palletizing, inventory management, and materials transport[11].

1.2 Future of the technology

Frost and Sullivan expects bin picking and palletizing using robots to be the most likely areas for market expansion in the next five years, with flexible feeding of parts close behind. Robot-assisted machining is, at this point, mainly a research challenge rather than a suite of available technologies. Low accuracy

[8] Frost and Sullivan. (2012). Adaptive Robotics for Flexible Manufacturing (Technical Insights).
[9] Ibid.
[10] Ibid.
[11] Ibid.

and lack of integration potential are holding this technology back, but once these are overcome, robot-assisted machining is likely to be rapidly adopted in the automotive and aerospace industries[12].

Bin picking is one of the more advanced applications of vision-guided robotics. Due to significant efforts to improve bin picking, adoption into the mainstream manufacturing industry is increasing. It is estimated that by 2022, major industries, such as electronics and pharmaceuticals will utilize it as a part of the standard assembly line. Development of integrated robotic solutions capable of integrating "adaptive gripper manipulation, robot movement and vision sensor modules coupled with laser guidance" are not expected until 2020 or later[13].

Flexible feeding is one of the fastest growing applications of vision guided robotics. Currently, its primary use is in the electronics and food manufacturing industries. Improvements in machine vision are expected to enable adoption of this technology into industries using micro-sized parts in the next 5 years. Further developments in integrated picking and feeding robots are expected to displace traditional feeders across the manufacturing industries by 2021. High adoption of this technology is also expected in the food and beverage industry by 2021[14].

Palletizing robots, like flexible feeding robots, are one of the fastest growing sectors of industrial robotics. Advances in machine vision and tactile sensors will enable robots to handle a wider variety of materials in the next five years and by 2021 they are expected to be integrated into packing/palletizing systems[15].

Robot-assisted machining is of great interest to corporations and SMEs due to cost saving and flexibility, but it is still largely in the R&D stage. While aerospace and automotive sectors are the initial adopters of this technology, it is not expected to be adopted by the mainstream of these industries until 2025[16].

Mobile robots are expected to become the standard for large warehouse automation in the next five years, especially for e-retail and logistics businesses[17].

[12] Frost and Sullivan. (2012). Adaptive Robotics for Flexible Manufacturing (Technical Insights).
[13] Ibid.
[14] Ibid.
[15] Ibid.
[16] Ibid.

In addition to industrial manufacturing, intelligent robots are expected to be of great importance in a variety of healthcare applications in the near future. Intelligent robots are also expected to continue making strides in defense applications, particularly in terms of unmanned vehicles and explosives detection, food processing applications, and agriculture (automating farms and factories)[18].

1.3 Technology leaders

The technology value chain for adaptive robotics includes five major areas:

- **Robot Manufacturers** develop specialized and general purpose robots to be used in various manufacturing processes.
- **Sensor developers** manufacture the sensors that enable robot flexibility by providing the control system with positional and environmental data which aid the control system in decision making. There are three major types of sensors being widely used in robotics, vision sensors (particularly useful in part identification or packaging), force/torque sensors (used for materials handling and collision avoidance), and tactile sensors (used in grippers to aid handling of materials with appropriate force).
- **End Effector Developers** manufacture end-of-arm tooling for robotics.
- **Simulation/Offline Programming Software Developers** monitor robot movement and simplify the arduous task of robot programming.
- **System Integrators** take multiple component technologies and integrate them into a single robotic system[19].

The listing of companies compiled below represents the major players in each of the five areas of the value chain.

[17] Frost and Sullivan. (2012). Adaptive Robotics for Flexible Manufacturing (Technical Insights).
[18] Frost and Sullivan. (2013). Global Sensor Outlook 2013 Increasing Smartness, Diagnostics, and Intelligence Drive Growth of the Global Sensors Market.
[19] Frost and Sullivan. (2012). Adaptive Robotics for Flexible Manufacturing (Technical Insights).

Table 1: Companies in the value chain

Company	Technology type
3D LMI	Sensor Developer
ABB Robotics	Robot manufacturer
Adept	Sensor Developer/Robot Manufacturer
Advatek	System Integrator
Aris bv	Sensor Developer
Artis	Robot Simulation
ATI Automation	Sensor Developer
Axium Industrial Automation	Robot manufacturer
Barret	End Effector Developer
Cognex	Sensor Developer
Comau Robotics	Robot manufacturer
Datalogic	Sensor developer
Delcam	Robot Simulation
Denso Robotics	Robot manufacturer
Epson Robots	Robot manufacturer
ESS Technologies	System Integrator
Fanuc	System Integrator/Robot Manufacturer/Software
FlexFactory	Robot manufacturer
Flexicell	System Integrator
Fraunhoffer IFF	System Integrator/Robot Simulation/Software
IPR Robotics	Robot manufacturer
iRobot	Robot manufacturer
ISRA Vision	Sensor Developer
JR3 Automation	Sensor Developer
Kawasaki Robotics	Robot manufacturer
Keyence	Sensor Developer
Kiva Systems	Robot manufacturer
KUKA	Robot manufacturer
Leutron Vision	Sensor Developer
Mesa Imaging	Sensor Developer
MIT	Robot Simulation/Software
Motoman	Robot manufacturer/Software
Nachi Robotics	Robot manufacturer
OC Robotics	Robot manufacturer – robots for aerospace sector
Perceptron	Sensor Developer

Company	Technology type
Rethink Robotics	End Effector Developer/Robot manufacturer
RIEGL	Sensor Developer
RMT Robotics	Robot manufacturer
Robotiq	End Effector Developer
RobotMaster	Robot Simulation
Scape Technologies	Sensor Developer
SeeGrid	Robot manufacturer
Shunck	Sensor Developer/End Effector Developer
SICK Sensor Intelligence	Sensor Developer
Staubli	Robot manufacturer
Syntouch	Sensor Developer
Teldyne Dalsa	Sensor Developer
Touchence	Sensor Developer
Velodyne	Sensor Developer
Yamaha Robotics	Robot manufacturer/Sensor Developer

List compiled from: Frost and Sullivan. (2012). Adaptive Robotics for Flexible Manufacturing (Technical Insights)., Frost and Sullivan. (2011). Advances in Sensors for Robotics Automation –Technology Market Penetration and Roadmapping (Technical Insights)., Freedonia (2012). Robots: United States., Marketline (2012). "Global Robots.", Frost and Sullivan. (2013). Collaborative Robotics for Manufacturing—Technology Benchmarking and Stakeholder Analysis (Technical Insights).

1.4 Aerospace applications

According to Frost and Sullivan, robot-assisted machining is ideal for the aerospace industry due to its flexibility in machining large parts. It is currently used for deburring aircraft engines, carbon compostite trimming for aircraft wings, milling for aircraft seats, machining aircraft engine parts, and automated drilling operations for aircraft parts. "Some of the early adopters of robots for machining are Armatec Survivability (Military), AV&R Vision & Robotics (Aircraft engines), General Atomics Aeronautical Systems and Weber Aircraft (Aerospace)."[20] Frost and Sullivan suggests that intelligent robots can also be of use on aircraft assembly, in-service inspection, and automation of tasks like polishing, correction, profiling, buffing, cutting and grinding. They claim that the use of robotics in the aerospace industry will facilitate

[20] Frost and Sullivan. (2012). Adaptive Robotics for Flexible Manufacturing (Technical Insights).

advanced inspection and quality control, ensure precision manufacturing in high-stress environments, and be cost-effective[21].

While not related to aerospace manufacturing, Strategic Business Insights' report *Space: A Robotic Frontier* discusses the possibility of robotic space missions taking the place of manned space exploration. As the technology reaches maturity, we may be able to utilize intelligent robots to explore space and conduct space-based resource extraction[22].

1.5 Sources

Sources consulted during the course of this search include:

IDC

Business Source Complete

Innovaro

Freedonia

OneSource

Frost.com

Profound

SCOPUS

Strategic Business Insights

[21] Frost and Sullivan. (2010). Robots for Maintenance and Safety.
[22] Shoop, P. (2012). September 2012 Viewpoints: Robotics. Strategic Business Insights.

STI Assessment

Title	**Self-Reconfiguring Robotic Systems**
Project Numbers	STI 17174
Date	2013.07.26
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC
Prepared by	Tamara McLaughlin, Information Specialist (Tamara.mclaughlin@nrc-cnrc.gc.ca)
Contact	Tamara McLaughlin 778-410-2356

Contents

1 SELF-RECONFIGURING ROBOTIC SYSTEMS

Self-reconfiguring robots are robots composed of a number or repeated modules that can arrange and rearrange their connections into a large variety of shapes and structures adapted to suit the task at hand.

This report attempts to address the following four questions:

1. Where is this technology currently being used?
2. Where is it likely to be used in 5, 10 and 15 years?
3. Who is the world leader (company, university, research institute) in the development of the technology?
4. Has this technology been identified for applicability in the aerospace industry?

1.1 Industries using the technology

Unfortunately, no market research was identified that discussed self-reconfiguring robotics, and none of the available scientific and technical literature discussed the industrial applications of the technology. Product descriptions and technical research only discuss demonstration projects and small-scale testing. This technology is largely in the research and development phase at this time, but it seems to hold great promise for the future. The exception to this seems to be in the medical devices industry where self-reconfiguring robotics are in limited use as surgical tools[1].

1.2 Future of the technology

The listing of industries likely to utilize, or currently testing, this technology has been compiled from robotics manufacturers' websites.

[1] http://www.medrobotics.com/technology.html

Table 1 : Future adopters of self-reconfiguring robotic systems

Industry	Use
Aerospace – demonstration only	Snake arms for aircraft assembly, tool or sensor delivery to restricted access sites, in-service inspection, repair, deburring, drilling, extraction of foreign bodies; installation of components; insertion of wire looms; laser welding; leak detection; non destructive testing; nut-running; painting; removal of liquids, gases or particulate matter; removal of swarf; and thermal imaging[2].
Nuclear - demonstration only	Snake arms used for visual inspection, remote handling, radiological inspection, sampling loose material, and recovery in the event of failure, nuclear decommissioning
Security	Snake arms used for remote vehicle inspection and towing, firefighting, explosives inspection[3]
Industrial	Snake arms for confined spaces work.
Search and rescue	
Pipe inspection	Oil and gas pipe inspection, sewage pipe inspection, etc.
Electrical transmission line inspection[4]	

The article *Modular Self-Reconfigurable Robot Systems*[5] identifies three long term applications for self-reconfiguring robots: space exploration, search and rescue, and bucket of stuff. Long-term space missions, manned or unmanned, would benefit greatly from a robotic technology that could modify itself to tackle any issue that arises during the mission. Not having to send fixed configuration systems capable of dealing only with predicted problems would both save on space and mass and provide the potential to address unforeseen problems. Bucket of stuff refers to the idea that in the future, consumers would have a "container of self-reconfigurable modules" that could address any household need on demand. The consumer could request the robot to perform a variety of household tasks (clean the gutters, change the oil in the car, etc) and the robot would assume the shape necessary to perform

[2] http://www.ocrobotics.com/applications--solutions/aerospace/aerospace-case-study/
[3] http://www.defencetalk.com/army-technology-expands-snake-robotics-27726/
[4] http://transsensorsrobots.epri.com/snake-robot.html
[5] Modular Self-Reconfigurable Robot Systems: Challenges and Opportunities for the Future, by Yim, Shen, Salemi, Rus, Moll, Lipson, Klavins & Chirikjian, published in IEEE Robotics & Automation Magazine March 2007. http://www.cs.rice.edu/~mmoll/publications/yim2007modular-self-reconfigurable-robot-systems.pdf

the assigned task.[6] Search and rescue represents a perfect opportunity for self-reconfigurable robots to shine. Their reconfigurable properties could allow them to squeeze through small spaces to locate victims, send out a homing beacon and reform to form a shelter around victims until they can be rescued[7].

1.3 Technology leaders

The article *Modular Self-Reconfigurable Robot Systems* provides a listing of self-reconfigurable modular systems in development up to 2006. This list represents the majority of self-reconfigurable modular robotics systems mentioned in more recent research.

Table 1. List of self-reconfigurable modular systems.

System	Class	DOF	Author	Affiliation	Year
CEBOT	mobile	various	Fukuda et al.	Nagoya	1988
Polypod	chain	2 3-D	Yim	Stanford	1993
Metamorphic	lattice	3 2-D	Chirikjian	JHU	1993
Fracta	lattice	3 2-D	Murata	MEL	1994
Tetrobot	chain	1 3-D	Hamlin et al.	RPI	1996
3D Fracta	lattice	6 3-D	Murata et al.	MEL	1998
Molecule	lattice	4 3-D	Kotay & Rus	Dartmouth	1998
CONRO	chain	2 3-D	Will & Shen	USC/ISI	1998
PolyBot	chain	1 3-D	Yim et al.	PARC	1998
TeleCube	lattice	6 3-D	Suh et al.	PARC	1998
Vertical	lattice	2-D	Hosakawa et al.	Riken	1998
Crystal	lattice	4 2-D	Vona & Rus	Dartmouth	1999
I-Cube	lattice	3-D	Unsal	CMU	1999
Pneumatic	lattice	2-D	Inoue et al.	TiTech	2002
Uni Rover	mobile	2 2-D	Hirose et al.	TiTech	2002
MTRAN II	hybrid	2 3-D	Murata et al.	AIST	2002
Atron	lattice	1 3-D	Stoy et al.	U.S Denmark	2003
Swarm-bot	mobile	3 2-D	Mondada et al.	EPFL	2003
Stochastic 2D	stochastic	0 2-D	White et al.	Cornell U.	2004
Superbot	hybrid	3 3-D	Shen et al.	USC/ISI	2005
Stochastic 3D	stochastic	0 3-D	White et al.	Cornell U.	2005
Catom	lattice	0 2-D	Goldstein et al.	CMU	2005
Prog. parts	stochastic	0 2-D	Klavins	U. Washington	2005
Molecube	chain	1 3-D	Zykov et al.	Cornell U.	2005
YaMoR	chain	1 2-D	Ijspeert et al.	EPFL	2005
Miche	lattice	0 3-D	Rus et al.	MIT	2006

Source: Modular Self-Reconfigurable Robot Systems: Challenges and Opportunities for the Future, by Yim, Shen, Salemi, Rus, Moll, Lipson, Klavins & Chirikjian, published in IEEE Robotics & Automation Magazine March 2007. [8]

[6] ibid
[7] ibid
[8] Modular Self-Reconfigurable Robot Systems: Challenges and Opportunities for the Future, by Yim, Shen, Salemi, Rus, Moll, Lipson, Klavins & Chirikjian, published in IEEE Robotics & Automation Magazine March 2007.
http://www.cs.rice.edu/~mmoll/publications/yim2007modular-self-reconfigurable-robot-systems.pdf

More recent self-reconfiguring robotic systems research and development is taking place in the following institutions. Please note, this is not an exhaustive list.

Table 2: Major players

Organization	Technology
AIST – Advanced Industrial Science and Technology	M-TRAN (Modular Transformer) is a self-reconfigurable modular robot that has been developed by AIST and Tokyo-Tech since 1998. A number of M-TRAN modules can form a 3-D structure which changes its own configuration a 3-D structure which generates smaller robots a multi-DOF robot which flexibly locomotes a robot which metamorphoses[9]
BioRobotics Lab at Carnegie Mellon	Snake robotics
BioRobotics Lab – Ecole Polytechnique Federale de Lausanne	Biorobotics Laboratory is featuring two hardware Modulare Robotics platforms; Roombots and Yamor. Roombots modules are designed to self-assemble into changing, active every-day environment elements, e.g. pieces of furniture. As they have multi-purpose features they can be used to assemble legged robots, like quadruped robots (link simulation results). The Yamor project is an earlier project, featuring one-degree of freedom self-sufficient modules with Bluetooth scatternet communication. They are assembled using a pin-and-hole plug system. The Locomorph project is a current EU-project.
Defense Research and Development Organisation's Centre for Artificial Intelligence and Robotics (CAIR), Bangalore	Snake robots for rescue operations.[10]
Distributed Robotics Laboratory – MIT	Multiple modular self-reconfiguring robotics systems.
Imperial College London	i-Snake – surgical robot.
MedRobotics	The Company has built a highly articulated multi-linked robot that will enable minimally-invasive procedures to replace open surgical procedures for many parts of the anatomy that are difficult or previously impossible to reach.
ModLab at University of Pennsylvania	Multiple modular self-reconfiguring robotics systems.
OC Robotics	"OCRobotics is working with Airbus UK and KUKA to develop aerospace robots to deliver end effector packages capable of inspection, drilling, sealing and swaging… A snake-arm robot can be

[9] http://unit.aist.go.jp/is/frrg/dsysd/mtran3/what.htm
[10] http://zeenews.india.com/news/science/indian-scientists-develop-snake-robots-for-rescue-ops_826726.html

Organization	Technology
	considered as an additional tool that the larger industrial robot can deliver or as an extension to the industrial robot. … Three interchangeable end effectors were designed by OCRobotics for the demonstrator: • An inspection tool (pictured above) containing several cameras with various functions • A swage tool (pictured right) to swage a rivet and direct the removed section into a collection area • A sealant tool (pictured below) incorporating a standard sized sealant cartridge and nozzle, with cameras to allow automatic orientation of the toolpiece to the seam."
PARC – Palo Alto Research Center	PolyBot, is a modular chain reconfiguration robot being developed at PARC (it's not clear if development is ongoing). It has demonstrated "several abilities, including locomotion, manipulating simple objects, and reconfiguring itself. Different versions vary the on-board computational power; the on-board battery power; the ability of modules to automatically dock, attach, and detach themselves; and the power of the modules' motors. [11] [12]
Robotics and Mechanisms Laboratory at Virginia Tech	Serpentine robot
SINTEF	Firefighting, and pipe inspecting snake robots.
University of Michigan Mobile Robotics Lab	OmniTread serpentine robots.

1.4 Aerospace applications

OC Robotics is currently working with its aerospace partners, including Airbus, on developing a robotics toolkit for aircraft assembly, specifically focussing on inspection, swaging and sealant tools. This toolkit includes a self-reconfiguring snake robot[13]. OC Robotics (in concert with KUKA[14]) seems to be the only commercial company developing self-reconfiguring robotics for the aerospace industry, though I was only able to identify two commercial companies with products in this area. This is a developing technology area, and most of the research is being undertaken by university researchers and not industry. Some industry suggestions for potential applications for modular self-reconfiguring robotics in

[11] https://www.parc.com/content/attachments/modular-robots-IEEE.pdf
[12] http://www2.parc.com/spl/projects/modrobots/publications/pdf/space.pdf
[13] http://www.ocrobotics.com/applications--solutions/aerospace/
[14] http://www.kuka-robotics.com/united_kingdom/en/pressevents/news/NN_120515_Snake_Arm_Robot.htm

the aerospace sector include: snake arms for aircraft assembly, tool or sensor delivery to restricted access sites, in-service inspection, repair, deburring, drilling, extraction of foreign bodies; installation of components; insertion of wire looms; laser welding; leak detection; non destructive testing; nut-running; painting; removal of liquids, gases or particulate matter; removal of swarf; and thermal imaging[15] [16].

1.5 Sources

The following sources were consulted during the course of this search:

IDC

Business Source Complete

Innovaro

Freedonia

OneSource

Frost.com

Profound

SCOPUS

Strategic Business Insights

[15] http://www.ocrobotics.com/applications--solutions/aerospace/aerospace-case-study/
[16] http://www.vision-systems.com/articles/2007/03/snake-arm-robots-speed-aircraft-assembly.html

STI Assessment

Title	**Aerospace Environmental Scan (WG3) : Ceramic Matrix Composites (CMCs)**
Project Numbers	STI 17174
Date	2013.07.12
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, Envirotrec
Prepared by	Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca) Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca) Mike Culhane, Strategic Information Analyst (mike.culhane@nrc-cnrc.gc.ca) Jean Kneale, Information Specialist (jean.kneale@nrc-cnrc.gc.ca)
Contact	C Jean Kneale, 613-998-3327

Contents

1 CERAMIC MATRIX COMPOSITES (CMCS)

Ceramic matrix composites (CMCs) are defined as "A reinforced ceramic material such as an aluminum oxide matrix reinforced with silicon carbide fibers".[1]

Ceramic matrix composites (CMCs) consisting of ceramics and reinforcing short fibers were developed due to their properties such as tolerance to high temperatures, reliability, low weight yet with strength close to metals. They have various classifications of which oxide- and monoxide CMCs are significant. In the aerospace sector, they are used in rocket motors, aircraft brakes, heat shields for space vehicles, and aircraft hot and cold structures of the engine. [2]

In ceramic matrix composites, only those fibre components are used that withstand the relatively high temperatures required for the production of ceramics, without significant damage. Other requirements to be met are long term high temperature stability, creep resistance, and oxidation stability. The importance of each of the demands depends on the type of application.[3]

This report attempts to answer the following questions:

1. What are the drivers and barriers, from technical, economic and regulatory perspectives, to the advancement/adoption and use of these materials in aerospace applications?
2. What are the most recent investments and projects on the use CMCs in aerospace applications
3. Who is using CMC's commercially and for what aerospace applications ?
4. What is the commercial availability of CMCs ?

1.1 Drivers and Barriers

[1] Definition copyrighted to the CRC Press. Source: http://composite.about.com/library/glossary/c/bldef-c1010.htm
[2] Frost & Sullivan. (2010) Aerospace Composites. *Technical Insights Reports*, 30 Sep 2010. Frost.com
[3] Park, S. (2011) Chapter 7.5 Ceramic Matrix Composites in Park, S. & Seo, M.-K. Interface science and composites. Amsterdam : Elsevier Academic Press, 2011. pp. 598.

The main drivers for [composite] usage are the demand for lightweight and stiffer materials, and their capability to be fabricated in any desired shape.[4]

Table 1: Composite Drivers and Barriers [ibid]

Drivers	Barriers
• Light weighting of components • Component stiffness • Ability to be fabricated in any desired shape	• High cost • Difficulty of processing • Material reliability.

Drivers and barriers depend on the field of application. Within the gas turbine market, there is tremendous commercial pressure on gas turbine manufacturers to increase the plant efficiency and reduce specific costs whilst continuing to meet the ever more stringent emission limits. The major drivers for advanced gas turbine technology are improved efficiency, reduced emission and lower costs.

1.1.1 Technical Drivers / Barriers

Table 2: Ceramic Matrix Composite Technical Drivers and Barriers [5]

Drivers	Barriers

• Improved gas turbine efficiency
• Reduced emissions
• Lower costs than traditional materials due to:
    o High temperature stability
    o High thermal shock resistance
    o High hardness
    o High corrosion resistance
    o Lightweight (1/3 weight of traditional alloys)
	• Lack of specifications
	• Lack of knowledge databases
	• Lack of attachment concepts
	• Lack of in-service repair methodologies
	• Difficulty in industrial manufacturing scale-up
	• Low toughness (brittle fracture behavior) [6]
	• Poor reliability under many loading conditions [ibid]
	• Microstructure optimization[7]

[4] Frost & Sullivan (2010) Aerospace Composites. Technical Insights Reports, 30 Sep 2010, frost.com.
[5] Except where otherwise noted: Park, S. (2011) Chapter 7.5 Ceramic Matrix Composites in Park, S-J. & Seo, M-K. Interface science and composites. Amsterdam : Elsevier Academic Press, 2011. pp. 612-613, 620.
[6] Strategic Business Insights [2013] Novel Ceramic/Metallic Materials – Technology Map. [Courtesy of NRC Knowledge Management subscription]

Drivers	Barriers
o Non-magnetic o Non-conductive o Versatility	• Path to entry into service [ibid]

1.1.2 Economic Drivers / Barriers

According to S. Park, the editor of the book *Interface Science and Composites*, as user confidence continues to grow and as energy savings, increased productivity and reduced maintenance are confirmed, the need has emerged for advanced ceramics with improved toughness (also known as ceramic composites). The future of ceramic matrix composites is directly dependent on the progress that would be achieved with the availability of higher performance constituents (fibres, interphases and tailored matrices) as well as in processing cost reduction. [5]

Increased use of CMCs in aerospace will require microstructure optimization, a path to entry into service, and improved affordability. Todd E. Steyer , Manager, Extreme Environment Materials, The Boeing Company, believes fundamental and applied research in damage accumulation mechanisms/models, life prediction methodologies and modeling, nondestructive inspection techniques, and robust field and depot-level repair methods will result in more CMCs in aerospace applications. [8]

[7] Steyer, T. (2013) Shaping the future of ceramics for aerospace applications. International Journal of Applied Ceramic Technology, v. 10, Issue 3, pp. 389-394. Article first published online: 9 APR 201. DOI:10.1111/ijac.12069
[8] Destelfani, J. (2013) Ceramic matrix composites make inroads in aerospace. Published on May 14th, 2013, http://ceramics.org/ceramic-tech-today/aeronautics/ceramic-matrix-composites-make-inroads-in-aerospace?wpmp_tp=0&wpmp_switcher=mobile [Last consulted: 2013.07.11]

Table 3: Ceramic Matrix Composite Economic Drivers and Barriers

Drivers	Barriers
• Superior performance to conventional materials at an affordable price	• High processing costs • Unconfirmed energy costs • Unconfirmed productivity improvements • Unconfirmed maintenance requirements

1.1.3 Regulatory Drivers / Barriers

Table 4: Ceramic Matrix Composite Regulatory Drivers and Barriers

Drivers	Barriers
• Requirement for light weight components to meet fuel efficiency demands • Requirement for higher operating temperatures for aircraft engine components	• Increasing international occupational health and safety environmental regulations for production lead to corresponding increase in cost of production • Increasing international recycling requirements

Because of the nature of some of these materials and the increase in environmental legislation around the world, a variety of regulatory factors are important. For example silicon-carbide whiskers to reinforce ceramic and metal-matrix composites produce the same carcinogenic effect in the lungs of laboratory rats that asbestos produces. Companies using these fibers or whiskers in the products have to adopt safe-handling procedures (such as closed systems) to protect their workers and many favour particulates as an alternative material.

The European Union wants to increase the proportion of recycled vehicles to 95% in 2015. Producers must address recycling issues by creating materials that are recyclable. Environmental concerns will hamper the introduction into automobiles of many advanced materials on a large scale until recycling these materials is feasible [assumed to be a similar trend in aircraft and aircraft engine components recycling].

However, the increasing movement toward lightweight vehicles and high-performance components will continue to drive the development and use of advanced materials in the long term. For example, by operating at higher temperatures, engines could burn fuel more efficiently. As low-density materials, ceramic can have a cascading effect on weight reductions in engines and vehicles overall, saving more fuel.[9]

[9] Strategic Business Insights [2013] Novel Ceramic/Metallic Materials – Technology Map. [Courtesy of NRC Knowledge Management subscription]

1.2 Recent Investments and Projects

The European Commission CORDIS database was searched for relevant research projects currently underway in Europe. The only other research program found was in Japan and has been listed although no detail on the level of investment was found. I would suspect that there are research programs in Japan, China and the US at the institutions identified in Table 3 – their research programs just weren't found during the search. According to the Handbook of Ceramic Composites, during the last 25 years, tremendous progress has been made in the development and advancement of CMCs under various research programs funded by the U.S. Government agencies: National Aeronautics and Space Administration (NASA), Department of Defense (DoD), and Department of Energy (DOE).[10]

By far the most active company in this field of research appears to be GE with its recent and well publicized $27M investment in its laboratory in Newark, NJ which manufactures advanced engine components made of ceramic-matrix composites (CMCs).

[10] Bansal, N.P. (ed.) (2005) Handbook of Ceramic Composites. Springer. http://books.google.ca/books/about/Handbook_of_Ceramic_Composites.html?id=oSYdgu3on_oC&redir_esc=y [Last consulted: 2013.07.16]

Table 5: Global Research Investments

Project (Country)	Investment	Description and website for further information
ATLLAS : Aerodynamic and thermal load interactions with lightweight advanced materials for high-speed flight **Coordinator: ESA (Netherlands)** **(European Commission)** http://cordis.europa.eu/projects/rcn/81457_en.html	2006-10-01 - 2009-12-31 Total cost: € 8.4M EU contribution: € 4.8M Project completed	At high speeds above Mach 3, classical materials used for airframes and propulsion units are no longer feasible and need to be replaced by high-temperature, lightweight materials, with active cooling of some parts. Both Ceramic Matrix Composites (CMC) and heat resistant metals will be tested to evaluate their thermal and oxidiser resistance. Participants (selection only): EUROPEAN AERONAUTIC DEFENSE AND SPACE - ASTRIUM GMBH - BUSINESS DIV. SPACE TRANSPORTATION DEUTSCHLAND EADS DEUTSCHLAND GMBH- CORPORATE RESEARCH CENTER GERMANY DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT E.V. OFFICE NATIONAL D'ETUDES ET DE RESCHERCHES AÉROSPATIALES' (France)
ATLLAS II : Aero-Thermodynamic Loads on Lightweight Advanced Structures II **Coordinator: ESA (Netherlands)** **(European Commission)** http://cordis.europa.eu/projects/rcn/97725_en.html	2011-05-01 - 2015-04-30 Total cost: € 6.5M EU contribution: € 4.7M	Objectives: the identification and assessment of advanced light-weight and high-temperature resistant materials for high-speed vehicles up to Mach 6. Both metallic (Titanium Matrix Composites and Ni-based Hollow Sphere Stackings) and non-metallic materials (Ceramic Matrix Composites and Ultra High Temperature Composites) will be evaluated. Participants (selection only): DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV EADS DEUTSCHLAND GMBH OFFICE NATIONAL D'ETUDES ET DE RECHERCHES AEROSPATIALES
SMARTEES : MULTIFUNCTIONAL COMPONENTS FOR AGRESSIVE ENVIROMENTS IN SPACE APPLICATIONS **Coordinator: FUNDACION TECNALIA RESEARCH & INNOVATION (Spain)** **(European Commission)** http://cordis.europa.	2011-01-01 - 2013-12-31 Total cost: € 2.7M EU contribution: € 2.0M	The aim of this proposal is the development of ceramic composites structures which are needed for applications in aggressive environments, where (oxidative) and temperatures are required, such as hot parts of space vehicles for orbital re-entry (reusable launcher vehicles, RLVs). The technical approach is focused on the development of multilayer concept based on high temperature ceramics (HTCs) and ultrahigh temperature ceramics (UHTCs) with multiple tailored properties. Their joining processes to conventional structural ceramic matrix composites (CMCs) or novel porous sandwich structures, and the final attachment to metallic structures. Participants (selection only): EADS DEUTSCHLAND GMBH AEROSPACE & ADVANCED COMPOSITES GMBH

Project (Country)	Investment	Description and website for further information
eu/projects/rcn/97205_en.html		
THOR : INNOVATIVE THERMAL MANAGEMENT CONCEPTS FOR THERMAL PROTECTION OF FUTURE SPACE VEHICLES Coordinator: DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV (Germany) (European Commission) http://cordis.europa.eu/projects/rcn/106790_en.html	2013-01-01- 2015-12-31 Total cost: € 2.7M EU contribution: € 1.9M	The technical approach is focused non-local concepts for thermal management including active cooling as well as passive cooling technologies, in order to extend the capabilities of re-usable Thermal Protection Systems (TPS) towards the requirement of future space flight including hypersonic transport. To achieve this technical target radically new thermal management solutions will be implemented in a new concept of TPS together with innovative materials and unique ceramic structures, reaching a TRL 2-3 at the end of the project. The passive systems will be based on thermal equilibration establishing an efficient heat transfer from highly loaded areas to regions with less loading. New ceramic matrix composites incorporating a new generation of highly thermal conductive fibres will be applied. Participants (selection only): THALES ALENIA SPACE ITALIA SPA AEROSPACE & ADVANCED COMPOSITES GMBH JAPAN AEROSPACE EXPLORATION AGENCY FUNDACION TECNALIA RESEARCH & INNOVATION
ADMACOM : Advanced manufacturing routes for metal/Composite components for Aerospace Coordinator: POLITECNICO DI TORINO (Italy) (European Commission) http://cordis.europa.eu/projects/rcn/108897_en.html	2013-10-01 - 2016-09-30 Total cost: € 3.9M EU contribution: € 2.7M	The aim of ADMACOM (Advanced manufacturing routes for metal/Composite components for aerospace) is to develop innovative manufacturing technologies based on advanced design of interfaces and of joining materials for aerospace components. As an example, an innovative joining technology for Ceramic Matrix Composites (CMC) to metals for aerospace components will be developed. This project gathers three industrial partners, academia and research institutions with proven world class expertise in production and joining of CMC. In particular C/SiC are produced by two industrial partners of this project (MTA and EADS). The industrial partner Nanoforce will exploit the innovative manufacturing technologies. Participants (selection only): FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V CONSIGLIO NAZIONALE DELLE RICERCHE EADS DEUTSCHLAND GMBH MT AEROSPACE AG NANOFORCE TECHNOLOGY LIMITED
HELM: High-frequency ELectro-Magnetic technologies for advanced processing	2012-06-01 - 2016-05-31 Total cost: € 10.3M EU contribution: € 7.2M	Lightweight ceramics and fibre reinforced ceramic composites, such as non-oxide Ceramic Matrix Composites (CMCs) and Expanded Graphite (EG), represent very promising solutions for high temperature applications in strategic industrial sectors, such as transport and energy. In

Project (Country)	Investment	Description and website for further information
of ceramic matrix composites and graphite expansion Coordinator: CONSORZIO INTERUNIVERSITARIO NAZIONALE PER LA SCIENZA E TECNOLOGIA DEI MATERIALI (Italy) (European Commission) http://cordis.europa.eu/projects/rcn/103660_en.html		fact, these materials are one of topical priorities of the European Technology Platform EuMAT and a strategic issue of the EC Research Roadmap on Materials. Huge market opportunities are expected for CMC and EG provided to overcome the three major identified gaps: high cost, difficulty of processing and materials reliability. New and more efficient manufacturing technologies can pave the way to improve material quality, reduce processing time, converge towards near-net shape fabrication, trim energy spent and abate production costs. Participants (selection only): EADS DEUTSCHLAND GMBH CONSIGLIO NAZIONALE DELLE RICERCHE FUNDACION TECNALIA RESEARCH & INNOVATION SNECMA PROPULSION SOLIDE
REBECCA : Réduction du bruit des turboréacteurs Herakles (France) http://www.safran-group.com/site-safran-en/press-media/media-section/article/commercial-aircraft-engines-use?12733	n.a.	Herakles is conducting some of its work on CMCs as part of the French "Rebecca" project, one of the Aerospace Valley competitiveness cluster's seven collaborative R&D projects involving twelve industrial and academic partners.[Jan. 2013]
ESPR : Environmentally Compatible Propulsion System for the Next Generation Super Sonic Transport Research Program (Japan)	n.a.	Kawasaki Heavy Industries is developing a Si-Zr-C-O/SiC composite for combustor liners with the goal of reducing CO_2 emissions by 25%. In another project, Ishikawajima-Harima Heavy Industries is developing a SiC/SiC vane for gas turbine engines http://composite.about.com/od/aboutcompositesplastics/l/aa030205.htm

Table 6: Research Organizations involved in CMC Research[11]

Organization	Description and Website for further information
Argonne National Laboratory (USA)	NDE Technologies for Ceramic Matrix Composites: Oxide and Non-oxide http://www.ornl.gov/sci/de_materials/documents/EllingosnNDEofCFCC_revised.pdf http://www.ne.anl.gov/capabilities/sinde/highlights/power_technology.html
DARPA (USA)	FY2012 : Demonstrate proof of concept for disruptive manufacturing of ceramic matrix composites. http://nextbigfuture.com/2011/06/darpa-2012-budget-details-project.html
Missouri University of Science and Technology (USA)	Listed in the CMC development activities chapter[11]
NASA (USA)	NASA Ames - HfB_2 and ZrB_2 are candidates for leading edge applications on future hypersonic reentry vehicles because of their high melting temperatures and good oxidation resistance[6] NASA Glenn has been directly involved in the effort to bring CMCs to turbine hot section components. The NASA Ultra Efficient Engine Technology program (UEET) was focused on driving the next generation of turbine engine technology. More recently, the NASA CLEEN and NextGen programs also aim to improve efficiency in aircraft propulsion. One of the major thrusts is the development and demonstration of advanced high-temperature materials which are capable of surviving the extreme environments of turbine combustion and exhaust. http://sbir.gsfc.nasa.gov/SBIR/abstracts/12/sttr/phase1/STTR-12-1-T12.01-9928.html Dever, J., Nathal, M., and DiCarlo, J. (2013).”Research on High-Temperature Aerospace Materials at NASA Glenn Research Center.” *J. Aerosp. Eng.* 26, SPECIAL ISSUE: Seventy Years of Aerospace Research and Technology Excellence at NASA Glenn Research Center, 500–514. http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29AS.1943-5525.0000321?journalCode=jaeeez
Oak Ridge National Laboratory (ORNL) (USA)	Listed in the CMC development activities chapter[11]
University of Illinois at Urbana-Champaign (USA)	Listed in the CMC development activities chapter[11]
CNRS - Centre National de la Recherche Scientifique	Listed in the CMC development activities chapter[11]

[11] BCC Research.(2010) Ceramic Matrix Composites : Technologies and Global Markets. Table of contents only. 10/01/2010. http://www.reportlinker.com/p0326188/Ceramic-Matrix-Composites-Technologies-and-Global-Markets.html [Last consulted: 2013.07.11]

Organization	Description and Website for further information
(France)	
EMPA (Swiss Federal Laboratories for Materials Science and Technology, Laboratory for High Performance Ceramics) (Switzerland)	Design, process and characterize ceramic based composites for innovative and challenging structural and functional applications. Projects are the center of attention, in which ceramic-ceramic composites (CMC), … polymer derived ceramic composites (PDC), … are required. We develop new and optimize state of the art production routes and transfer know-how and technologies to industry. http://www.empa.ch/plugin/template/empa/614/*/---/l=2
Fraunhofer ISC (Germany)	The work of this center focuses on the development and production-oriented design of ceramic high-temperature lightweight materials of the kind employed not only in the aerospace industry, but also to an increasing extent in power and propulsion engineering and in mass markets such as automotive engineering. The Center for High-Temeratur Materials and Design - in Bayreuth and Wurzburg - is currently setting up a self-contained process chain for the development, manufacture and testing of ceramic matrix composites (CMC). Founded 2012 http://www.isc.fraunhofer.de/bayreuth.html?&L=1
German Aerospace Laboratory (DLR - Forschungszentrum der Bundesrepublik Deutschland für Luft- und Raumfahrt.) (Germany)	The high performance ceramic brake pads were contributed by DLR, bringing in its experiences from various applications in space, automotive industry and emergency brake systems. [aircraft propeller brake] http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10661/1148_read-4507/#gallery/6855
Imperial College, Composites Centre (UK)	Damage and strength degradation in thermally loaded glass matrix composites A R Boccaccini (+Collaborators in Institute of Physics of Materials, Brno, Czech Republic, and University of Alabama at Birmingham, USA) http://www3.imperial.ac.uk/compositescentre/research/researchprojectsportfolio/ceramic#generalceramic
National Aerospace Laboratory (Japan)	Evaluating ceramic matrix composites for air breathing engines being designed for two-stage to orbit reentry space vehicles.[12] http://composite.about.com/od/aboutcompositesplastics/l/aa030205.htm
National Institute of Advanced Industrial Science and Technology (Japan)	Listed in the CMC development activities chapter[11]
University of Tokyo (Japan)	Our major research has been focused on processing, evaluation of properties, and performance evaluation relating to polymer, metal, and ceramic matrix composites. For structural composites, high temperature ceramic matrix composites and high temperature ceramic coatings are major research areas. The goal of this

[12] Sheppard, L.M. (s.d.) Emerging Applications of Ceramic and Metal Matrix Composites. http://composite.about.com/od/aboutcompositesplastics/l/aa030205.htm [last consulted: 2013.07.10]

Organization	Description and Website for further information
	research is to contribute to the solution of our energy and environmental problems and the realization of safe structures. http://www.cm.rcast.u-tokyo.ac.jp/research-e.html
Shanghai Institute of Ceramics, Chinese Academy of Sciences, Structural Ceramics Engineering Research Center (China)	Making use of excellent properties of advanced ceramics, such as high strength, high hardness, high-temperature resistance, wear and corrosive resistance, etc., the industrialization of oxide, nitride, carbide ceramics and corresponding composites are being studied to meet the demand for modern industry. Ceramic matrix composites, e.g. Cf/SiC, SiCf/SiC, Cf/C and Cf/SiO2. http://english.sic.cas.cn/rh/RD/scerc

Table 6: Company Involvement

Company	Description and Website for further information
Boeing Company	BCC Research.(2010) Ceramic Matrix Composites : Technologies and Global Markets. Table of contents only. 10/01/2010
EADS Astrium	BCC Research.(2010) Ceramic Matrix Composites : Technologies and Global Markets. Table of contents only. 10/01/2010
General Electric (USA) GE Ceramic Composite Products	On May 21, 2013, GE Aviation reported that it plans to invest $27 million (USD) and add up to 70 jobs in the next five years to develop a Lean Lab at its Newark, Del., facility, which manufactures advanced engine components made of ceramic-matrix composites (CMCs). Production technologies for CMC components will be developed and proven in Newark then transitioned to GE mass-manufacturing facilities.[13] Targeting SIC-based CMCs for use in several components in gas turbines – notably vanes, blades, shrouds and liners. Has developed and is starting to commercialize a range of CMCs for use in high-end aerospace, energy and industrial applications – such as gas turbines (aircraft engines and power generation), rocket motors, structural airframe components, structures for optical systems and other high- temperature systems. Produces these components using both MI and CVI technologies: MI components are lightweight and thermally conductive and can see use at very high temperatures; CVI components are extremely erosion resistant, strong and stiff. [14]

[13] [s.n.] (2013) GE Aviation opens composites plant in Mississippi, expands Delaware plant. Posted on: 7/9/2013, High-Performance Composites, CW : Composites World http://www.compositesworld.com/news/ge-aviation-opens-composites-plant-in-mississippi-expands-delaware-plant [Last consulted: 2013.07.11]

[14] Strategic Business Insights. (2013) Explorer, Novel Ceramic/Metallic Materials Technology Map. Pp. 44 [courtesy of NRC Knowledge Management subscription]

Company	Description and Website for further information
	Indeed, CMCs are already being introduced and have been utilized with the CFM LEAP high-bypass turbofan engine, currently being development in a joint venture between GE and Snecma. [15] Currently GE has developed a composite material branded as HiPerComp. Further the company is planning to apply HiPerComp CMC materials in flight-testing engines by the end of 2010, which will pave a way for the commercialization of the CMC materials in aviation industry. [16]
Goodrich Aircraft Wheels and Brakes	BCC Research.(2010) Ceramic Matrix Composites : Technologies and Global Markets. Table of contents only. 10/01/2010
Kennametal	BCC Research.(2010) Ceramic Matrix Composites : Technologies and Global Markets. Table of contents only. 10/01/2010
Mitsubishi Heavy Industries (Japan)	Includes development of CMCs for gas turbine applications [3]
Pratt & Whitney (UTC)	BCC Research.(2010) Ceramic Matrix Composites : Technologies and Global Markets. Table of contents only. 10/01/2010 GE's chief competitor in the jet engine business is United Technologies Corp's Pratt & Whitney, which has not invested in ceramic matrix composites and instead focused on a new engine design. http://ceramics.org/ceramic-tech-today/ceramics-and-glass-business-news-of-the-week-95
Rolls-Royce	Rolls-Royce, the global power systems company, announced today it has acquired Hyper-Therm High Temperature Composites, Inc. (Hyper-Therm HTC, Inc.), a producer of state-of-the-art composite materials, including ceramic matrix composites (CMCs), engineered coatings and thermal-structural components. "We expect CMCs will revolutionize the weight and performance of engines that currently rely on single-crystal superalloys found in today's most advanced engines." [17]
Safran	A year ago, Herakles (Safran) achieved a world first in commercial aircraft design when it developed an engine fitted with an exit cone made from ceramic matrix composites (CMCs), new variants of thermostructural composites.

[15] Podrug, D. (2013) Testing new materials and technology for the aerospace industry. SAE Aerospace Engineering, July 3, 2013, p. 15-19.
[16] Frost & Sullivan (2009) Ceramic Matrix Composite Materials with Enhanced Mechanical Property. *High Tech Materials Alert*. 10 Apr. 2009. Frost.com
[17] Rolls Royce. (2013) Rolls-Royce Acquires Hyper-Therm HTC, Inc. Wednesday, 1 May 2013 http://www.rolls-royce.com/northamerica/na/news/2013/020513_hyper_therm_htc.jsp [Last consulted: 2013.07.12]

Company	Description and Website for further information
	http://www.safran-group.com/site-safran-en/press-media/media-section/article/commercial-aircraft-engines-use?12733
Snecma	Indeed, CMCs are already being introduced and have been utilized with the CFM LEAP high-bypass turbofan engine, currently being development in a joint venture between GE and Snecma. [18]
United Technologies Corp. (USA)	Includes development of CMCs for gas-turbine applications [3] Yet GE's chief competitor in the jet engine business is United Technologies Corp's Pratt & Whitney, which has not invested in ceramic matrix composites and instead focused on a new engine design. http://ceramics.org/ceramic-tech-today/ceramics-and-glass-business-news-of-the-week-95

[18] Podrug, D. (2013) Testing new materials and technology for the aerospace industry. SAE Aerospace Engineering, July 3, 2013, p. 15-19.

1.3 Commercial Availability and Uses

1.3.1 Commercial Availability

Table 7: Representative Ceramic Composite Suppliers[19]

Continuous fiber ceramic composites	Discontinuous reinforced ceramic composites
3M Co.	Advanced Regractory Technologies, Inc.
Synterials, Inc.	ALANX Wear Solutions, Inc.
B.F. Goodrich	Cercom
Composite Optics, Inc.	DuPont Lanxide Composites, Inc.
Dow Corning Corp.	Greenleaf Corp.
DuPont Lanxide Composites, Inc.	
McDermott Technology, Inc.	
Techniweave, Inc.	
Textron Systems Corp.	

Other advanced ceramic composite suppliers encountered during the search were:

- Nippon Carbon Co. (Japan) [20]
- Coorstek (USA) [21]
- Ultramet (USA) [ibid]

1.3.2 Aerospace Uses

According to the Handbook of Ceramic Composites, ceramic matrix composites (CMCs) are at the forefront of advanced materials technology because of their light weight, high strength and toughness, high temperature capabilities, and graceful failure under loading. Ceramic composites are considered as enabling technology for advanced aeropropulsion, space propulsion, space power, aerospace vehicles, and space structures. CMCs would also find applications in advanced aerojet engines, stationary gas

[19] Park, S. (2011) Chapter 7.5 Ceramic Matrix Composites in Park, S. & Seo, M-K., Interface science and composites. Amsterdam : Elsevier Academic Press, 2011, pp. 613.
[20] Croft, J. (2012) GE: CMCs may yield 1.5% fuel burn cut in Leap engines. 10:44 12 Jul 2012, Source: Pro http://www.flightglobal.com/news/articles/ge-cmcs-may-yield-15-fuel-burn-cut-in-leap-engines-374337/ [Last consulted: 2013.07.11]
[21] Frost & Sullivan (2010) Aerospace Composites. Technical Insights Reports, 30 Sep 2010, frost.com.

turbines for electrical power generation, heat exchangers, hot gas filters, radiant burners, heat treatment and materials growth furnaces, nuclear fusion reactors, automobiles, biological implants, etc. Other applications of CMCs are as machinery wear parts, cutting and forming tools, valve seals, high precision ball bearings for corrosive environments, and plungers for chemical pumps.[22]

Table 8: Aerospace Uses of Ceramic Matrix Composites [23] [24] [25]

Uses	Specifics
Aero-engines / Gas turbines	• Cold sections • Hot sections (engines and exhaust systems) o Turbine disks o Combustor liners o Turbine airfoils / blades o Transition duct convergent flags o Acoustic liners o Shrouds o Exhaust nozzles
Aircraft brakes	
Space vehicles	• Heat shields (nosecaps, leading edges of wings, etc.)
Rocket motors	

There is an excellent illustration of the CMC Candidate Components for Aeronautics on page 2 of the paper on *Advances in ceramic matrix composite blade damping characteristics for aerospace turbomachinery* (unable to reproduce it here). It illustrates the specifics in the gas turbine applications listed above.[26]

[22] Bansal, N.P. (ed.) (2005) Handbook of Ceramic Composites. Springer. http://books.google.ca/books/about/Handbook_of_Ceramic_Composites.html?id=oSYdgu3on_oC&redir_esc=y [Last consulted: 2013.07.16]
[23] King, D. et al. [s.d.] Advanced aerospace materials: past, present and future. Smith School of Enterprise and the Environment, Oxford University. http://www.chriscarey.co.uk/a&e_materials.pdf [Last consulted: 2013.07.11]
[24] Frost & Sullivan. (2010) Aerospace Composites. *Technical Insights Reports*, 30 Sep 2010. Frost.com
[25] Strategic Business Insights. (2013) Explorer, Novel Ceramic/Metallic Materials Technology Map. Pp. 44 [courtesy of NRC Knowledge Management subscription]
[26] Min, J.B.; Harris, D.L.; Ting, J.M. (2011) Advances in ceramic matrix composite blade damping characteristics for aerospace turbomachinery applications. (2011) Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, art. no. AIAA 2011-1784, p. 2.

2 SOURCES

Databases:

- CORDIS database (Community Research and Development Information Service) European Commission. http://cordis.europa.eu/newsearch/index.cfm?page=advSearch
- Frost.com
- Profound
- SCOPUS
- Strategic Business Insights

STI Assessment

Title	**3D Fibre Preforms in Composite Products**
Project Numbers	STI 17174
Date	2013.07.19
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, Envirotrec
Prepared by	Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca) Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca) Mike Culhane, Strategic Information Analyst (mike.culhane@nrc-cnrc.gc.ca) Jean Kneale, Information Specialist (jean.kneale@nrc-cnrc.gc.ca)
Contact	C Jean Kneale, 613-998-3327

Contents

1 3D FIBRE PREFORMS IN COMPOSITE PRODUCTS

A preform can be defined as: (1) A preshaped fibrous reinforcement formed by distribution of chopped fibers by air, water flotation or vacuum over the surface of a perforated screen to the approximate contour and thickness desired in the finished part. (2) A preshaped fibrous reinforcement, of mat or cloth, formed to desired shape on a mandrel or mock-up prior to being placed in a mold press. Normally, the mat is lightly bonded with a fast curing resin in approximately the shape of the end product, for use in processes such as matched-die molding. (3) Also applies to tablets, biscuits and pellets of thermosetting and thermoplastic compounds which are formed by compressing premixed material to facilitate handling and control of uniformity of charges for mold loading. (4) May be used as a verb for the fabrication of molding powders into pellets, tablets or shapes designed to facilitate filling of cavities in molding processes.[1]

In today's technical textiles marketplace, when people mention 3D weaving or 3D fabrics, they usually are referring to a growing category of products used primarily in highly performance-driven composite applications. Such applications range from jet engine components and engineered shapes to composite billets for bulkheads and ballistic armor panels. The attraction and interest in 3D woven products specifically for composite applications stems from the following attributes:

- design flexibility and versatility;
- inherent resistance to delamination;
- improved damage tolerance;
- ability to tailor composite properties to the application;
- near net-shape preform capabilities;
- weight reductions vis-à-vis most metal counterparts
- reduced lay-up complexity and handling time.[2]

[1] About.com – Composites and Plastics. http://composite.about.com/library/glossary/p/bldef-p4222.htm [Last consulted 2013.07.24]
[2] Kaufmann, J. (2012) 3D Weaving: Applications and a Range Of Possibilities. Textile World. September/October 2012, v. 162, Issue 5, p. 30-33. 3p. http://www.textileworld.com/Articles/2012/October/Sept-Oct_issue/3D_Weaving.html [Last consulted: 2013.07.17]

This report attempts to answer the following questions:

1. Where is this technology likely to be used over the next 5 to 10 years and for what purpose?
2. Who (company, university, research institute) is the world leader in the development of the technology?
3. What are the latest investments and projects in the area?

1.1 Technology Forecast

1.1.1 Near-Term Technology Forecast

I found no recent or applicable technology forecasts that predicted the near or long term use of 3D preforms for composite products.

According to a 2008 report by the National Composites Network in the UK on technical textiles, "The transportation (Mobiltech) market, for example, while continuing to be the largest and most valuable application sector for the foreseeable future, is expected to experience some distinctly contrasting trends with declines in the per unit consumption of reinforcing textiles for tyres, hoses and belts due to changing product technologies and longer working lifetimes being only partially offset by newer applications, such as air bags and composite materials. A trend towards smaller cars, lighter weight materials and a projected slowdown in total vehicle construction before all add to the complexity of the situation facing suppliers to this market.

Meanwhile, the highest growth rates are to be found in relatively small and newer application areas for technical textiles such as geotextiles (fabrics used in conjunction with soil), protective clothing, sport textiles and environmental products. Nonwovens are projected to become the largest single product group overtaking woven fabrics. Better prospects are seen for knitted and braided textiles, but the use of fibres and textiles for composite reinforcement is the only area where higher growth rates are expected more or less across the board."[3]

[3] National Composites Network. (2008) Technical Textiles & Composite Manufacturing - a Guide to Best Practice. http://www.compositesuk.co.uk/LinkClick.aspx?fileticket=QjRRsrWRDQs%3D& [Last consulted: 2013.07.19]

This report goes on to claim that the Mobiltech market is the single most valuable world market for technical textiles with an estimated global value of $30B USD in 2010. The mobiltech market in this report is defined as all technical textiles used in the construction and furnishing of all transportation vehicles for passengers and goods, both civil and military, by land or air.

In his article on rapid layup published in 2012, Malnati makes the following statement: “Today, it is beyond dispute that three-dimensional (3D) fabric preforms can produce high-performance composite parts in sizes ranging from small to gigantic. But for high-volume industries, such as the automotive sector, 3D preforming processes have been, thus far, too time consuming and, therefore, too expensive to be a serious materials/process option for production cars. But that could change with a new technology that offers the opportunity to automate time-consuming and labor-intensive hand layup of 3D preforms. The technology, a 2010 JEC Innovation Award winner in the Materials category, is trade named Han-3D fabrics and Han-3D composites (global pat. pend.).”[4]

1.1.2 Applications

According to Kaufmann in his article entitled “An Introduction to 3D Weaving”, near net-shape preforms can have rather complex geometries tailored to specific applications including airfoils, fan blades, radomes, tubes, bifurcated shapes, contours and structural cross sections such as T's, Pi's and X's. Many are made from ultra-high-performance fibers and used in extreme high-temperature applications in which traditional metals are not able to withstand the operating environment. Other applications include unique cross-section components that help to improve joint strength for composite assemblies. For these applications, the flexibility of 3D weaving allows for the orientation and positioning of fiber paths that are more in line with physical stresses, resulting in improved product design and efficiency. [5]

According to Alistair McIlhagger, Ph.D., senior lecturer at the Engineering Research Institute at the University of Ulster in Belfast, Northern Ireland, the implications of [3D fiber textiles] advancement

[4] Malnati, P. (2012) Rapid layup: New 3D preform technology. High-Performance Composites, Composites World. http://www.compositesworld.com/articles/rapid-layup-new-3D-preform-technology [Last consulted: 2013.07.17]
[5] Kaufmann, J. (2012) An Introduction To 3D Weaving. Textile World, July/August 2012, v. 162, issue 4. http://www.textileworld.com/Articles/2012/July/July_August_issue/An_Introduction_To_3D_Weaving.html [Last consulted: 2013.07.17]

could mean large-scale change for the use of composites across major commercial markets such as automotive, wind and aerospace.[6]

Although perhaps too far removed from 3D woven textiles, the Polymer Matrix Composites Technology Map produced by Strategic Business Insights lists a number of possible applications.

Table 1: Applications of Complex Near Net Shape Preforms[7]

End Use	Examples
Aircraft	High performance engine components – vanes, airfoils, fan blades, fan casings and containment systems Fuselage advanced structural assemblies
Wind turbines	Rotor blades
Automobiles, trucks, recreational vehicles, and buses	Race car components
Marine craft	High performance boat components, hull materials
Bridges and marine pilings	Girders and beams
Construction	Girders and beams
Sports equipment	Fishing rods, tennis rackets, oars, windsurf masts, hockey sticks, skis, bicycle parts, golf-club shafts
Biomedical applications	No detail provided
Ballistics	Sabots, missile fins and nose cones, armor
Energy Infrastructure	Power plants Oil rigs[8]

6 McPherson, A. (2012) A New Dimension for Aerospace: The growing interest for 3D wovens in the aerospace market. December 26, 2012. http://www.compositesmanufacturingblog.com/2012/12/a-new-dimension-for-aerospace/ [Last consulted: 2013.07.19]
7 Kaufmann, J. (2012) 3D Weaving: Applications and a Range Of Possibilities. Textile World. September/October 2012, v. 162, Issue 5, p. 30-33. 3p. http://www.textileworld.com/Articles/2012/October/Sept-Oct_issue/3D_Weaving.html [Last consulted: 2013.07.17]
8 3Tex, Inc. website. Current Markets. http://www.3tex.com/Current_Markets.html [Last consulted: 2013.07.19]

1.2 World Leader

No market research reports were found that identified the leading authors, research institutions or companies using or researching the use of 3D preforms in the production of composites.

A dated 2009 assessment by the Inter-Agency Composites Group for the UK states “In global terms, the UK is a little behind mainland Europe in developing the technical textile industry for producing composite preforms. In no case, however, has any European country truly established an industrial capacity to manufacture preforms on a large economic scale. The leading country is the USA where Techniweave (and to some extent Bally Ribbon Mills) has attempted to move to a semi-industrial scale manufacture and has a very broad capability for producing all forms of textile products. However, its products are still considered very expensive due to the low volume of manufacture. 3Tex has also been promoting 3D orthogonal billet-like materials to defense markets.”[9]

This report goes on to describe the expertise held in 2009 by the UK. It states, “The UK is currently a recognized leader in the development of 3D textile preforming technology within the research environment. There is a strong university sector with the University of Manchester and the University of Ulster possessing capabilities for design and manufacture of 3D textile forms using carbon and glass, and those universities along with Nottingham and Bristol having capabilities in modeling textile performance. Cranfield has developed expertise in automated preforming and z-reinforcement technologies, whereas centres such as Qinetiq have specialist facilities in robotic stitching and tufting. “[5]

A search was performed in the SCOPUS database which yielded 189 articles published during the period 2008-2013. What follows is an analysis of those publications where we can note:

1. China and the United States would appear to be the leading countries undertaking research in this field.

[9] Inter-Agency Composites Group. [2009] Technology Needs to Support Advanced Composites in the UK. November 2009. http://avaloncsl.files.wordpress.com/2013/01/composites-tech-needs-nov-2009.pdf [Last consulted: 2013.07.19]

2. Expertise, as illustrated in Figure 1, is spread out among a number of institutions (based on the author affiliations associated with published papers in the field). With no particular institution publishing the majority of the articles.
3. The most prolific author for the period 2008-2013, A.E. Bogdanovich, is from the Department of Textile Engineering, Chemistry and Science, at North Carolina State University , USA.

Figure 1: Country Expertise

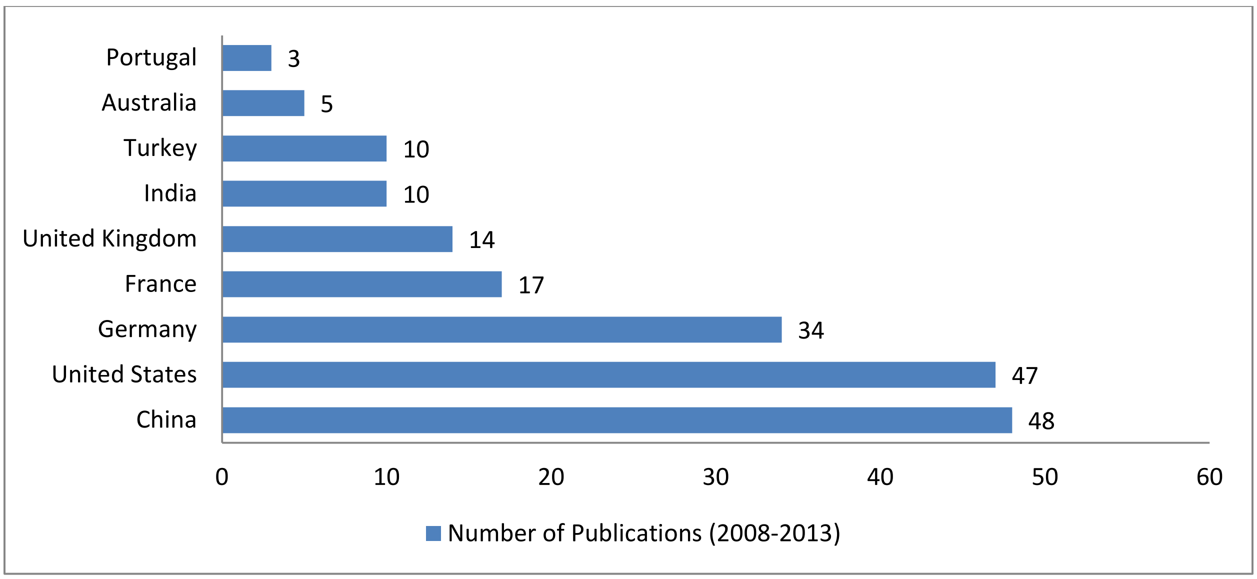


Figure 2: Top Research Institutions

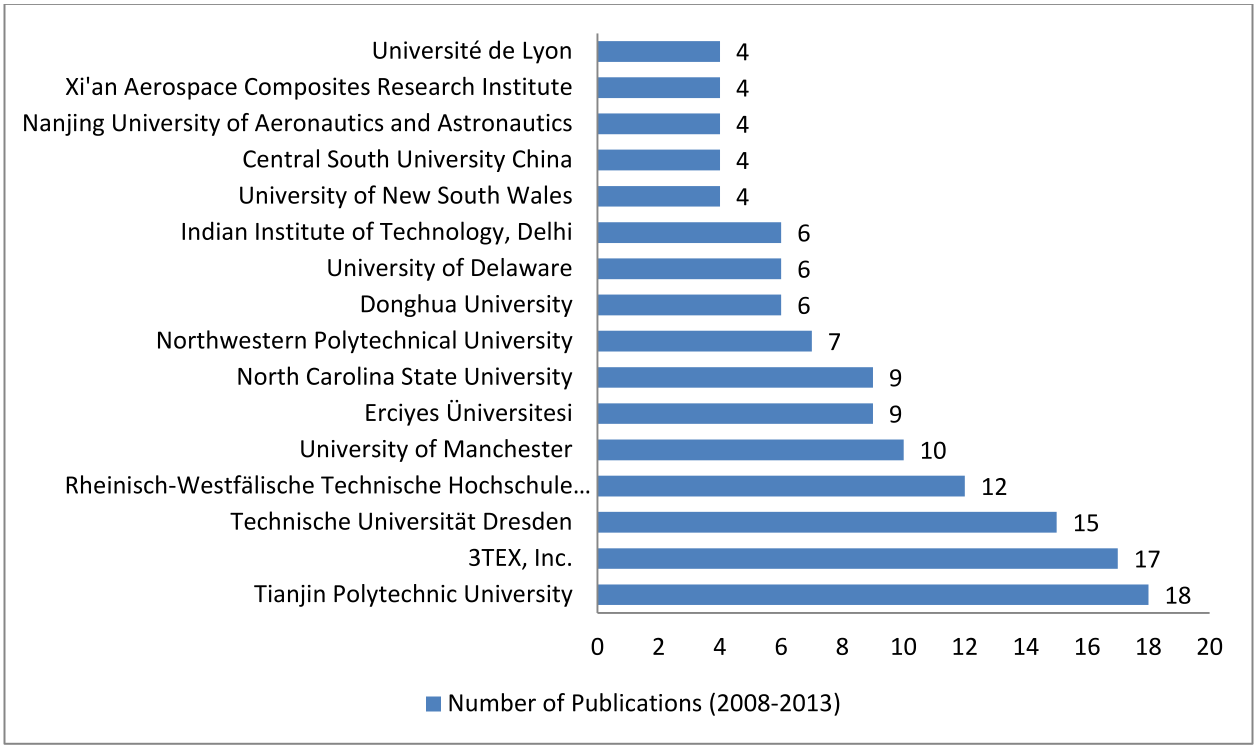
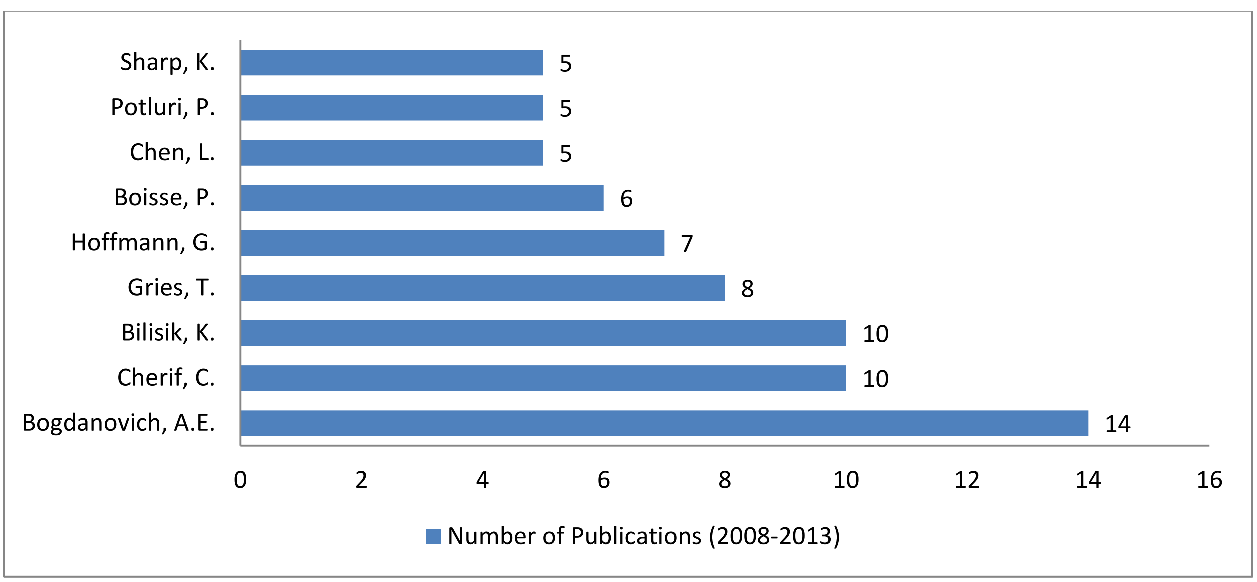


Figure 3: Prolific Authors



1.3 Latest Investments / Projects

I found no market research reports that provided summaries of the research performed in technical textiles or 3D preforms for composite products. The previously mentioned Scopus database search would indicate that interest in this field is spread throughout the world and it is assumed that the research is being funded by government programs, academic, or private interests. A CORDIS database search identified the following European research programs. The one US research program identified below, PRSEUS, is part of ongoing NASA's Environmentally Responsible Aviation Program. I encountered no Asian research programs during my research although the Scopus database search results would indicate otherwise.

Table 2: Global Research Investments

Project (Country)	Investment	Description and website for further information
FIBREMAP: Automatic Mapping of Fibre Orientation for Draping of Carbon Fibre Parts (Coordinator: PROFACTOR GMBH) (Europe)	2013-09-01 - 2016-08-31 Total cost: € 2.9 EU contribution: € 2.0M	Draping is the process of placing woven carbon material on typically complex 3D parts (preforms) with the goal of having the fibres oriented along specific directions predicted by finite element calculations. This is done to maximize the strength-to-weight ratio of the part. There is a strong trend in the automotive industry towards lightweight parts to increase fuel efficiency, also considering the needs of electrical vehicles. Setting up the draping process for a complex part takes up to 50 preforms for trial-and-error improvements. Current production processes are thus not yet adequate to cover the expected volumes of several 100.000 parts per year. The project aims at shortening process development times by 90% and allowing automatic 100% quality control of fibre orientation. http://cordis.europa.eu/projects/rcn/108534_en.html
MAPICC 3D : One-shot Manufacturing on large scale of 3D up graded panels and stiffeners for lightweight thermoplastic textile composite structures (Coordinator: ECOLE NATIONALE SUPERIEURE DES ARTS ET INDUSTRIES	2011-12-01 - 2015-11-30 Total cost: € 8.9M EU contribution: € 5.8M	The MAPICC 3D project and concept aims at developing manufacturing system for 3D shaped, multilayered products based on flexible materials. The ultimate goals are: - The development of integrated and automated process chain able to produce from hybrid thermoplastic yarn to 3D complex shaped thermoplastic composite structure in single step thermoplastic consolidation process. - The development of flexible industrial tools, able to produce customized final composites: possibility to reinforce the preform by coating, weaving multilayers, by injection of foam, by introduction of sensors (control quality of preform during the production or monitor the integrity of composite during use)

Project (Country)	Investment	Description and website for further information
TEXTILES) (Europe)		- The development of modelling tool in order to help understanding of the mechanisms involved in the new technologies and to prototype virtually 3D preform, predictive tools to evaluate the physical and mechanical properties of final 3D preform and final composites structure and at the last step reverse engineering. http://cordis.europa.eu/projects/rcn/101354_en.html
ACHSO: Automated Chemical Stitching and Preforming (Coordinator: FASERINSTITUT BREMEN EV) (Europe)	2012-10-01 - 2014-03-31 Total cost: € 0.29 EU contribution: € 0.22	Today's preforming technologies are largely manual, thus increasing the costs of Liquid Composite Molding (LCM) technologies e.g. RTM. Systems that can drape 3D profiles automatically and continuously, such as the one developed by FIBRE, have just left the development stage but are in need of further development to increase productivity and quality. The chemical stitching (CS) technology offers a way to reduce the lead time by replacing the time consuming binder application with localised adhesives application. The aim of this proposal is to develop an efficient process chain for the continuous production of profiles such as stingers and spars for the CS EDA WP2 torsion box generator. Extensive knowledge gathered during the development of 3D preforming technology by the applicant reduces the development time of the core preforming equipment, so that the majority of the work can be focused on developing the integrated preforming/chemical stitching process. http://cordis.europa.eu/projects/rcn/106333_en.html
COSPI: Composite Stiffened Panels Infusion (coordinator: UNIVERSITE DE BRETAGNE OCCIDENTALE) (Europe)	2011-09-01- 2013-07-31 Total cost: € 0.19M EU contribution: € 0.15M	The CoSPI project aims at developing and manufacturing flat stiffened skin composite panel using infusion process. This kind of process often leads to the reduction of manufacturing costs while lessening the environmental impact of the production. Several parameters will be studied such as the resins, the weaving, the preform type, curing in an oven or an autoclave, in order to optimise the triptych process-composite preform-resin. Thus a trade-off study will be carried out in order to choose the best infusion process in terms of mechanical behaviour, costs and environmental impact. Some new weaving method will also be investigated. http://cordis.europa.eu/projects/rcn/100227_en.html
Recently Completed Projects		
APRIL : Advanced Preform manufacturing for industrial LCM-Processes (Coordinator:	2011-05-01 - 2013-04-30 Total cost: € 0.25M EU contribution: €0.19	Liquid Composite Moulding (LCM) techniques are becoming more and more interesting for aircraft manufacturers due to their advantages against traditional prepreg-autoclave processes (reduction of waste, energy and waste toxicity and economic benefits). For environmental and economic improvement of the

Project (Country)	Investment	Description and website for further information
UNIVERSITAET STUTTGART) (Europe)		consolidation techniques, new techniques will be developed based, on one hand, on novel 3D robotic stitching and, on the other hand, on the use of low temperature activation thermoplastic veils and ultrasonic binder. A demonstration phase will follow, consisting of the manufacturing of different scaled preforms representing skins, stringer and spars sections. Therefore, the braiding technology will also be used to manufacture integral and cost-effective parts. Impregnation tests will then be performed to evaluate the permeability of the obtained preforms. The objective is to be able to scale the techniques to automated serial manufacturing of big preforms (up to 8x3 m). http://cordis.europa.eu/projects/rcn/100228_en.html
EMBROIDERY: Development of energy efficient / lightweight composite parts and tooling based on Tailored Fibre Placement technology / self heating technology (Europe)	2011-01-01 - 2012-12-31 Total cost: € 1.5M EU contribution: € 1.1M	Composite materials are being used extensively in many industrial applications with higher production needs than are yielded by current technologies. New developments such as textile preforming combined with liquid moulding technologies will support this tendency. Nevertheless, there are still some drawbacks. More repeatable and automated processes are required and tools must be developed to assist in both design and manufacturing phases. http://cordis.europa.eu/projects/rcn/97521_en.html
IMAC-PRO : Industrialization of manufacturing technologies for composite profiles for aerospace applications Coordinator: EADS (Europe)	2008-07-01 - 2012-12-31 Total cost: € 7.9M EU contribution: € 5.0M	Main aim of the project is the development of a complete, integrated process chain for the cost effective serial production of various aerospace CFRP stiffener profiles. The project will focus on complex profile geometries with variable cross sections, single or multiple curvature and integrated load introduction areas. The technology offers a high potential for the cost effective production of net shaped fibre preforms with respect to optimized load paths and light weight design. Selected participants: EUROCOPTER DEUTSCHLAND GMBH ALENIA AERMACCHI SPA DASSAULT AVIATION SA ISRAEL AEROSPACE INDUSTRIES LTD. http://cordis.europa.eu/projects/rcn/89903_en.html
PRECARBI : Materials, Process and CAE Tools Developments for Pre-impregnated Carbon Binder Yarn Preform Composites (Coordinator:	2006-09-01 - 2009-08-31 Total cost: €3.9M EU contribution: €2.3M	The critical issues today are performance improvements, development of faster, more cost effective manufacturing and simulation tools to optimise their manufacture and design. The PreCarBi project will develop new materials (carbon fibers and liquid resins) as well as supporting technologies, already proven on a laboratory scale, that bring together prepreg and LCM technologies to combine the advantages of each. Essentially pre-impregnated carbon

Project (Country)	Investment	Description and website for further information
ENGINEERING SYSTEMS INTERNATIONAL GMBH) (Europe)		fibers with a polymer binder formulation are developed for LCM and tow placement processes. FP6-AEROSPACE Selected participants: AIRBUS OPERATIONS GMBH EUROCOPTER DEUTSCHLAND GMBH http://cordis.europa.eu/projects/rcn/79958_en.html
MOJO : Modular Joints for Aircraft Composite Structures (Coordinator: EADS) (Europe)	2006-09-01 - 2009-11-30 Total cost: € 4.4M EU contribution: € 2.5M	MOJO is set to introduce a material driven design for Aeronautics composite components. Composites are associated with integration, complexity, manufacturing risk, weight savings and high costs. Cost savings are achieved with out-of autoclave infusion processes and tailored preforms made of high performance textiles. Adhesive bonding, as the most compatible joining method for composite parts, provides also significant cost and weight saving. The profile preforms will be realised using advanced textiles, among them a unique 3D profile weaving technology. For precision manufacturing of moderately integrated parts new rig concepts will be developed and proved. For a continuous process pultrusion technology will be investigated. Methods of adhesive bonding (e.g. pressure free bonding) will be investigated. FP6-AEROSPACE Selected participants: DASSAULT AVIATION EUROCOPTER DEUTSCHLAND GMBH http://cordis.europa.eu/projects/rcn/79960_en.html
ITOOL : Integrated tool for simulation of textile composites (Coordinator: EADS) (Europe)	2005-03-01 - 2008-08-31 Total cost: €3.9M EU contribution: € 2.6M	The overall aim of ITOOL is to increase the usage of textile preforming for composites in Aeronautics applications. It is well-known from related projects that preforming offers a potential cost saving of 20-30% in materials and processing compared with prepreg technology. But a still missing prerequisite for taking advantage of this potential are adequate design and analysis methods and especially validated simulation tools. Focus is laid on braiding, weaving and stitching technologies including also Non Crimp Fabrics. Further impact of the enhanced simulation capabilities will be a distinct reduction of at least 20% in necessary testing effort as well as a lead time reduction of more than 15%. FP6-AEROSPACE Selected participants: DASSAULT AVIATION ALENIA AERONAUTICA S.P.A. http://cordis.europa.eu/projects/rcn/75789_en.html
Innovative Multi-material and Multi-architecture	n.a.	The aims of this project are to develop manufacturing concepts for 'near-net' preforms requiring minimum post-processing and at the same time incorporating multi-

Project (Country)	Investment	Description and website for further information
preforms (Coordinator: EPSRC Centre for Innovative Manufacturing in Composites) (UK)		materials This will include the exploitation of textile techniques such as 3D weaving, braiding, stitching/embroidery and discontinuous fibre processes which, crucially, offer a route for incorporating recycled fibres. Names of any industrial partners (with cash/in-kind contribution): Bentley, Luxfer, Rolls-Royce, Airbus, GKN, BAE Systems http://www.epsrc-cimc.ac.uk/Projects/InnovativePreforms.aspx
PRSEUS: Pultruded Rod Stitched Efficient Unified Structure (Coordinator: NASA) (USA)	2010-2016 $412.6M[10]	The concept uses blankets of composites which are stitched together, infused using resin, cured and assembled into a larger structure. Part of NASA's Environmentally Responsible Aviation Program[11]

What follows is a listing of the companies, considered worthy of note, encountered during the search.

Table 3: Company Involvement

Company	Description and Website for further information
3Tex Inc.	Why 3D fibre reinforcement, Why 3Weave™, Why 3Braid™[12]
Airbus	Both Boeing and Airbus have implemented 3D woven parts in their new fuel-efficient aircraft models to help reduce weight.[13]
Alenia Aeronautica	Preform has the advantages: lower material and material storage costs, indefinite shelf life (for the textiles) and the ability to manufacture integrated structures having complex geometries only limited by shapeabilty of the dry preforms.[14]

[10] NASA's Budget: Environmentally Responsible Aviation (ERA) Project. http://www.govbudgets.com/project/Aeronautics_Research/Aeronautics/Integrated_Systems_Research/Environmentally_Responsible_Aviation_%28ERA%29/ [Last consulted: 2013.07.19]
[11] Reals, K. (2013) IN FOCUS: NASA steps up a gear with Environmentally Responsible Aviation project. Flight Global, 7 May 2013. http://www.flightglobal.com/news/articles/in-focus-nasa-steps-up-a-gear-with-environmentally-responsible-aviation-project-386314/ [Last consulted: 2013.07.19]
[12] 3Tex Inc. website. http://www.3tex.com/index.html [Last consulted: 2013.07.19]
[13] McPherson, A. (2012) A New Dimension for Aerospace: The growing interest for 3D wovens in the aerospace market. December 26, 2012. http://www.compositesmanufacturingblog.com/2012/12/a-new-dimension-for-aerospace/ [Last consulted: 2013.07.19]
[14] Amendola, A. et al. (2011) Future aerostructure for the next generation green civil aircraft [presentation slides] http://www.cdti.es/recursos/doc/eventosCDTI/Aerodays2011/4F3.pdf [Last consulted: 2013.07.19]

Company	Description and Website for further information
Albany Engineered Composites (AEC), (USA) **A subsidiary of Albany International Corp. (USA)**	Albany International (Rochester, N.H.). Albany is a specialist in weaving and preforming.[15] - 18 engine blades, a disk and fan casing for CFM's LEAP engine[7] - 3D woven, through-thickness-reinforced carbon fiber preforms for the manufacture of composite drag and side braces on the 787
Bally Ribbon Mills (USA)	Our Advanced Products Group's 3D weaving capabilities allow preforms to be fabricated into lightweight, low-cost net-shaped structures Customer listing: Airbus, The Boeing Company, CASA Aerospace, Dassault Aviation, EADS, Eurocopter, Lockheed Martin, NASA, Northrop Grumman Corp., Sikorsky Aircraft, Snecma, U.S. Department of Defense[16]
Boeing Company	Both Boeing and Airbus have implemented 3D woven parts in their new fuel-efficient aircraft models to help reduce weight.[7]
CFM International (joint venture between GE and Snecma)	First company to successfully integrate 3D woven composite parts into aerospace engine designs.[7]
EADS	Technology for licensing: Fiber-patch preforming technology enables the automated production of composite preforms from a software lay-up plan, with the positioning of short fiber patches that have their fibers oriented along specific force paths to optimize the mechanical properties of carbon-fiber reinforced plastics.[17]
General Electric (USA)	See CFM International above
GKN Aerospace (UK)	UK-based GKN Aerospace has created a composite wing structure using out-of-autoclave (OOA) processes and materials, as well as PI-shaped woven preforms, as part of its composite manufacturing and assembly research programme.[18]
Hexcel Composites Ltd. (UK)	Hexcel is a world leader in weaving technologies and PrimeTex® is a unique carbon fiber fabric in which the fibers are spread in both the warp and weft direction to provide a uniform weave and gap-free finish. PrimeTex® carbon

[15] Sloan, J. & Griffiths, B. (2012) 2012 Farnborough International Airshow Report. High Performance Composites, September 2012. http://www.compositesworld.com/articles/2012-farnborough-international-airshow-report [Last consulted: 2013.07.19]
[16] Bally Ribbon Mills. (2013) Advanced Products Group [brochure]. http://www.l-aadvertising.com/images/BallyRibbon_PocketFolder.pdf [Last consulted: 2013.07.19]
[17] EADS. (2013) Automated Fiber-Patch Preforming. http://www.technology-licensing.com/etl/int/en/What-we-offer/Technologies-for-licensing/Composites-and-Related-Manufacturing-Technologies/Automated-Fiber-Patch-Preforming.html [Last consulted: 2013.07.19]
[18] [s.n.] (2013) UK's GKN Aerospace creates composite wing structure using new processes and technologies. 14 may 2013. http://www.aerospace-technology.com/news/newsuks-gkn-aerospace-creates-composite-wing-structure-using-new-processes-technologies [Last consulted: 2013.07.19]

Company	Description and Website for further information
	fiber reinforcements are ideal for Aerospace laminates as the gap-free structure reduces porosity and requires less part finishing thereby reducing man hours. [19]
Safran	The operation of Safran Aerospace Composites will be co-located with Albany Engineered Composites at the new complex, which is to employ some 400 people in the production of parts for the LEAP jet engine. Albany Engineered Composites has been an exclusive Safran partner since the late 1990s for the three-dimensional weaving of carbon-fiber performs.[20]
Snecma	3D woven resin transfer molding (RTM) process developed by Snecma[7]

1.4 Sources

Databases:

- CORDIS database (Community Research and Development Information Service) European Commission. http://cordis.europa.eu/newsearch/index.cfm?page=advSearch
- EBSCOHost Business Source Complete
- Frost.com
- Profound
- SCOPUS
- Strategic Business Insights

[19] Hexcel Composites Ltd. (2013) Hexcel at the Paris Air Show. 10 June 2013. http://www.hexcel.com/news/market-news/news-20130610 [Last consulted: 2013.07.19]
[20] Safran. (2012) Preparations advance for Safran Aerospace Composites' new U.S. production facility 06/08/2012. http://www.safran-na.com/spip.php?article1752 [Last consulted: 2013.07.19]

STI Assessment

Title	**Additive Manufacturing of Composites**
Project Numbers	STI 17174
Date	2013.07.05
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC
Prepared by	Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca) Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca) Mike Culhane, Strategic Information Analyst (mike.culhane@nrc-cnrc.gc.ca) Jean Kneale, Information Specialist (jean.kneale@nrc-cnrc.gc.ca)
Contact	C Jean Kneale, 613-998-3327

Contents

1 ADDITIVE MANUFACTURING OF COMPOSITES

1.1 Additive Manufacturing of Composites

The ASTM F42 Technical Committee defines additive manufacturing (AM) as the "process of joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies". It is also known as additive fabrication, additive processes, direct digital manufacturing, rapid prototyping, rapid manufacturing, **layer manufacturing** and solid freeform fabrication. The term AM describes additive fabrication processes in the broadest way that includes AM of prototypes (for design verification, form and fit checking), tools, patterns, and concept parts, as well as functional parts with required properties for direct industrial applications and services.

According to Stratasys, one of the leading producers of Additive Manufacturing equipment, "The aerospace industry has incorporated additive manufacturing (AM) throughout all processes and functions; from the design concept to near-end-of-life repairs. With each success, it then drives AM deeper into related processes, making it multi-purpose. And aerospace continues to investigate new applications and invest in research to make them possible. Ultimately, the outcome of that research trickles down to AM users in a wide spectrum of disciplines and applications." [1]

This report attempts to address the following three questions:

1) What are the drivers and barriers (technical, economic and if possible, regulatory) to the advancement, adoption and use of Additive Manufacturing for composites ?
2) Who (company, university, research institute) is the world leader in the development of the technology? and
3) What are the latest investments and projects in the area?

[1] Stratasys Inc. (2013) Additive Manufacturing Trends in Aerospace – Leading the Way. White paper available: http://web.stratasys.com/EN_WPAerospaceTrends_Mar13_LP.html?cid=701a0000000aTpt [Last consulted: 2013.07.08

1.2 Drivers and Barriers

No market research or technical reports were found that summarized the technical or economic drivers and barriers to the use of additive manufacturing processes for composite components for aircraft, so what follows was derived from various sources. Some information on the regulatory requirements is provided below.

One of the main drivers for the use of composites in the aerospace sector is weight.
According to the 2012 Umeco annual report: "The growing demand for lower fuel consumption, aligned with advances in composite construction techniques, has led to a significant increase in the use of composites in civil aircraft in the last few years. New aircraft such as the Airbus A380 XWB and the Boeing 787 have approximately 50% composites compared to approximately 20% for current models."

The same report lists the following advantages of composites over conventional metallic alloys

- Optimised structural performance utilising the directional properties of fabrics and fibres.
- Component integration.
- Ability to manufacture complex shapes at lower costs compared with fabricated or machined metallic alloys.
- Time and cost reductions on tooling and manufacturing of one-offs, prototypes and short length production runs.
- Excellent fatigue life, i.e. carbon fibre composites can be designed to be essentially fatigue free.
- Improved energy absorbing safety structures.
- Easy repair of damaged structures.
- Exceptional environmental degradation and corrosion resistance properties.[2]

[2] UMECO plc. UMECO Annual Report 2012.
http://www.umeco.com/~/media/Files/Annual_reports/annual_report_2012.pdf [Last consulted: 2013.07.08]

In general, Frost.com has listed the challenges and barriers that need to be addressed by the composite manufacturing industry in the aerospace sector.

Table 1: Barriers to Composite Use in the Aerospace Sector [3]

For new aircraft	• Idea generation for new materials for composites i.e. improvements on the existing ones • Market realization – speed up processes for certification of new composites to meet aviation standards • Parts integration and compatibility – composite part compatibility with metal components • **Cost-effectiveness - best economic process and materials**
In service aircraft	• Integration of Damage Detection Systems and Knowledge Expertise
Ageing Aircraft	• Inability to service failed parts • Negative environmental impact – environmental hazard, recycling

1.2.1 Technical Barriers – Additive Manufacturing of Composites

No one publication was located that addressed the technical drivers or barriers to the use of additive layer manufacturing to produce composite components, however the following challenges were gleaned from several sources:

1) According to Potluria, fibre preforming has been identified as a key bottleneck in the composites supply chain. [4]
2) Schnabel claims with regard to large scale fibre reinforced plastic components, challenges in the production of these parts are the handling of large textile semi- finished fabrics as well as their storage management. [5]
3) According to Wohlers, another obstacle is a technical issue with laser sintering. A fiber-filled material can offer improved strength in the x-y direction of a part, but it typically offers little or

[3] Frost.com (2010) Aerospace Composites. Technical Insights, Published: 30 Sep 2010.
[4] Potluria, P. et al. (2012) Innovative material systems for composite vehicle structures. International Journal of Vehicle Structures and Systems, 4 (3), pp. 86-91.
[5] Schnabel, A, et al. (2010) New approaches for fiber reinforced composite production. Proceedings of the 10th International Conference on Textile Composites - TEXCOMP 10: Recent Advances in Textile Composites, pp. 65-72.

no additional strength in the z-direction because the fibers do not span the divide between build layers. Currently, laser-sintered parts must be designed with that limitation in mind. [6]

4) According to EADS researcher, B.L. Farmer, "Polymeric additive layer manufacturing (ALM) processes such as Selective Laser Sintering (SLS) or Stereo Lithography (SLA) have received limited attention for structure applications as the materials commonly have either very low glass transition temperatures (T_g) (example polyamides), or are brittle ultraviolet light curing materials (example epoxies) and are reinforced by crude means (glass particles or intermingled short carbon fibres) at low volume fractions and with no means of controlling orientation." [7]
5) Ruffo summarizes limitations for rapid manufacturing systems in 2007 as:
   - Material variety and properties
   - Process speed
   - Dimensional accuracy
   - Surface finish
   - Repeatability
   - Cost effectiveness[8]

[6] Wohlers, T. (2010) Additive manufacturing a new frontier for composites. Composites Technology. Source: http://www.compositesworld.com/columns/additive-manufacturing-a-new-frontier-for-composites [Last consulted: 2013.07.03].
[7] Farmer, B.L. et al. (2011). Assembly Strategies for Fully Aligned and Dispersed Morphology Controlled Carbon Nanotube Reinforced Composites Grown in Net-Shape. MRS Proceedings, 1304, mrsf10-1304-z03-04 doi:10.1557/opl.2011.602.
[8] Ruffo, M. & Hague, R. (2007) Cost estimation for rapid manufacturing – simultaneous production of mixed components using laser sintering. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, v. 221, p. 1585-1591.

1.2.2 Economic Drivers/Barriers - Additive Manufacturing of Composites

The following economic drivers and barriers to the use of additive manufacturing of were mentioned in the identified sources.

Drivers	Barriers
• Streamlines and expedites product development process [9] • May help to reduce time to market, improve product quality and cut costs [9]	• High testing costs for aerospace applications makes focusing on multiple materials simultaneously cost prohibitive [10] • Additive manufacturing equipment must transition from comparable low-reliability laboratory-grade equipment to hardened, cost-effective, high-temperature, industrial-grade machines [5] • Slower than conventional manufacturing methods [11]

A white paper, produced by Stratasys Inc., lists some specific examples where the use of additive manufacturing processes has provided economic savings (only those examples involving composites have been listed) [12].

Table 2: Economic Savings from Additive Manufacturing of Composite Components

Company / Product	Traditional Methods	Additive Manufacturing Methods
Advanced Composite Structures (ACS) repairs fixed-wing and rotary-wing aircraft and performs low-volume component manufacturing,	This work needs layup tools, mandrels, cores and drill guides. When these are CNC machined, ACS invests several months and many	The solution is AM for nearly all of its composite tooling needs. On average, layup tools cost only $400 and are ready for use in 24 hours,

[9] Katz, D. & Farquar, H. (2011) Assessing the Economic Impact of LLNL's Additive Manufacturing Technology [presentation] LLNL-PRES-500312. https://ipo.llnl.gov/data/assets/docs/katz_final_pres_2011.pdf [Last consulted: 2013.07.04]
[10] Lyons, B. (2012) Additive Manufacturing in Aerospace: Examples and Research Outlook. The Bridge on Frontiers of Engineering, Spring 2012, volume 42, number 1. http://www.nae.edu/Publications/Bridge/57865/58467.aspx [Last consulted: 2013.07.04]
[11] Friedman, P. (2012) The Achilles' Heel of 3D Printing. Innovation Investment Journal, 30th December 2012 08:29 PM. http://www.iijiij.com/2012/12/30/the-achilles-heel-of-3d-printing-015281 [Last consulted: 2013.07.04]
[12] Stratasys Inc. (2013) Additive Manufacturing Trends in Aerospace – Leading the Way. White paper available: http://web.stratasys.com/EN_WPAerospaceTrends_Mar13_LP.html?cid=701a0000000aTpt [Last consulted: 2013.07.08]

Company / Product	Traditional Methods	Additive Manufacturing Methods
using composite parts.	thousands of dollars. And when changes occur, costs rise and delays mount.	which means that changes are no longer serious issues.
Kelly Manufacturing Co. (KMC) makes the R.C. Allen line of aircraft instrumentation and is the world's largest manufacturer of general aviation instruments. Its example of production AM applications is a toroid housing in a turn-and-bank indicator.	Previously, parts were made from urethane molded in soft (rubber) tooling. This was the process of choice for low-volume production because it is much cheaper and faster than a composite layup. But AM has replaced rubber molding since it further reduces cost and time. The toroid housing, cast in a rubber mold, would have taken three to four weeks for a 500-piece order.	KMC produces 500 toroid housings in one overnight run of its FDM system. Justin Kelley, KMC president, said, "From order to delivery, it takes only three days to have certified production parts."
Aurora Flight Sciences, which develops and manufactures advanced unmanned systems and aerospace vehicles, fabricated and flew a 62-inch wingspan aircraft — the wing composed entirely of AM components.		This manufacturing approach reduces the design constraints engineers face when using traditional fabrication techniques. The design of the wing's structure was optimized to reduce weight while maintaining strength. "The success of this wing has shown that 3D printing can be used to rapidly fabricate the structure of a small airplane," said Dan Campbell, structures research engineer at Aurora. "If a wing replacement is necessary, we simply click print, and within a couple days we have a new wing ready to fly."
Leptron produces remotely piloted helicopters.	For this project, there were multiple designs for specific applications, such as eight variations for the nesting integrated fuselage components. If it had used injection molding, as it had in the past, tooling expense would have exceeded $250,000 and production parts would have arrived six months later.	For its RDASS 4 project, AM allowed Leptron to make 200 design changes — each component had at least four modifications — without incurring a penalty in time or cost. When the design was ready to take off, Leptron had flight-ready parts in less than 48 hours, all thanks to AM. This mid-sized company embodies the aerospace trend: No machine shop; instead, an additive manufacturing machine that is used for prototyping through production.

1.2.3 Regulations

Regulations are also a key element when it comes to composites in aerospace applications. To meet the stringent conditions necessary to ensure safety in air travel, aerospace manufacturers must satisfy a long list of complex requirements for even the simplest part. The consistent production of parts with identical, well-understood properties requires that both materials and production processes be understood to a very high level. This complicated manufacturing context, which blends low-volume economics, acute weight sensitivity (weight is often the deciding factor in choosing materials and manufacturing processes for aerospace and defense components), and the need for highly controlled materials and manufacturing processes, has led companies like Boeing to focus on transitioning additive manufacturing techniques from the laboratory and model shop to the factory floor.

Safety regulations are considered mandatory for materials that go into the making of aircraft parts. Since a lot of composites are currently being used in aircraft; they need to meet safety standards such as the flame, smoke, and toxicity regulations. Stringent flame/smoke/toxicity regulations have already been established by FAA and the EASA. Hence, an increasing number of companies have started using phenolic resins and thermoplastic resins in seating and other interior applications in aircraft.

The US Environmental Protection Agency (EPA) enacted regulations specifically for the composites industry, requiring emission controls using maximum achievable control technology (MACT) in 2003. However, the regulations took effect in early 2006 only. It is one of the most important regulatory criteria that are to be followed by composite manufacturers.

Carbon footprint is another environmental issue to be kept under check.[13]

The Frost & Sullivan study on Aerospace Composites provides a listing of the standards and standards organizations involved in developing composites standards for aircraft applications.

[13] Frost & Sullivan (2010) Aerospace Composites. Technical Insights, Frost.com. Published: 30 Sep 2010

1.3 World Leaders

No publications were found that identified world leaders in the development of additive manufacturing methods for composites.

In terms of an internet presence, the UK has proclaimed itself a world leader in the application of additive manufacturing to metals and polymers. The following research centres were identified.

Table 3: UK Research Centres

Organization	Expertise / Source
Additive Manufacturing Research Group (AMRG) University of Loughborough (UK)	The Additive Manufacturing Research Group (AMRG) is widely regarded as the world's leading centre for Additive Manufacturing (AM) research, development and dissemination. http://www.lboro.ac.uk/departments/mechman/research/groups/additivemanufacturing/
Centre for Additive Layer Manufacturing (CALM) University of Exeter (UK)	The Centre for Additive Layer Manufacturing (CALM) is a £2.6 million investment in innovative manufacturing for the benefit of businesses in the South West and across the rest of the UK. CALM is delivered in collaboration with EADS UK Ltd. http://www.eurekalert.org/pub_releases/2012-07/uoe-rpt070212.php UK additive manufacturing research leads the field 13 September 2012 http://www.eurekamagazine.co.uk/design-engineering-features/technology/uk-additive-manufacturing-research-leads-the-field/44790/
National Composites Centre (NCC), Bristol (UK)	The UK government has announced an investment of £28 million to enhance the capabilities of the National Composites Centre (NCC) located near Bristol, UK. http://www.reinforcedplastics.com/view/31670/the-uk-composites-industry-turning-ideas-into-investments/

A number of companies and research organizations were encountered during the search.

Table 4: Companies and Research Organizations

Organization	Description / Source
EADS	Airbus and parent company EADS has development an assembly strategy to combine a nano-enabled composite approach with the net-shape freedoms offered by ALM. Coined Utopium (ultimate Toughness and Other properties Introduced by Ultimate Manufacturing) [14] http://nextbigfuture.com/2010/10/utopium-project-to-use-carbon-nanotube.html Airlines could save $300bn with laser manufacturing http://www.telegraph.co.uk/finance/newsbysector/transport/7158520/Airlines-could-save-300bn-with-laser-manufacturing.html
GE Aviation	GE stole a march on its competitors with its recent acquisition of Morris Technologies – which has established itself as a specialist in the production of 3D aerospace parts. The move means that other companies which had relied on Morris' expertise will not have to go elsewhere, or develop their own. Printing Flyers. Aerospace Manufacturing http://magazine.aero-mag.com/2013/january/
Northrup Grumman	S&T's additive manufacturing project selected for funding March 22, 2013 by Linda Fulps http://news.mst.edu/2013/03/sts_additive_manufacturing_pro/ Missouri University of Science and Technology / Northrop Grumman Aerospace Systems Samples constructed by a Stratasys' Fortus machine using ULTEM 9085, a flame-retardant, high-performance thermoplastic material, will go through a series of compression and flexure tests at both room and elevated temperatures.
Oak Ridge National Laboratory (ORNL), Manufacturing Demonstration Facility (USA)	Carbon Fiber Reinforced Polymer Additive Manufacturing http://www.cfcomposites.org/PDF/Carbon%20Fiber%20Consortium%20-%20CFRP%20Duty.pdf http://energyoutlook.naseo.org/presentations/McGetrick.pdf
Advanced Laser Materials LLC (Belton, Texas)	Offers a line of glass-filled polyamides, specially formulated for high thermal stability, including a highly recyclable polyamide composite material for laser sintering — and offers custom formulations http://www.cfcomposites.org/PDF/Carbon%20Fiber%20Consortium%20-%20CFRP%20Duty.pdf

[14] Farmer, B.L. et al. (2011). Assembly Strategies for Fully Aligned and Dispersed Morphology Controlled Carbon Nanotube Reinforced Composites Grown in Net-Shape. MRS Proceedings, 1304, mrsf10-1304-z03-04 doi:10.1557/opl.2011.602.

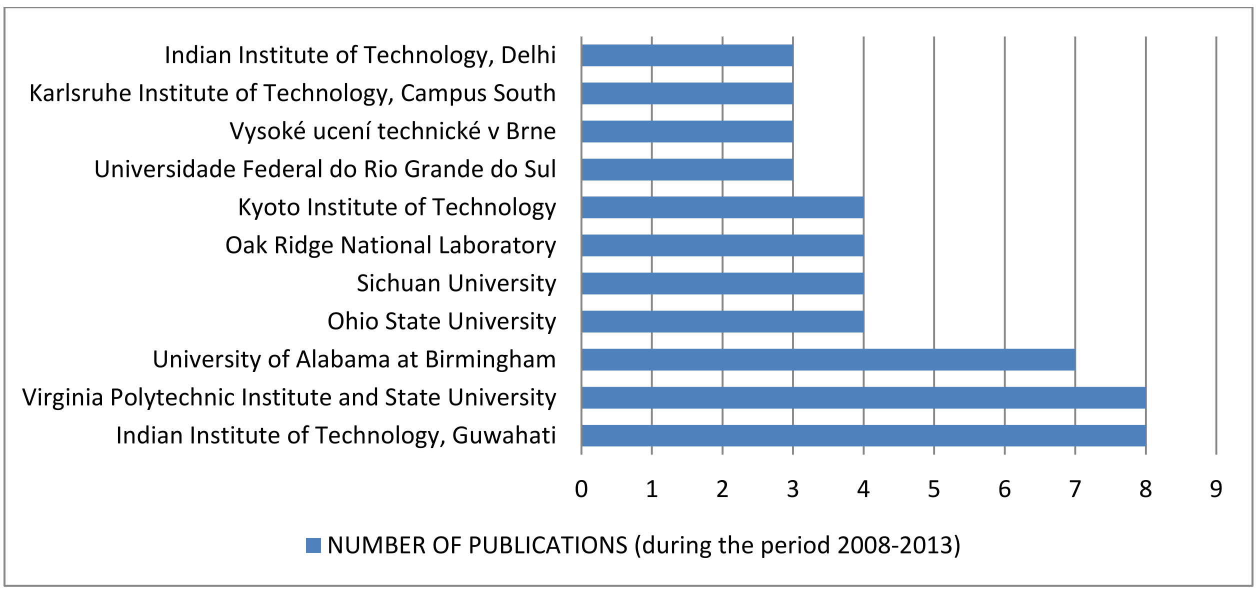
Organization	Description / Source
EOS GmbH (Munich, Germany)	Markets PA 3200 GF material, a glass-filled polyamide that withstands high mechanical loads, and CarbonMide, a carbon fiber-filled polyamide powder that produces stiff, lightweight parts[4]
CRP Technology (Modena, Italy)	Developed Windform XT, a carbon-filled polyamide, and Windform Pro, an aluminum- and glass-filled polyamide[4]
Stratasys, (Eden Prairie, USA)	Developed the Fortus three-dimensional (3D) production system. FDM technology and thermoplastic materials allow building accurate, durable parts.[15]
3D Systems, Rock Hill, SC (USA)	Offer their Accura Bluestone and Accura Greystone composite materials for stereolithography[14]
DSM Somos, Elgin, Ill. (USA)	Offers a nanomaterial for stereolithography [14]

[15] Frost & Sullivan (2011) Additive Manufacturing of End-Use Thermoplastic Parts. Advanced Manufacturing Technology Alert. Frost.com, published: 29 Apr 2011.

One of the questions asked during client consultations was who is working towards long fibre reinforcement of composites?

No market research or analysis reports were found that answered this question however a **rough** idea can be drawn from the analysis of the publications that deal with this subject. In order for this to be considered definitive a more comprehensive search, more analysis and cleaning of the results would have to be done. A preliminary search was performed in SCOPUS and an analysis of the search results' author affiliations was performed[16]. What follows are the top publishing research institutions associated with the 159 papers identified in the search.

Figure 1: Publication Leaders Addressing the Problem of Lengthening Fibres in Composites



[16] The search concepts used to produce the table above:
long*/medium concept within 3 words of fibre concept + carbon/glass/fibreglass within 3 words of fibre concept + reinforcing concept + composite* + 2007-2013 AND NOT ceramic OR metal or alloy or wood or bone concepts etc.

1.4 Latest Investments and Projects

The European Commission CORDIS database was searched for relevant research projects currently underway in Europe. In the previous report on Additive Manufacturing of Metals, it was evident that Asian government and research institutions are actively pursuing research in the development of additive manufacturing processes, however no specific research programs were encountered during this search that specifically mentioned composites programs. It is hard to believe that this is true given the increasing trend to use composites in aircraft, this region's interest in developing its aerospace manufacturing sector and given that several Asian research organizations appear in Figure 1 (4 of the 11 top publishing organizations on long fibre reinforced composites).

Table 5: European Investments and Projects

Research (Country) / Source	Investment	Description and website for further information
Selective laser printing of high performance polymers (SPRINT), (UK) http://www.emeraldinsight.com/journals.htm?issn=0144-5154&volume=30&issue=4&articleid=1886367&show=html	2010-?? £750,000	Explore selective laser printing (SLP), an additive manufacturing process where fine polymeric powder is printed and then fused together to make complex parts essential to industries such as the aerospace and automotive sectors De Montfort University Leicester (DMU) As well as the Technology Strategy Board, other partners include rapid manufacturing specialists MTT Technology, Renishaw and Parker. The Sprint project team intends to develop a compact, energy-efficient machine, together with a range of compatible polymer materials. The machine will precisely deposit powder using an adapted industrial laser printer before the entire layer is fused by infrared radiant heater.
NANOMASTER: Graphene based thermoplastic masterbatches for conventional and additive manufacturing processes (Europe) (Coordinator: Netcomposites, UK) http://cordis.europa.eu/projects/rcn/101393_en.html	2011-12-01 - 2015-11-30 Total cost: € 6.3M EU contribution: € 4.2M	The aims of the NanoMaster project are to reduce the amount of plastic used to make a component by 50% and hence reduce component weight by 50%, at the same time as imparting electrical and thermal functionality. This will be achieved by developing the next generation of graphene-reinforced nano-intermediate that can be used in existing high-throughput plastic component production processes. Graphene reinforced polymers have been demonstrated at lab scale in both Europe and the USA, and it has been shown that very low loadings of graphene can have a dramatic impact on the mechanical and physical properties of the polymers it is added to. However, industrial compounding processes have only so far been developed in the United States, where Ovation Polymers are already offering

Research (Country) / Source	Investment	Description and website for further information
		graphene thermoplastic masterbatches and compounds based on graphene from XG Sciences.
3D-LIGHTTRANS : Large scale manufacturing technology for high-performance lightweight 3D multifunctional composites (Europe) (Coordinator: Austrian Institute of Technology GMBH, Austria) http://cordis.europa.eu/projects/rcn/98253_en.html	2011-04-01 - 2015-03-31 Total cost: €7.8M EU contribution: €5.2M	The goal of 3D-LightTrans project is to provide ground breaking, highly flexible and adaptable low-cost technologies for manufacturing of 3D textile reinforced plastic composites (in the following referred to as textile reinforced plastics or TRP), including innovative approaches for the individual processes and its integration in complete manufacturing chains, which will enable to shift them from its current position in cost intensive, small series niche markets, to broadly extended mass product applications, not only in transportation, but also in other key sectors, like health and leisure. The Consortium brings together multidisciplinary research teams involving five industrial stakeholders from machine tools and machine automation (P-D Glasseiden, Van de Wiele, Lindauer Dornier, Coatema) and several OEM active in the field of processing of flexible materials and composite manufacturing, including Federal Mogul, among others, as well as from the application sector (FIAT and Bentley), and extensive expertise from well known research specialists in the area of materials, production research and technical textiles in particular, like AIT, TU-Dresden and University of Ghent.
HICOMP : Development and Manufacture of High Temperature Composite Aero Engine Parts (Europe) (Coordinator: Cobham, UK) http://cordis.europa.eu/projects/rcn/100662_en.html	2011-10-01 - 2013-09-30 Total cost: €0.7M EU contribution: €0.3M	Cobham Advanced Composites Ltd. will develop and manufacture lightweight carbon fibre reinforced polymer matrix composite test components for the SAGE 4 Geared Turbofan demonstrator. The components will be manufactured from suitable high temperature resistant thermoset resin which is capable of a continuous service temperature of 350°C. Initial working sessions shall be held to review the candidate components and to develop the draft technical requirement specifications. The composites manufacturing process selection shall be dependent upon the components to be manufactured. A study shall be carried out by Cobham to identify the most cost effective manufacturing route which achieves the required performance requirements for the selected components. Development of the selected manufacturing process will be conducted in collaboration with MTU so that key design-for-manufacturing requirements are captured. Demonstrator components will be manufactured in accordance with MTU specifications and drawings. Material characterisation data will be generated for un-aged and thermally aged test coupons in order to validate the composite designs.
MAPICC 3D : One-shot Manufacturing	2011-12-01 - 2015-11-30 Total cost: € 8.M	Aims at developing manufacturing system for 3D shaped, multilayered products based on flexible materials. The

Research (Country) / Source	Investment	Description and website for further information
on large scale of 3D up graded panels and stiffeners for lightweight thermoplastic textile composite structures (Europe) (Coordinator: Ecole nationale superieure des arts et industries textiles, France) http://cordis.europa.eu/projects/rcn/101354_en.html	EU contribution: €5.8M	ultimate goals are: - The development of integrated and automated process chain able to produce from hybrid thermoplastic yarn to 3D complex shaped thermoplastic composite structure in single step thermoplastic consolidation process. - The development of flexible industrial tools, able to produce customized final composites: possibility to reinforce the preform by coating, weaving multilayers, by injection of foam, by introduction of sensors (control quality of preform during the production or monitor the integrity of composite during use) - The development of modelling tool in order to help understanding of the mechanisms involved in the new technologies and to prototype virtually 3D preform, predictive tools to evaluate the physical and mechanical properties of final 3D preform and final composites structure and at the last step reverse engineering.
NFRP : Nano-Engineered Fiber-Reinforced Polymers (Europe) (Coordinator: Fundacion imdea materiales, Spain) http://cordis.europa.eu/projects/rcn/107525_en.html	2013-04-01 - 2017-03-31 Total cost: € 0.1M EU contribution: €0.1M	Proposes to develop a novel nano-architecture to enhance the mechanical and electrical properties of the composite in the through-the-thickness direction. This nano-architecture will also act as a sensing system, enabling damage detection and localization by resistive-heating based non-destructive evaluation. In summary, the nano-engineered composite proposed here is an intrinsically multifunctional material, with expected over the state-of-the-art mechanical and multifunctional properties.
KARMA : Knowledge Based Process planning and Design for Additive Layer Manufacturing (Europe) (Coordinator: Federacion empresarial metalurgicavalenciana, Spain) http://cordis.europa.eu/projects/rcn/94835_en.html	2010-07-01 - 2013-06-30 Total cost: €2.0M EU contribution: €1.6M	Additive Layer Manufacturing (ALM) -also known as Free Form Fabrication and formerly Rapid Manufacturing-, is a novel fabrication method of parts directly from the electronic model by layer manufacturing, using active principles such as laser and Electron beams. Currently, ALM is the first and the best option for short series of customized products. However, layered manufacturing is not without challenges. Part properties, dimensional accuracy and surface quality depend strongly on process planning, and sometimes prevent ALM parts to be considered as fully functional. The objective of KARMA is to respond to above mentioned challenges with a knowledge-based engineering system (KBE) that can estimate functional properties of ALM parts automatically and in short time. The KBE system would define the optimal production parameters automatically and execute a virtual test of the fabricated part.
STEPUP : Step up in polymer based RM processes (Europe)	2009-01-01 -2012-12-31 Total cost: €4.4M EU contribution: €3.2M	An innovative mechano-chemical approach (based on the high energy ball milling) will be used for the development of innovative nanopolymers to be used in Rapid Manufacturing (RM) based on Selective Laser Sintering (SLS),by:

Research (Country) / Source	Investment	Description and website for further information
(Coordinator; MBN Nanomaterialia Spa, Italy) http://cordis.europa.eu/projects/rcn/89914_en.html		- Structural modification (up nanopolymers stage) using a currently widely used polymer like Polyammide PA (a nanoPA will be produced); - Alloying (at nanoscale) with different polymers to tune mechanical properties; - Nanocharging of polymers (development of nanocomposites).

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http://cordis.europa.eu/newsearch/index.cfm?page=advSearch
Frost.com
Profound
SCOPUS
Strategic Business Insights

STI Assessment

Title	**Aerospace Environmental Scan (WG4) : Simulation, Modeling and Analysis**
Project Numbers	STI 17174
Date	July 17th, 2013
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, Envirotrec Doug Roberge, StandardAero (Working Group 4)
Prepared by	Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca) Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca)

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1 GLOBAL SIMULATION SOFTWARE MARKET

According to Frost & Sullivan, the computer aided design (CAD) and modeling software market is expected to reach $US 11,648.8 million by 2018; current revenues are $US 6,288.2 million. The top three vendors are Dassault Systemes, Autodesk, and Siemens AG, with a combined market share of 65.1% of the total CAD market.

Table 1. Drivers and restraints to simulation software market growth

Driving factors	Restraints
• Higher productivity and work-flow efficiency requirements drive new technology adoption, like Product Life Cycle Management, Building Information Modeling, cloud computing, tablet PCs, and direct modeling; • Growth in emerging markets in many verticals, like construction and manufacturing; • New product functionalities like optimization and visualization drive product development and upgrades in more mature market segments.	• Market maturity and economic conditions slow CAD product replacement; • Lack of native support for essential functionalities results in a difficult market penetration for smaller vendors • Lack of sophistication in production workflows in emerging markets, causing a delay in solution implementation

Aerospace and defense represent 22% of the global mechanical computer aided design (MCAD) market.

According to the literature found[1], CAD, CAE and CAM systems are evolving in product lifecycle management (PLM). While PLM systems integrate more than the design and manufacturing of a product to encompass marketing, sales and after-sales services, it covers many of the aspects covered in this report, such as product design, simulation and modeling as well as work instructions delivery. The scientific and technical literature defines PLM as “a strategic business approach that applies a consistent set of business solutions in support of collaborative creation, management, dissemination, and use of

[1] Product lifecycle management in aviation maintenance, repair and overhaul. Computers in Industry, vol. 59 (2008), pp. 296–303.

product definition information across the extended enterprise, from concept to end-of-life, integrating people, processes, business systems, and information”.[2] According to the literature found, PLM is mostly used in the automotive and aerospace sectors and its adoption is still mainly limited to product design.

Examples of software platforms that are considered to be PLM products are Tecnomatix and Teamcenter (Siemens), and ENOVIA VPM (IBM-Dassault). PTC, which develops many products mentioned in this report, is considered the one of the supplier of PLM products for the aerospace and defense sectors.[3] Some of these products are listed in the sections below.

2 SIMULATION PLATFORM FOR COMPLEX INTERCONNECTED SYSTEMS

2.1 Current use

No market information was found on technologies for the simulation of complex interconnected systems. The market information found covers simulation software in a broader sense.

A recent article published in the Aerospace Manufacturing magazine on computer-aided engineering states that aerospace companies “are integrating the latest computer-aided engineering software products in their design process”.[4] According to industry players, the CADCAM software industry is seeing record levels of demand from the aerospace sector and this trend is expected to continue as subcontractors face pressure to reduce costs and increase productivity. This increased demand has lead to a shortage of skilled users for such software; the CADCAM industry is focusing on training to expand the capacity of aerospace manufacturers to use their products.[5]

Process simulation is also a key enabler for aerospace assembly. As stated in Aerospace Manufacturing, “such models provide users with a graphical, dynamic representation of the physical process in question

[2] Product lifecycle management in aviation maintenance, repair and overhaul. Computers in Industry, vol. 59 (2008), pp. 296–303.
[3] New Industry Report Identifies PTC As The Leading Provider Of PLM Software To Global Aerospace & Defense Manufacturers. PTC press release, June 18th, 2013.
[4] Richardson, Mike. Staying competitive. Aerospace Manufacturing, January 2012.
[5] Hill, Ed. The year ahead. Aerospace Manufacturing, January 2012.

and enable a multitude of performance related questions to be answered in the risk-free environment of a computer application".[6]

2.2 Commercial availability and top players

Many commercial product offerings in simulation have been found on the market, indicating that the market is very dynamic.

Table 2. Companies offering simulation platforms in the aerospace industry

Company	Products
ANSYS http://www.ansys.com/	ANSYS Mechanical Suite/ANSYS Workbench allows managing complex interactions between system components. The platform enables users to model all applications, from very simple to very complex.
Applied Dynamics International http://www.adi.com/products/advantage/	ADvantage Framework, a Model Based Systems Engineering (MBSE) software platform providing an agile, feature-rich environment for supporting system lifecycle through development, integration and test.
Dassault Systemes http://www.3ds.com/	• DELMIA Digital Manufacturing Solutions (3DEXPERIENCE Platform), allowing prototyping virtual builds in parallel with the design maturation. Engineers can interactively create assembly simulation scenarios of single parts or assemblies being installed. • SIMULIA provides realistic simulation solutions to allow simulation and analysis from early in the design phase through the product lifecycle, maximizing the return on your simulation investment while reducing costs associated with

[6] Bird, Oliver. Simulation goes dynamic! Aerospace Manufacturing, January 2012.

Company	Products
	redesign, rework and additional physical testing. • SolidWorks CAD software, a product development solution capable of designing complex surfaces. • V5 DMU, wich enables digital product simulation, analysis and validation, improving product quality and accelerating decision making by providing real-time insight into real-world product performance. • CATIA, a 3D CAD software.
Delcam http://www.delcam.com/	PowerSHAPE, a complex 3D shape and part modeller.
EOS http://3eos.com/	EOS Solutions' 4D simulation allows decision makers to analyze the economic and operational impact of volatile resources and unpredictable events within complex systems.
Parametric Technology Corporation (PTC) http://www.ptc.com/	PTC Creo: allows design, simulation, visualization and digital mock-ups.
Siemens http://www.plm.automation.siemens.com/	Tecnomatix Plant Simulation is a discrete-event simulation tool that helps you to create digital models of logistic systems (such as production), so that you can explore a system's characteristics and optimize its performance.
SimTechnologies http://www.simtechcorp.com/	Flexible Manufacturing Simulation System (FMSS), which is capable of determining the system requirements based on the customer's production demand and operating parameters. The user can vary operating parameters to conduct "what-if" analyses.

3 MODELING OF NEW AND EMERGING COMPOSITE MATERIALS DRIVERS AND BARRIERS

3.1 Drivers and barriers

Market information on the composite modeling software area is not as widely available as the information on simulation software. However, a recent article from Composites World indicates that "a variety of structural simulation software programs have proven valuable in recent years by enabling composite component manufacturers to produce highly optimized products in less time, and at lower cost, compared to more traditional design/build/test development programs. Every year, the accuracy and capabilities of the different simulation programs increases."[7]

3.2 Commercial availability and top players

A large number of companies offer modeling and simulation software for composites.[8] The following table provides a listing of companies providing composites analysis and simulation solutions.[9]

Table 3. Companies offering composite materials modeling solutions

Category of Composites-Handling Software	Companies (Product)
Laminate analysis	• Anaglyph (Laminate Analysis Program LAP) (http://www.anaglyph.co.uk/LAP.htm) • Componeering (ESAComp, ComPoLyX) (https://www.esacomp.com/) • Lindell (The Laminator) (http://www.thelaminator.net/)
Substructure analysis	• Anaglyph (Component Design Analysis CoDA) (http://www.anaglyph.co.uk/CoDA.htm)

[7] Berenberg, Barry. GENOA modeling software closely predicts composite structural failure. Composites World, July 2004.
[8] Composites World's website provides an extensive listing of modeling and simulation companies at http://www.compositesworld.com/suppliers/product/520.
[9] Waterman, Pamela J. Desktop Engineering, May 2011 (http://www.deskeng.com/articles/aabawg.htm).

Category of Composites-Handling Software	Companies (Product)
	• Componeering (ESAComp) (https://www.esacomp.com/)
Micromechanical structure analysis	• e-Xstream Engineering (DIGIMAT) (http://www.e-xstream.com/en/digimat-software/) • Firehole Composites (Helius:MCT, Prospector:Composites and Helius:CompositePro) (http://www.firehole.com/) • Alpha STAR Corporation (ASC) (GENOA) (http://www.ascgenoa.com/) • Componeering (ESAComp) (https://www.esacomp.com/)
Finite Element Analysis (FEA)	• ADINA (http://www.adina.com/) • Altair (HyperWorks) (http://www.altairhyperworks.ca/) • ANSYS (http://www.ansys.com/) • Autodesk (Algor) (http://www.autodesk.com/) • COMSOL (http://www.comsol.com/) • Cranes Software (NISA) (http://www.cranessoftware.com/products/nisa.php) • LUSAS (LUSAS Plus Composite) (http://www.lusas.com/products/composite.html) • MSC.Software (http://www.mscsoftware.com/) • NEi Nastran (http://www.nenastran.com/) • SAMTECH (http://www.samtec.com/) • Siemens PLM Software (NX) (http://www.plm.automation.siemens.com/en_us/products/nx/) • SIMULIA (Dassault Systemes) (http://www.3ds.com/products-services/simulia/portfolio/) • Strand7 (http://www.strand7.com/) • Vanderplaats R&D (GENESIS) (http://www.vrand.com/)
FEA optimization	• Collier Research Corp. (HyperSizer) (http://hypersizer.com/) • ESI Group (SYSPLY) (http://www.esi-group.com/) • e-Xstream Engineering (DIGIMAT) (http://www.e-xstream.com/en/digimat-software/)

Category of Composites-Handling Software	Companies (Product)
	• Vanderplaats R&D (GENESIS) (http://www.vrand.com/) • Componeering (ESAComp) (https://www.esacomp.com/)
FEA-based Integrated Design/Analysis/Manufacture	• MSC.Software (Patran Laminate Modeler) (http://www.mscsoftware.com/) • Simulayt Composites Modeler for Abaqus/CAE (SIMULIA) (http://www.simulayt.com/)[10] • Simulayt Composites Modeler for Femap (Siemens PLM Software) (http://www.simulayt.com/)[11] • VISTAGY with ANSYS (Composite PrepPost and FiberSIM) (http://www.ansys.com/; http://www.plm.automation.siemens.com/en_gb/)[12] • Anaglyph (Laminate Tools for Nastran and ANSYS) (http://www.anaglyph.co.uk/)
CAD-based Integrated Design/Analysis/Manufacture	• Dassault Systemes (CATIA V5/V6 Composites Design) (with Partner Products: ESI Group — PAM-RTM for CATIA V5, Simulayt — Advanced Fiber Modeler for CATIA V5/V6, Composites Link for CATIA V5/V6) (http://www.3ds.com/products-services/catia/; http://www.esi-group.com/; http://www.simulayt.com/[13]) • VISTAGY (FiberSIM for NX, ANSYS, Pro/ENGINEER and CATIA V4/V5) (http://www.plm.automation.siemens.com/en_gb/)[14] • Simulayt (Composites Modeler for SolidWorks) (http://www.simulayt.com/)[15] • Anaglyph (Laminate Tools for SolidWorks) (http://www.anaglyph.co.uk/)

[10] Website was not working at the time of our visit.
[11] Website was not working at the time of our visit.
[12] Vistagy was bought by Siemens.
[13] Website was not working at the time of our visit.
[14] Vistagy was bought by Siemens.
[15] Website was not working at the time of our visit.

4 ENHANCED TRAINING AND MAINTENANCE INSTRUCTION DELIVERY AND DEVELOPMENT

4.1 Current use

Very little information was found on the market for interactive training, especially when it comes to manufacturing in general and aerospace in particular. No market report was found on the topic. Finding information on this area is especially difficult given the wide array of applications for such systems and the variety of enabling technologies involved.

While no market figures were found on this area, some information, mostly published by industry players was found in technical and white papers. A white paper published by Dassault states that "the business drivers for this are lower shop-floor costs and better reliability, which result from reducing the time spent creating and consuming accurate, comprehensive work instructions for each unit, while accommodating late changes as fast as possible."[16]

Digital manufacturing encompasses the production of work instructions, but covers more than just this application. According to an IBM white paper, "Digital Manufacturing solutions help define the steps necessary to build a product, test those steps for accuracy and then generate machine and work instructions for manufacturing the product."[17] Digital manufacturing is transforming into a key product segment under PLM.[18]

Frost & Sullivan indicates that the Digital Manufacturing market is dominated by major product lifecycle management (PLM) vendors with well-defined product suites for different end-user industries.[19] Frost & Sullivan also states that "the need for innovation and manufacturing flexibility in aerospace and defence generates high demand for digital manufacturing solutions."[20] Frost estimates that the aerospace

[16] Dassault Systemes, Manufacturing Work Instructions (Whitepaper). 2012. (Available from http://files.solidworks.com/images/Alia/Manufacturing-Work-Instruction-WP.pdf)
[17] IBM, Digital Manufacturing: Extending the value of PLM. 2007. (Available at ftp://ftp.software.ibm.com/software/plm/uk/digital_manufacturing_broch.pdf)
[18] Frost & Sullivan, Analysis of the Global Digital Manufacturing Market. December 2012.
[19] Frost & Sullivan, Analysis of the Global Digital Manufacturing Market. December 2012.
[20] Frost & Sullivan, Analysis of the Global Digital Manufacturing Market. December 2012.

segment of the global digital manufacturing market was $US 171.2 million in 2011; it is forecasted to reach $US 240.8 million in 2016.[21]

For the aerospace industry, the aerospace standards (AS) series of AS9100, AS9110 and AS9120 provide the quality specifications for the aerospace supply chain. These standards are a key driver and influence in the market for digital manufacturing solutions in the aerospace segment and aerospace and defense manufacturers are encouraged to adopt the digital manufacturing approach that helps in validating new product designs and streamlining manufacturing process planning.[22]

4.2 Commercial availability and top players

Some products have been found in the area; very few have a strong focus on the aerospace market segment.

Table 4. Companies offering simulation platforms in the aerospace industry

Company	Products
Cortona3D http://www.cortona3d.com/	Cortona3D is a suite of Rapid Authoring tools used to create technical publications such as parts catalogs, manuals, work instructions and even training modules. The company targets the aerospace sector, but not exclusively.
Dassault Systemes http://www.3ds.com/	DELMIA Work Instruction Composer, part of Dassault Systemes' PLM system, allows detailed work instructions to be transferred to workers through the MES (Manufacturing Execution System) in the form of instructions that include 3D assembly sequences to help minimize errors.
EASEworks	EASEworks is an integrated software solution for

[21] Frost & Sullivan, Analysis of the Global Digital Manufacturing Market. December 2012.
[22] Frost & Sullivan, Analysis of the Global Digital Manufacturing Market. December 2012.

Company	Products
http://www.easeinc.com/	developing Work Instructions, Labor Standards, Line Balancing and Product Cost Estimating. EASEworks supports Lean, Kaizen and 5S projects and can be linked to ERP, MRP and MES solutions. Does not seem to have a focus on aerospace.
EOS Solutions http://3eos.com/	3D PDF Converter allows users to convert 3D CAD data from applications to interactive3D PDF documents with product manufacturing information (PMI),assembly structure, metadata, and views.
NGRAIN http://www.ngrain.com/	NGRAIN Production Suite: interactive 3D digital content creation.
Parametric Technology Corporation (PTC) http://www.ptc.com/	• PTC Windchill, supports product data management (PDM) system, assists in the definition of the mBOM, process plan, resources and work instructions needed to manufacture a particular product). • PTC Arbortext, dynamic publishing solution enabling organizations to create, manage, and publish technical information.
Sequence Software http://www.sequencesoftware.com/	Sequence, a software solution for electronic production and delivery of work instructions. The company doesn't focus only on aerospace, but does mention it as a market segment for their products.
Siemens http://www.plm.automation.siemens.com/	Teamcenter Manufacturing Documentation provides a work instructions solution where all product, process, resource and plant information is fully associated under a managed environment.
SILKAN	Simulators for training and maintenance.

Company	Products
https://www.silkan.com/	
SAP http://www.sap.com/	SAP 3D Visual Enterprise, a solution for creating 3D work instructions based on CAD files and deliver them electronically via tablets and other mobile devices wherever they are needed.

4.3 Latest investments and projects

Very few research projects and organizations focusing on software and platforms for the delivery of work instructions have been found. Some organizations working on Digital Manufacturing have been identified but very few provide details on their research and projects on work instructions and training materials production and platforms.

- The German Aerospace Center (DLR) is involved in research into interactive visualization and simulation. According to the organization's website, the research activities focus on "component-based software for distributed systems, software technologies for embedded systems and software quality assurance"[23].
- The Competence Center for Manufacturing is a laboratory of ITA - Instituto Tecnológico de Aeronáutica (Technological Institute of Aeronautics). CCM focuses on all stages of the lifecycle of the product and develops products and solutions in the areas of manufacturing processes, automation, and digital manufacturing.
- The creation of a Department of Defense Manufacturing Institute was announced by the US government in May 2013. The institute's objective is to "address the life cycle of digital data interchanged among myriad design, engineering, manufacturing and maintenance systems, and flowing across a networked supply chain."[24]

[23] German Aerospace Center (DLR) (http://www.dlr.de/sc/en/desktopdefault.aspx/tabid-1185/1634_read-3062/)
[24] AFS, White House Announces Two New DOD Manufacturing Institutes, May 2013. (Available at http://www.afsinc.org/news/news.cfm?ItemNumber=14884)

5 SOURCES

- Business & Industry
- Business Source Complete
- OneSource
- SBI
- IDC
- Frost & Sullivan
- Profound

STI Assessment

Title	**Aerospace Environmental Scan (WG5) : Custom Design of Specialized Gas Turbine Engine Instrumentation Materials**
Project Numbers	STI 17174
Date	July 17th, 2013
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, Envirotrec Brent Ostermann, Standard Aero (Working Group 5)
Prepared by	Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca) Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca)

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1 GAS TURBINE ENGINE TEST INSTRUMENTATION

Turbine engine instrumentation, such as sensors and actuators, face higher requirements than other engine instruments, in the sense that they must operate in very harsh environments (high temperature, pressure and vibration) compared to more pedestrian applications.[1]

The report focuses at answering the following questions:

1. What is the expected market size for this technology?
2. What are the drivers and barriers to adoption of a particular technology?
3. Which products are commercially available?

1.1 Expected market size

No information was found on engine test instrumentation; the market information found covers aerospace sensors, but not engine sensors specifically. The sensor market for aerospace and defense applications in the United States totaled $US 2.2 billion in 2011; the market is expected to rise to 2.8 billion in 2016; these numbers include many sensor types including altitude, speed, temperature and pressure sensors as well as landing gear and aileron control.[2]

However, some detailed numbers were found for specific sensors. The pressure sensors MEMS market is estimated at $US 26.9 million in 2010. This market is small compared to other pressure sensor market segments but prices are high. Pressure sensors are used in engines and FADEC, but also flight control instruments, cabin pressure and hydraulic systems. Some of the main applications in the civil aerospace are engine monitoring (FADEC) and flight test.[3]

According to the market literature found, the microelectromechanical systems (MEMS) market for pressure sensors in the high-value military and aerospace segments is growing, showing an 8.9% annual

[1] North Atlantic Treaty Organization (NATO), MEMS Aerospace Applications. February 2004. (Available at http://ftp.rta.nato.int/public//PubFullText/RTO/EN/RTO-EN-AVT-105///EN-AVT-105-$$ALL.pdf)
[2] Freedonia, Focus on Sensors. October 2012.
[3] MEMS Market Brief, vol. 4, no 9.

growth rate between 2010 and 2015 with additional growth expected in the coming years. Revenue for pressure sensors in both military and civil aerospace applications will reach $35.7 million in 2012. By 2016, military- and aerospace-related MEMS takings will reach $45.5 million.[4]

1.2 Drivers and barriers

The need to operate in an engine environment where harsh conditions, combined with high frequency response requirements, creates a need for advanced engine sensors.[5]

Some sensor technologies used in aerospace sensors have been described in the literature. Table 1 lists these technologies as well as their main advantages and disadvantages.

Table 1. Drivers and barriers to sensor technologies used in the aerospace sector

Technology	Drivers[6]	Barriers[7]
Fibre optic based sensors	• Low weight; • Small size; • High bandwidth; • Immunity to electromagnetic and radio frequency interferences.	• Research must still address issues like: ○ adhesive selection and bonding procedures; ○ quality control processes; ○ optimum selection of sensor configuration; ○ sensor material and host structure for embedded configurations; ○ characterization of embedded fibre optic sensors at elevated and cryogenic temperatures; ○ resolution optimization for desired parameters from multi-gratings; ○ sensitivity to transverse and temperature effects.

4 IHS, MEMS in Military and Aerospace Sectors to See Strong Growth. December 2012 (Available at http://www.isuppli.com/MEMS-and-Sensors/News/Pages/MEMS-in-Military-and-Aerospace-Sectors-to-See-Strong-Growth.aspx)

5 Pulliam, Wade; Russler, Patrick, High-Temperature, High Bandwidth, Fiber-Optic, MEMS Pressure Sensor Technology for Turbine Engine Component Testing. SPIE conference paper, February 2002. (Available at http://www.isa.org/Content/ContentGroups/InTech2/Features/20023/January4/memsfeature.pdf)

6 Mrad, Nezih. State of Development of Advanced Sensor Systems for Structural Health Monitoring Applications, North Atlantic Treaty Organization (NATO). June 2011. (Available at http://ftp.rta.nato.int/public//PubFullText/RTO/MP/RTO-MP-AVT-144///MP-AVT-144-29.pdf)

7 Mrad, Nezih. State of Development of Advanced Sensor Systems for Structural Health Monitoring Applications, North Atlantic Treaty Organization (NATO). June 2011. (Available at http://ftp.rta.nato.int/public//PubFullText/RTO/MP/RTO-MP-AVT-144///MP-AVT-144-29.pdf)

Technology	Drivers[6]	Barriers[7]
MEMS based sensors	• A greater amount of information can be gathered, leading to reduced downtime and improved quality; • Increased distributed intelligence leading to complete knowledge of a system, subsystem, or component's state of awareness and health for better decision making; • Small size; • Integrated structure; • Can be embedded into composites structures or sandwiched between metallic components for remote wireless and internet based monitoring; • Intelligent signal processing and decision making protocols can be implemented within the node structure to provide ready to use decisions for reduced downtime and increased maintenance efficiency.	• Specific issues must be addressed and require more development, such as: ○ wireless and secure communications (particularly in harsh environment applications); ○ power requirements; ○ packaging; ○ system miniaturization and integration meeting practical requirements within an economical manufacturing environment.
Piezoelectric sensors	• High sensor multiplexing capability; • Suitability in harsh environment; • Sensitivity to pressure, temperature, vibration, and strain.	• In the passive mode, background noise needs to be accommodated for; • In the active mode, sensors/actuators must be spaced properly and excited with certain frequencies at selected energy level to be able to detect damage with certain sizes and regions; • The reliability of sensor and actuator wiring, networking and bonding requires validation; • Costs associated with added weight, complexity and system certification need to be reduced.

New materials used for engine sensors components are also drivers to the market growth. A topic of increasing interest in this area is active metal brazing. This technology allows the bonding of metal to ceramic without metallization, eliminating several steps in the joining process and creating an extremely strong, hermetic seal that can reach higher operating temperatures. Active metal brazing can be with any combination of ceramics, carbon, graphite, metals, and diamond. Active braze alloys (ABAs) are used for engine sensors that employ metal-to-ceramic strips to monitor engine functions.[8]

[8] Sandin, Tom, Aerospace Brazing Today, Tomorrow. Aerospace Manufacture Design, May 2012. (Available at http://www.onlineamd.com/amd0512-active-brazing-alloys.aspx)

1.3 Commercial availability and top players

Relatively few companies publicize their products and services by stating their gas turbine engine capacities. Some sensor companies are probably active in the area but market their products in a more global way without targeting the turbine testing segment. Table 2 lists the companies found that claim to offer their products for gas turbine engine testing purposes.

Table 2. Companies offering engine test instrumentation and sensors

Company	Products
ASE Holdings http://www.aseholdings.com/	ASE2000, a SIM engine test simulator Turbojet and turboprop mobile engine test stands and electronic systems
Applied Dynamics International http://www.adi.com/	Gas turbine engine test rigs.
Electronic Concepts & Engineering (http://www.eceinc.com/)	Turbine engine Hardware In-the-Loop simulator
Emprise Corporation http://www.emprise-usa.com/pet/	Portable and modular engine and component test cell.
Howell Instruments Inc. http://www.howellinst.com/	H355 Series Engine Test Cell Instrumentation System
Industrial Acoustics Company (http://www.industrialacoustics.com/)	Mobile aero-engine testing facilities.
Kulite http://www.kulite.com/	High temperature engine pressure monitoring transducers.
MDS http://mdsaero.com/testing/aviation/	Provides testing services but developed their own testing software.
Meggitt Sensing Systems http://www.meggittsensingsystems.com/	Health and condition-based monitoring systems, high performance sensors; temperature vibration, dynamic pressure and microwave sensors; software and electronics monitoring systems for aerospace and land-based turbo-machinery.
MTI Instruments http://www.mtiinstruments.com/	The PBS-4100R+ is designed for test cell use; it provides vibration monitoring and analysis capabilities.
MTS http://www.mts.com/	MTS provides the most advanced technology available for accurately simulating real-world aircraft engine forces, motions and operating temperatures in a test lab environment.
Opal RT Technologies http://www.opal-rt.com/	RT-LAB Turbine Engine Simulator, an integrated package of PC components for the model-based design of a FADEC, turbine controller, or turbine engine simulation.
PCB Piezotronics http://www.pcbsensors.co.uk/	High temperature engine vibration monitoring sensors.

Company	Products
VTI Instruments http://www.vtiinstruments.com/	Temperature, pressure and conditioned transducers; structural and strain tests.

A NATO project on gas turbine instrumentation took place between 2010 and 2012[9]. It focused on areas such as high temperature sensors, non-intrusive sensors (e.g., wireless, optical, paint, eddy current, etc.) and test cell instrumentation systems for effective technology evaluation and qualification.

2 SOURCES

- Aerospace Database (Proquest)
- Business & Industry
- Business Source Complete
- OneSource
- SBI
- Scopus
- Frost & Sullivan
- Profound

[9] More details on this project (Gas Turbine Engine Test Cell Instrumentation, project AVT-180) can be found at http://www.cso.nato.int/Activity_Meta.asp?Act=1759.

Component Materials Testing

Title	**Aerospace Environmental Scan (WG5) : Component Materials Testing – Gas Turbine Engines**
Project Numbers	STI 17174
Date	July 31th, 2013
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC Brent Ostermann, StandardAero
Prepared by	Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca) Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca)

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1 COMPONENT MATERIALS TESTING – GAS TURBINE ENGINE TESTING

This scan covers component materials testing of gas turbine engines. It focuses on answering the following questions:

1. Expected market size for this technology;
2. Drivers and barriers to adoption of the technology;
3. Products which are commercially available.

Market research reports focusing specifically on the component materials testing of gas turbine engines were not available. As a result information on drivers and barriers to adoption of the technology was not found. However drivers/restraints for material testing equipment and non-destructive test equipment markets are included in this report.

1.1 Expected market size

According to a 2013 published by Freedonia[1], turbine product demand for use in aircraft engine applications is forecast to increase 4.9% per year from 2011 to $12.5 billion in 2016. Continued recovery from the 2007-2009 recession, rising levels of air travel activity, and strong increases in the air cargo industry will contribute to advances. In addition, aircraft manufacturer Boeing has developed newer aircraft that promise improvements in range and fuel efficiency; this is expected to spur replacement of older, less efficient planes. Gains will also be supported by strong export sales of commercial airliners by Boeing from its US manufacturing facilities, particularly for the Chinese market. Furthermore, the large number of aircraft in use will support healthy aftermarket engine demand. Finally, the continued movement toward turbine engines in small aircraft will provide opportunities for engine manufacturers. On the commercial side of the business, these moves include the ongoing efforts to develop what are called "very light jets."

[1] Turbines: United States, March 2013, Freedonia

According to a recent report published by Deloitte[2], the global aerospace and defense (A&D) Industry's revenue grew overall by 5.9 % in 2012, all due to record commercial aerospace production, and even made up for global defense industry revenue declines. Boeing Commercial Airplanes and Airbus Commercial topped their previous year's combined production with the delivery of 1,189 aircraft in 2012, the highest production level achieved in commercial aircraft history. According to Deloitte's analysis of the leading global A&D companies, the commercial aircraft segment's revenue increased 16.2% or US$38.4 billion in 2012. Boeing Commercial and Airbus Commercial generated over half of the increase in commercial aircraft revenues, as combined revenue increased by 27.2 % or approximately $20.5 billion in 2012. To give a perspective on how large this is, if this were a company, it would rank as the 10th largest global A&D firm. Over the next 20 years, passenger travel demand growth is expected to continue to increase, especially in Asia and the Middle East markets. Growth is also being driven by demand from airline operators as they retire obsolete, less fuel efficient airplanes. Boeing forecasts 35,280 new aircraft will be produced from 2013 through 2032. With 7 years of backlog, production increases are expected to continue and record levels of commercial aircraft production may be expected again in 2013.

Analysis from Frost & Sullivan, *Analysis of the Material Testing Equipment Market*[3], finds that the materials testing equipment market earned revenues of $495.6 million in 2010 and estimates this to reach $591.1million in 2015. Market recovery has been fuelled by demand from traditional end-user markets such as automotive, aerospace, primary metals and plastics.

In addition to traditionally large end-user sectors, novel applications in the fields of biomedical, composites, medical devices and nanotechnology are expected to boost the market in the coming years. While new opportunities are emerging, a key challenge remains the dominance of established participants in the market. This has limited the business opportunities for smaller companies.

The material testing market comprises a range of competitors of varying size and reach. Material testing equipment includes universal testing machines, servohydraulic testing machines, hardness test

[2] Global Aerospace & Defense Industry Financial Performance Study, June 2013, Deloitte

[3] Analysis of the Material Testing Equipment Market, January 2012, Frost & Sullivan

equipment and impact test equipment. The top three market participants, Instron, MTS and Zwick/Roell, occupy a significant amount of market and mind share, and drive critical parameters that define this market – such as price points and regulatory and standardization trends – making it difficult for emerging participants to gain a foothold. While this is both a restraint and challenge for newer and smaller material test equipment vendors, it can be overcome by focusing on emerging opportunities from geographical, technological, and application perspectives.

Research indicates that this stability is expected to continue through the forecast period with a CAGR of 3.6 percent between 2010 and 2015. Asia Pacific is currently not only the biggest market for material testing equipment, accounting for 36.9 percent of total revenues but is also the fastest growing geographic segment. Aerospace sector is forecast to make up an average of 24% of the total material testing equipment market from 2007 to 2015. [4]

The global non-destructive testing equipment market generated $1,397.4 million in 2011, with a positive revenue growth rate of 5.5 percent over the previous year. The market is expected to grow at a 7.8 percent compound annual growth rate (CAGR) and generate $2,031.3 million in revenues by 2016. Radiography equipment is the fastest growing segment of the NDT equipment market, with a CAGR of 8.3 percent. Radiography equipment was also the second largest market segment in 2011 and by the end of forecast period, it is expected to overtake ultrasonics as the largest segment revenue-wise. Although radiography equipment is expected to be the largest revenue-generating segment of the market, ultrasonic test equipment is still expected to lead the NDT equipment market in units sold. However, since the average price for a unit of ultrasonic test equipment is extremely smaller than the average price for a unit of radiography equipment, the revenue generated from radiography equipment is expected to overtake ultrasonic test equipment. Major market participants include GE Measurement and Control Solutions, Olympus NDT and YXLON International GmbH.

[4] Analysis of the Material Testing Equipment Market, January 2012, Frost & Sullivan

1.2 Drivers/Restraints

Table 1.Total Material Testing Equipment Market: Key Market Drivers and Restraints, Global, 2011-2015[5]

Drivers	Barriers
• Market recovery driven by demand from traditional end-user markets • Service industry continues to drive opportunity for test equipment providers • Technology enhancements drive market demand • Demand from emerging application markets creates new growth opportunities	• Exchange rate restricts growth prospects for test equipment vendors • Recent events at Fukushima expected to hinder market growth • Presence of established participants limits business opportunities for smaller participants

Table 2. Total Nondestructive Testing Equipment Market: Key Market Drivers and Restraints, Global, 2012-2016[6]

Drivers	Barriers
• Market recovery driven by demand from traditional end-user markets • Service industry continues to drive opportunity for test equipment providers • Technology enhancements drive market demand • Demand from emerging application markets creates new growth opportunities	• Exchange rate restricts growth prospects for test equipment vendors • Recent events at Fukushima expected to hinder market growth • Presence of established participants limits business opportunities for smaller participants

1.3 Commercially Available Products

As previously mentioned, the top three materials testing equipment market participants are Instron, Zwick/Roell and MTS Systems, making up 60.8% of the market. They are followed by Shimadzu Corp. and Tinius Olsen, making up 14.5% of the market. Other companies make up 24.7% of the market.

[5] Analysis of the Material Testing Equipment Market, January 2012, Frost & Sullivan

[6] Analysis of the Global NondestructiveTesting Equipment Market, January 2012, Frost & Sullivan

Table 1: Companies with Commercially Available Products

Company	Website for Further Information
Bose	**Component Fatigue Testing:** Assuring strength, durability, and damage tolerance in automotive and aerospace applications requires not only testing of the basic materials used, but very often fatigue testing of the components or full scale structure is required in order to evaluate size effects, bulk effects, or just to understand the transfer function from material to structures. Bose® ElectroForce® test instruments are used worldwide in automotive and aerospace applications for the testing of components. ElectroForce testing systems provide a well-suited platform for the testing of metallic materials, components and structure. These systems have exceptional bandwith and the ability to resolve force, displacement or strain with a high level of accuracy and precision. This allows testing to be done in a timely manner, reducing overall testing program cost and the need for excessive test replication. http://worldwide.bose.com/electroforce/en_us/web/electroforce_load_frame_systems/page.html
Instron	http://www.instron.us/wa/product/default.aspx
MTS Systems	http://www.mts.com/en/products/industry/aerospace/index.htm
Shimadzu Corporation	List of products http://www.shimadzu.com/an/products/index.html Testing and Evaluation Equipment for the Aerospace http://www.shimadzu.com/an/literature/etc/jpz13001.html
Tinius Olsen	http://www.tiniusolsen.com/material-testing-groups/testing-Composites-calc.html
Zwick/Roell	http://www.zwickusa.com/en/news/news-detail/article/new-brochure-available-illustrating-solutions-for-aerospace.html
GE	A variety of inspection systems for applications ranging from single crystal blades to 3D turbine blade inspection http://www.ge-mcs.com/en/industry-solutions/aerospace.html?type=ndt
Olympus NDT	Aeroengine borescopes http://www.olympus-ims.com/en/aeroengine-borescopes/
Yxlon Industries	Digital Radiography http://www.yxlon.com/Meta/News/YXLON-strengthens-position-in-digital-radiography http://www.yxlon.com/Service/Application-Service http://www.yxlon.com/Meta/News/TITAL-banks-on-YXLON-Y-MU2000-D-X-ray-inspection-s

Company	Website for Further Information
	http://www.yxlon.com/Meta/News/YXLON-achieves-technological-breakthrough-in-digit http://www.yxlon.com/Applications/Welds/Aviation-and-aerospace-industry

1.4 Sources

Databases

- Frost & Sullivan
- MarketResearch.com
- Freedonia
- OneSource
- Internet

Market Research Reports

- Turbines: United States, March 2013, Freedonia
- Global Aerospace & Defense Industry Financial Performance Study, June 2013, Deloitte
- Analysis of the Material Testing Equipment Market, January 2012, Frost & Sullivan

Engine Test Simulator

Title	**Aerospace Environmental Scan (WG5) : Engine Test Simulator – Gas Turbine Engines**
Project Numbers	STI 17174
Date	July 18th, 2013
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC Brent Ostermann, StandardAero
Prepared by	Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca) Michèle Senay, Strategic Information Analyst (michele.senay@cnrc-nrc.gc.ca)

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1 ENGINE TEST SIMULATOR – GAS TURBINE ENGINE TESTING

This scan covers the area of gas turbine engine testing that includes the systems that could be used to simulate gas turbine engines prior to actual engine test.

The scan focuses on answering the following questions:

1. Expected market size for this technology;
2. Latest investments/projects;
3. Commercially available products and main players.

1.1 Expected market size

No market information was found on gas turbine engine testing simulators

1.2 Latest research/projects

Below is a list of recently completed or ongoing research in the area of gas turbine simulation:

PREMECCY – Predictive methods for combined cycle fatigue in gas turbine blades

Start date: 2006-06-01

End date: 2011-11-30

PREMECCY identifies the field of rotor blade combined cycle fatigue (CCF) as an area where there are shortcomings in the existing industry-standard design and prediction tools, and thus where significant benefits can be achieved.

The fundamental aim of the PREMECCY project is to deliver new and improved combined cycle fatigue (CCF) prediction tools for exploitation in the industrial design process. This will be achieved through a programme of material characterisation and advanced testing.

To meet these objectives the project will carry out the following key tasks:

- design advanced test specimens, representative of rotor blade critical features;
- define and execute a matrix of traditional testing to fully characterise the selected materials;

- modify existing test rigs to allow CCF testing of advanced specimens;
- define and execute advanced specimen testing to explore a range of CCF mechanisms on life;
- develop new and enhanced CCF prediction methods.

VIVACE PROJECT

Project completed; information posted on 04-01-2012

The EU-funded 'Value improvement through a virtual aeronautical collaborative enterprise' (Vivace) project set out to develop a comprehensive virtual design platform that enables collaboration between teams in an extended enterprise, taking a virtual product with all desired characteristics from the product design phase all the way through to the supply chain.

The project was divided into three different technical areas under the leadership of three industrial partners specialised in aircraft products, engine products and integration or advanced capabilities:

1) Virtual aircraft sub-project;
2) Virtual engine sub-project;
3) Advanced capabilities sub-project.

The result was the Vivace toolbox, a standalone re-usable collaboration/simulation platform. The virtual aircraft software included system and flight simulations in addition to component simulations throughout the development life-cycle.

The Vivace project produced an innovative aeronautical collaborative design environment validated through real industrial use cases that will advance aircraft and engine design. Implementation of the toolbox should lead to significant reductions in aircraft development costs, time associated with the development phase of new aircraft designs, and lead time and development costs of gas turbine engines. Thus, the virtual product foundation and virtual enterprise foundation should have significant impact on international standards, increase EU competitiveness in the aeronautics manufacturing industry and provide a boost to the European economy.

http://cordis.europa.eu/fetch?CALLER=OFFR_TM_EN&ACTION=D&RCN=7882

Flutter-free turbomachinery blades

Start date: 2008-07-01

End date: 2013-06-30 | FUTURE website

FUTURE brings together European and international centres-of-excellence in order to reach major scientific & technical objectives in striving towards flutter-free turbomachine blades. By advancing the state-of-the-art in flutter prediction capabilities and design rules, the FUTURE project will lead to benefits in terms of decreased development cost, reduced weight and fuel consumption, and increased ability to efficiently manage flutter problems occurring on engines at service. Eight interconnected turbine and compressor experiments will be performed in the project, in combination with numerical modelling of vibrating blades and the related unsteady aerodynamics. Cascade experiments will be employed to study unsteady aerodynamic properties in detail. These tests are supporting more complex rotating turbomachinery tests (turbine and compressor) to study the addressed phenomenon in engine-typical environment. The knowledge from both component tests will be then condensed into best practice for both experimental and computational (CFD) set-ups, and will be used towards a combined effort of physical understanding of travelling waves and interferences between the vibrating structures and the surrounding fluid. The acquired knowledge is aimed to be employed by the aeroelastic specialists in the companies, research institutes and universities to identify updated and better aeromechanical design rules.

In the process of reaching this unique knowledge status a sophisticated, measuring technique will be developed, and a new excitation mechanism will be implemented as back-up to the free-flutter experiments. Furthermore, a unique database with combined structural and unsteady aerodynamic results will be established and made available for further dissemination among the partners. This database will contain significantly more detailed data than any other existing database in the world.

http://cordis.europa.eu/projects/rcn/89404_en.html

Advanced Turbofan-Equipped Aircraft Noise Model

Start date: 2010-01-01

End date: 2012-08-31 | FLIGHT-NOISE website

The aim of this project was to adapt, improve validate and test a computer model for the simulation of aircraft noise. The project starts from a well-established basis of a multi-disciplinary computer model that includes flight mechanics, aerodynamics, gas turbine engine performance, numerical modelling, optimisation, aircraft operations, and aircraft noise. The latter discipline also includes wave propagation and diffusion.

The work programme includes the following main tasks:

1.) Review of requirements and systems compatibility.

2.) Software upgrades in a number of key areas of propulsion and airframe noise.

3.) Generation of databases (airplanes, turbofan engines and topographical information).

4.) Validation and Testing.

5.) Documentation, Training and Technical Support.

http://cordis.europa.eu/projects/rcn/98025_en.html

Main Annulus Gas Path Interactions

Start date: 2006-09-01

End date: 2011-08-31 | MAGPI website

Objective

In a modern aero engine, up to 20% of the main annulus flow is bled off to perform cooling and sealing functions. The vicinity of these bleed ports and flow sinks is characterised by complex unsteady swirling flows, which are not fully understood. Even the most up-to-date numerical tools have difficulties predicting the behaviour of the secondary flow system when interacting with the main annulus. The project addresses interactions between main gas path and secondary flow systems in commercial gas turbines in response to Research Activity AERO-2005-1.3.1.2a Concepts and technologies for improving engine thermal efficiency and reducing secondary air losses. Experiments are planned on turbine disc rim and compressor manifold cavity heat transfer, hot gas ingestion, and spoiling effects of cooling air flow and their impact on turbine and compressor performance, as well as a reduction of secondary air losses.

The experimental data will be used for better understanding of the complex flow phenomena and improvements of platform and cavity design. Furthermore, the industrial partners will validate their design tools with these test data and improve their prediction capability of secondary flow systems when interacting with the main gas path. The expected results are a reduction of cooling and sealing airflow rates, improvements of the turbine and compressor efficiency and increase of the safety margin of the engine components by better cooling.

Expected technical results are:

- Knowledge of the interaction phenomena and its effect on cavity heat transfer, spoiling and performance,
- Experimental results for validation of improved numerical tools for secondary flow systems,
- Optimised design methods and CFD best practice guidelines.

The targeted outcome will contribute to the ACARE goal of reduced CO2 emissions via reduced fuel burn of 2% to improve the environment and strengthening the competitiveness of European gas turbine manufacturers.

http://cordis.europa.eu/projects/rcn/81475_en.html

A Unified Approach for Vaned Diffuser Design in Advanced Centrifugal Compressors

Information posted on 02-01-2013

Modern internal combustion engines utilize high pressure ratio turbochargers combined with NOx control strategies to improve efficiency and reduce emissions. In such an application, the centrifugal compressor has to simultaneously achieve high efficiency, high pressure ratio and a broad operating range. To meet these requirements, the trend has been towards highly loaded compressors, utilizing high speed impellers with backward-leaning blades for extended operating range and vaned diffusers for enhanced pressure recovery with compact geometry.

The flow out of the impeller presents multiple challenges for the vaned diffuser: it is transonic, unsteady, and highly non-uniform in both axial and circumferential directions. The relative importance of each of these factors is not well understood: different researchers have reached different conclusions regarding, for example, the importance of the impeller largely depends upon historical correlations, CFD simulation and careful experimentation.

The objective of the investigation is therefore to rigorously establish the links between diffuser geometry, performance, component matching and stability. The technical approach combines first principles based modeling with high-fidelity calculations and experiments using a unique swirling flow diffuser test rig at the Gas Turbine Laboratory. The goal is to develop design criteria and to define performance metrics expressed in terms of overall vane parameters and appropriately averaged inflow properties that can be applied in the preliminary design stage.
http://termodinamicaindustrial.wordpress.com/2013/01/02/a-unified-approach-for-vaned-diffuser-design-in-advanced-centrifugal-compressors/

1.3 Commercial availability & main players

Table 1 is comprised of a list existing simulation software programs. The commercial availability of some of these programs is not clear at times, but they have been included in the list for completeness sake. NASA has also developed an object-oriented approach for gas turbine engine simulation in 1995[1], but the software is not available on the website.

Table 1. Companies offering products supporting adaptive machining

Company/Organization	Products
Dassault Systemes http://www.3ds.com/products-services/simulia/portfolio/isight-simulia-execution-engine/latest-release/	Isight from the Simulia brand is used by Rolls Royce to reduce the time for designing engines
Siemens http://www.lmsintl.com/jet-engine-testing	LMS Test.Lab Turbine Testing is designed for maximum team efficiency during design validation tests on engine prototypes.
Siemens http://www.lmsintl.com/aircraft-power-systems	The LMS Imagine.Lab Aircraft Power Systems solution allows for both transient and steady-state system simulation using a set of fully compatible, multi-domain

[1] http://webdev.archive.org/stream/nasa_techdoc_19950024173/19950024173_djvu.txt

Company/Organization	Products
	component libraries.
GE http://www.ge-ip.com/support/automation/training/northamerica/GTS_Simulators	Series 90-30 Training Simulator
NLR (Netherlands) http://www.gspteam.com	Developed the Gas turbine Simulation Program (GSP) in-house; GSP is under continuous development in close cooperation with the Delft University of Technology.
VisSim http://www.vissim.com/products/vissim.html http://www.vissim.com/solutions/gas_turbine_simulator.html	Preconstructed components giving access to high level models of subsystems including gas turbines
PennState http://muri.mne.psu.edu/sys_sim/gas_turbine.htm	Software for DES (Discrete event controller) control of aircraft gas turbine engines

Databases

- Aerospace Database (Proquest)
- Frost & Sullivan
- MarketResearch.com
- AWIN
- CORDIS
- Business Source Complete
- SBI
- Scopus

Wireless Instrumentation for Testing

Title	**Aerospace Environmental Scan (WG5) : Wireless Instrumentation for Testing of Gas Turbine Engines and Components**
Project Numbers	STI 17174
Date	July 31st, 2013
Prepared for	Jim Prendergast, IRAP Aerospace Sector Team Alfonz Koncan, EnviroTREC Brent Ostermann, StandardAero
Prepared by	Hirem Baran, Information Specialist (hirem.baran@nrc-cnrc.gc.ca)

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1 WIRELESS INSTRUMENTATION FOR TESTING

This scan covers the area of wireless instrumentation in the area of gas turbine engine and components.

The scan attempts to answer the following questions:

1. Main players, drivers and barriers to adoption of a particular technology; and expected market size
2. Latest investments/projects;
3. Commercially available products

1.1 Main players, drivers & barriers and market size

According to the Frost & Sullivan report entitled *Global Temperatures Sensors and Transmitters*[1], the total revenue generated by the global temperature sensors and transmitters market in 2012 amounted to $3,859.4 million. The annual growth rate registered in 2012 is estimated to exhibit a dip of 4.8 percent as compared to 2011, when the revenue grew at 6.2 percent. Total revenue is estimated to increase to $6,319.5 million by 2019. The annual revenue growth rate in 2019 is expected to be a high of 8.0 percent. The revenue of the global temperature sensors and transmitters market is estimated to grow at a compound annual growth rate (CAGR) of 7.3 percent between 2012 and 2019.

The market is segmented into the seven key product segments:

- Infrared temperature sensors
- Thermocouple temperature sensors
- Resistance temperature detector (RTD) temperature sensors
- Thermistors temperature sensors
- Integrated circuit (IC) temperature sensors
- Fiber optic temperature sensors
- Temperature transmitters

[1] Global Temperatures Sensors and Transmitters, Frost & Sullivan2013

Top industry challenges in the Total Temperature Sensors and Transmitters Market ranked in order of impact are:

- Infrared (non-contact) temperature sensors are mostly confined to industrial applications
- Overseas production affects growth
- Harsh Environments Pose Threat to the Temperature Sensors
- Increased user-controlled monitoring needs sustain development
- Increased emphasis on service supports market penetration
- High level of competition and price discounts restrict survival
- Shift in distribution ratio mix alters sales overheads

Drivers and restraints mentioned in the report are not included here as they were not specific to the aerospace industry.

The key participants competing in global temperature sensing market include:

- ABB
- Emerson Process management (ROSEMOUNT Division)
- GE Sensing and Control
- Honeywell Sensing and Control
- SIEMENS
- Endress & Hauser
- Weed Instruments
- Dwyer Instruments
- Measurement Specialties
- FLIR Systems
- FLUKE (Ircon+ Raytek + FLUKE)
- Thermometrics,
- JUMO Gmbh & Co. KG,
- Watlow Electric Company
- Minco products
- EPCOS AG

A survey of their websites didn't provide any commercial products for the Aerospace industry. When products related to the Aerospace industry were found, it was not clear if they were wireless or not.

1.2 Latest research/projects

A CORDIS database search identified the following 2 European research programs. An Internet search identified a NATO unclassified project:

Table 1: Research Investments

Project (Country)	Investment	Description and website for further information
STARGATE Sensors towards Advanced Monitoring and Control of Gas Turbine Engines	Start date: 2012-11-01 End date: 2015-10-31 Total cost: € 7 819 426 EU contribution: €4 999 002	The headline objective of this project is to develop a suite of advanced sensors, instrumentation and related systems in order to contribute to the development of the next generation of green and efficient gas turbine engines http://cordis.europa.eu/projects/rcn/104300_en.html
HEATTOP (Accurate high temperature engine aero-thermal measurements for gas-turbine life optimisation, performance and condition monitoring)	Project status: Completed	The HEATTOP project developed sensors and probes which are critical for efficient, economic, reliable and environmentally friendly operation of gas turbines in aero engines and in stationary power generation facilities. The current limits of instrumentation had to be stretched, while at the same time accuracy and reliability needed to be improved. Final Report - HEATTOP (Accurate high temperature engine aero-thermal measurements for gas-turbine life optimisation, performance and condition monitoring)
Gas Turbine Engine Test Cell Instrumentation (AVT-180)	Start date: 2010-01-01 End date: 2012-12-31 NATO Unclassified	The topics to be covered by the study include areas such as high temperature sensors, non-intrusive sensors (e.g., wireless, optical, paint, eddy current, etc.) and test cell instrumentation systems for effective technology evaluation and qualification. Consideration of long life sensors, real-time data acquisition and reductions methods, real-time and residual stress measurement, vibration monitoring, etc. will

Project (Country)	Investment	Description and website for further information
		be included. Additional topics include efficient test instrumentation protocols including the identification of the role of pre-test predictions of critical parameters and statistical variations in data. https://www.cso.nato.int/Activity_Meta.asp?Act=1759

1.3 Commercially available products

Table 2 is comprised of a list existing commercial products and products that are in development for wireless instrumentation for testing of gas turbine engines and components.

Table 2: Companies offering products for testing of gas turbines engines and components

Company/Organization	Products
Sporian Sporian AssetOverseer® HT-1000 sensors http://www.sporian.com/harsh.html	Sporian AssetOverseer® HT-1000 sensors are proving to operate robustly in high temperature (1000+ Celsius) and high pressure (1000 PSI) environments.
Prime Photonics – FOCIS Turbine Blade Monitoring http://www.primephotonics.com/technical/fiber-optic-sensors/focis-turbine-blade-monitor.html	Optical system for monitoring turbine blades on gas and steam turbines. FOCIS™ makes real-time blade-by-blade measurements, identifying and tracking individual blades for health monitoring and providing blade passing, blade clearance and engine tachometer data.
Prime Photonics – Phoenix™ Ultra-High Temperature Wireless Sensors http://www.primephotonics.com/technical/wireless-sensors/phoenix-ultra-	Prime is developing Phoenix™, a revolutionary ultra-high temperature sensor technology that uses electrically passive metamaterial-based

Company/Organization	Products
[high-temperature-wireless-sensors.html]	sensor 'patches' that can be remotely monitored from outside of the hot environment. By using a metamaterial-based analogy of radio frequency identification (RFID) tags, Phoenix™ is being developed for use in environments up to 3000F.
Prime Photonics – Magnetic and Electric Field Sensors http://www.ge-ip.com/support/automation/training/northamerica/GTS_Simulators	Prime is developing a suite of all-optical full vector (3D) electric and magnetic field sensors that can survive the harshest high electromagnetic high temperature environments. The compact sensor probes can be used in high field strength environments that exceed 2 Tesla with rapid transients, have a response of over 50 kHz and are immune to electro-magnetic induction.
Prime Photonics – High Temperature Pressure and Temperature Sensors http://www.primephotonics.com/technical/fiber-optic-sensors/high-temperature-pressure-and-temperature-sensors.html	Prime is currently developing the next generation of high temperature pressure and temperature sensors which show significant promise in providing dynamic pressure measurements and highly accurate temperature measurements in the most demanding applications up to 3000F. Prime's all optical Resonant Beam Sensor (RBS) technology combines the advantages of currently available fiber optic pressure and temperature sensors with the proven reliability of mechanical resonator-based electrical sensors. Low-cost interrogation/signal conditioners will allow

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	Prime's RBS sensor technology to be applied in a wide range of industrial and aerospace applications.
Makel Engineering Miniature Sensor for Emissions Monitoring http://www.makelengineering.com/dir/Technologies/Overview/Overview.htm	A compact, robust multi-species monitor for high temperature gas emission streams is developed. The system is based on advanced micro-machined gas detection sensors developed for detection of CO, NOx, CO_2, O_2, and Hydrocarbons. Monitoring of the multiple species is based on several sensor platforms, each having a different sensing mechanism.

Databases

- Frost & Sullivan
- MarketResearch.com
- AWIN
- CORDIS
- Business Source Complete
- SBI
- Scopus