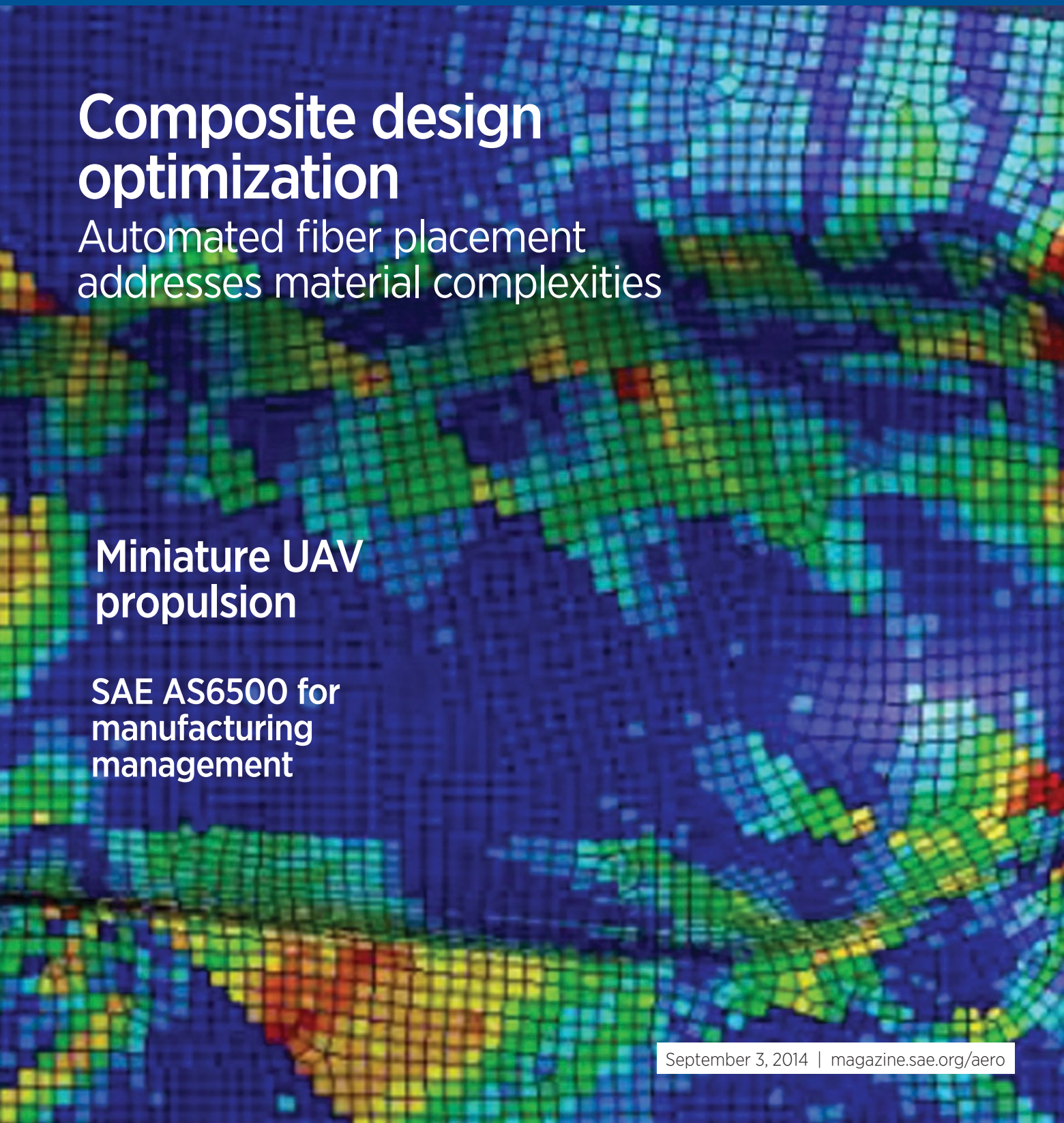
SAE INTERNATIONAL™

# AEROSPACE ENGINEERING™



## Composite design optimization

Automated fiber placement addresses material complexities

## Miniature UAV propulsion

## SAE AS6500 for manufacturing management

September 3, 2014 | magazine.sae.org/aero

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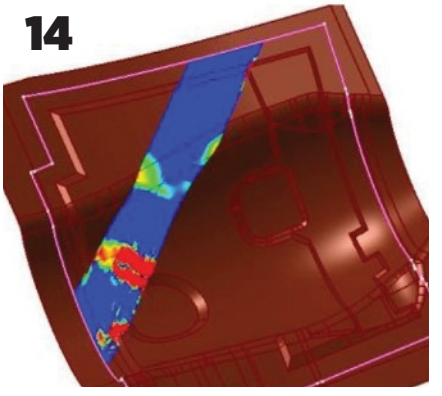
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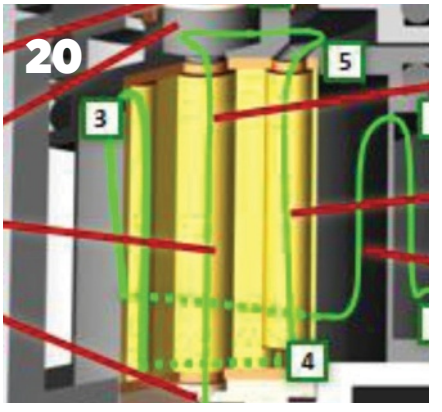
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# TOP PRODUCTS

## Field-deployable computing platform



**Elma Electronic** Inc.'s S50J computing platform is a reliable and rugged, field-deployable system with abundant configurable I/O for maximum design versatility. Most I/O schemes can be supported using tailored I/O panels, and the S50J also features expandable aluminum sidewalls for easy sizing. The fanless system platform is suited for applications in which system reliability is critical and environmental conditions can be extreme. Specific uses include signal processing, hyperspectral imaging, tactical command and control, as well as surveillance and reconnaissance. More detail at http://articles.sae.org/13288.

## RTD sensors

**Omega**'s PR-21 series of RTD (resistance temperature detector) sensors with M12 connector feature a welded 316L stainless steel housing and an integral four-pin M12 connector for easy connection. They provide a fast response time and a temperature range of -50 to +250°C. The series is suited for process control and test and measurement applications. More detail at http://articles.sae.org/13286.

## Strut integrated isolator

For fuselage-mounted equipment, **ITT**'s strut integrated isolator technology incorporates a fail-safe elastomeric cartridge directly in a strut, eliminating the need for separate elastomeric mounts. The isolator cartridge can be placed in each leg of a multi-leg assembly to control system dynamics. More detail at http://articles.sae.org/13413.

## Tension/compression load cell

The Model XLUS88 subminiature, bidirectional tension/compression load cell from **tecsis LP** operates from 150 g to 1000 lb. It features a compact size of 0.5 to 0.75 in. in diameter for limited-space applications. The stainless steel material is fully welded and built for rugged conditions with an overload capacity of 150% full scale. More detail at http://articles.sae.org/13412.

## MEMS wafer inspection

**Sonoscan**'s AW322 200 automated system for ultrasonic inspection of MEMS wafers images and identifies internal gap-type defects down to 5 µm in size. It is especially useful for finding non-bonds, voids, and other defects in the seals surrounding the MEMS wafer cavities. System features include two loadports, two stages, and multiple transducers, enabling it to image two 8-in MEMS wafers simultaneously. More detail at http://articles.sae.org/13414.

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# TOP NEWS



**The hybrid Solaris plant was developed as an energy-producing crop that farmers could grow instead of traditional tobacco. A test farm for aviation biofuel production in Limpopo province, South Africa, is shown.**

**Boeing**, **South African Airways** (SAA), and **SkyNRG** are collaborating to make sustainable aviation biofuel from a new type of tobacco plant. This initiative broadens cooperation between Boeing and SAA to develop renewable jet fuel in ways that support South Africa's goals for public health as well as economic and rural development. More detail at http://articles.sae.org/13473.

**KUKA Aerospace** is locating its first U.S. facility outside of Michigan in Everett, WA. The 29,000-ft$^2$ center will provide a service and maintenance hub close to KUKA Aerospace customers on the West Coast and help support current expansion. It is expected that about 75 employees will work out of the facility when it is fully operational. More detail at http://articles.sae.org/13472.

**Redstone Defense Systems** selected **Northrop Grumman** Corp. to supply and integrate mission avionics equipment for a digital cockpit upgrade of the **U.S. Army**'s UH-60L Black Hawk helicopters. Northrop Grumman will provide a scalable, fully integrated mission equipment package for the UH-60L cockpit and will replace the older analog gauges with digital electronic instrument displays. The new designation for this upgraded aircraft will be UH-60V. More detail at http://articles.sae.org/13471.

**GKN Aerospace** is leading a consortium of U.K. companies in a 3½ year, £13.4 million research-and-development program called Horizon (AM) that builds on GKN Aerospace's additive manufacturing (AM) capability. The Horizon (AM) team includes GKN Aerospace, **Renishaw**, **Delcam**, and the **Universities of Sheffield and Warwick**. The program is backed by the U.K.'s **Aerospace Technology Institute**. More detail at http://articles.sae.org/13436.

**Airbus**, **British Airways**, Heathrow Airport, and **NATS** (the main air navigation service provider in the U.K.) have established a partnership to study and develop operational procedures to reduce the number of people affected by noise around London's Heathrow. This project uses the capabilities of British Airways' A380 and looks at how the aircraft manufacturer, airline, airport, and air navigation services provider can further reduce the noise impact of flight operations for local communities. More detail at http://articles.sae.org/13433.

# Test & Measurement Solutions



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# WEBCASTS

## Sept. 11: Deploying and leveraging simulation



**Sriram G, R&D Director, Valeo India R&D Center**



**Karthic Sethuraman, Engineering Manager, Comfort and Driving Assistance Systems, Valeo India**



**Sandeep Sovani, Ph.D., Director, Global Automotive Industry, ANSYS Inc.**

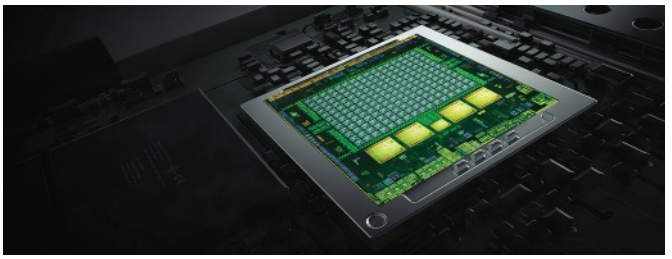
The **Valeo** India R&D Center is Valeo's only global offshore engineering center dedicated to the mechanical engineering needs of all of the company's business groups. Engineering simulation is a central part of the R&D Center, which develops transmission systems, electrical systems, driver assistance systems, wiper systems, and thermal systems. In a free 60-min webcast, the center's director and engineering manager will present the best practices that were developed to systematically deploy and leverage simulation across different product groups and different physics as well as for advanced uses such as design optimization. "Systematic Deployment of Simulation at an R&D Center: Evolution of Automotive Sub-System Simulation at Valeo" will explore these best practices, illustrated by numerous examples of automotive subsystem simulation. An audience Q&A will be included. Click here to register.

# TOP ARTICLES

Check out these most-read articles from SAE International's online publications covering the aerospace, automotive, and off-highway industries.

### Nvidia chipset to enable greater autonomy

Powerful visual computing processors for dashboard displays are now taking on safety-critical driver assistance functions.



**Nvidia's Tegra K1 system-on-a-chip module handles digital dashboard displays and, increasingly, driver assistance functions.**

### Growth in telematics capabilities bring more benefits to more users

Telematics services are rapidly moving from a luxury option to a commonly used tool. Expanded capabilities and improved coverage continue to make it easier for fleet owners and private operators to justify the expense of connectivity.

### Boeing reveals at Farnborough innovative method of building 777 fuselages

The company says the Fuselage Automated Upright Build advanced manufacturing technology is expected to yield safety and

quality benefits; it has been in development since 2012.

### Formula E racers zap expectations

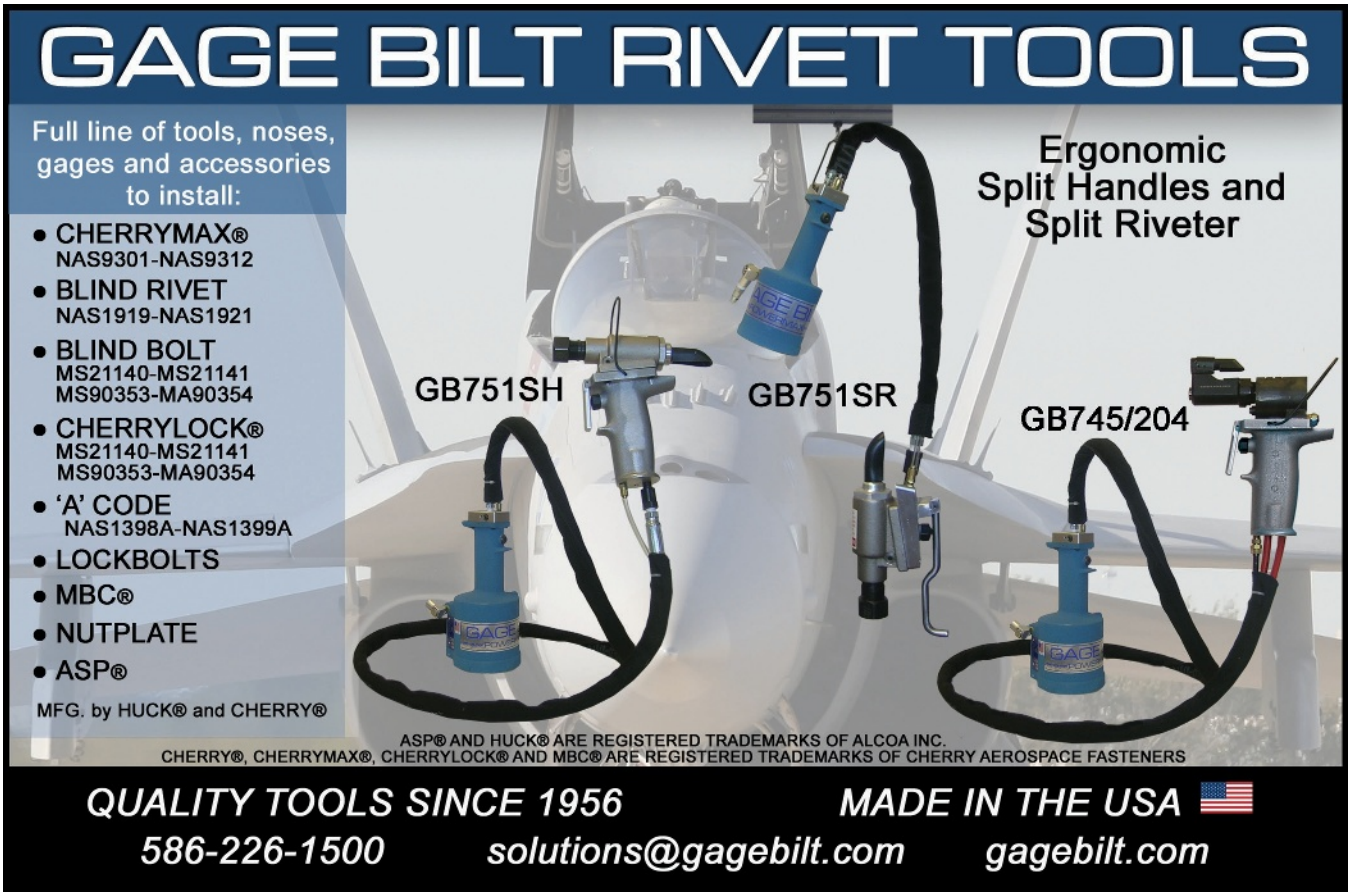


**The Spark-Renault SRT_01E, with its aerodynamic shrouds ahead of its wheels, strongly resembles the current Indycar, which is also built by Dallara.**

The new series' electric racecars are intended to pioneer new technology for broader use in production, encouraging fans to think differently about the technologies they use.

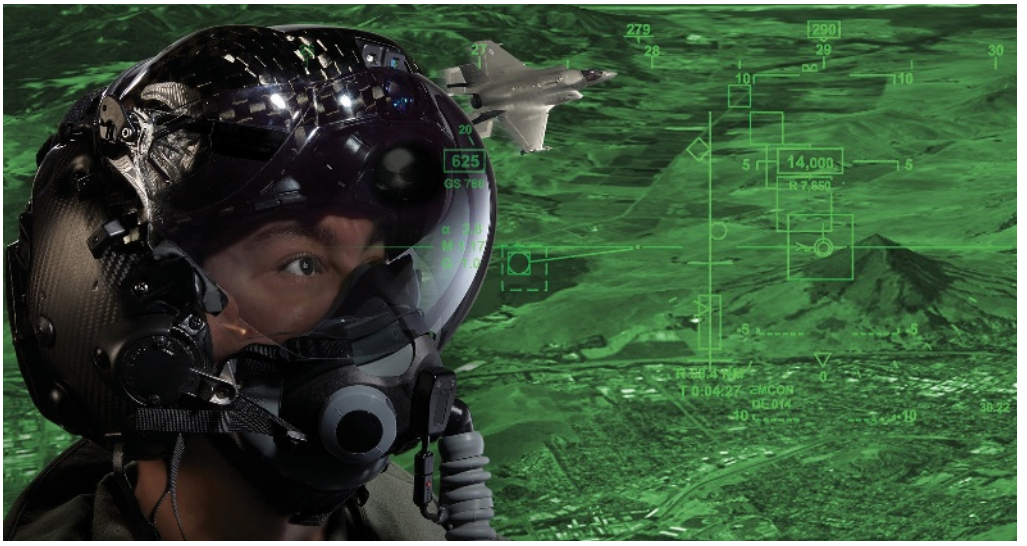
### Chrysler's new Hellcat V8 gets 707-hp SAE rating

The automaker's first production supercharged V8 uses a Lysholm-type twin-screw supercharger supplied by **IHI**. The engine's high-output spec required extensive upgrading of engine reciprocating components to handle the extra loads.



## Avionics

# Rockwell Collins and Elbit show off F-35 Gen III helmet at Farnborough



**Speaking to his own experience, F-35 Chief Test Pilot Al Norman said at Farnborough that the new helmet gives him "the choice of what I see, the choice of what to do. When I plug in my HVI [helmet vehicle interface] cable, I truly become one with the aircraft."**

The F-35 Gen III Helmet Mounted Display System (HMDS)—developed by **Rockwell Collins ESA Vision Systems**, LLC, a joint venture between **Rockwell Collins** and **Elbit Systems** Ltd.—which is said to provide "unprecedented situational awareness (SA) for fighter pilots," will be delivered to **Lockheed Martin** for software integration into the F-35 aircraft in the next two or three weeks, it was announced at the Farnborough Air Show. The Gen III HMDS will be integrated into Low Rate Initial Production 7 for the F-35 program.

The F-35 Gen II HMD was demonstrated at the Rockwell Collins booth at the air show in July.

"This helmet changes the paradigm for the display of information to fighter pilots," said Phil Jasper, Executive Vice President and COO, Government Systems, for Rockwell Collins. "It is the first to have a fully integrated head-up display, which gives pilots all the critical information they need on the helmet's visor. Pilots who have flown this new system have provided positive feedback about their ability to respond faster with reduced workload, resulting in an enhanced ability to complete missions successfully."

"The HMDS provides F-35 pilots with the most advanced digital night vision and head tracking capabilities available today," said Raanan Horowitz, President and CEO, **Elbit Systems of America**. "Providing an accurate and readable virtual HUD with high resolution night vision, combined with low latency, is essential to the execution of the F-35 complex missions during

day and night operations."

The state-of-the-art HMD features a biocular 40x30° field-of-view, high brightness and high resolution display, with integrated digital night vision. When fully integrated with the aircraft sensors and systems, the HMDS heightens the F-35 pilot's SA. The HMDS displays the distributed aperture system (DAS) imagery from **Northrop Grumman**, which gives pilots the ability to see through the structure of the aircraft for a 360° view as well as a direct picture of the ground beneath them.

Speaking to his own experience, F-35 Chief Test Pilot Al Norman said the new



**"The HMDS provides F-35 pilots with the most advanced digital night vision and head tracking capabilities available today," said Raanan Horowitz, President and CEO, Elbit Systems of America.**





**A Northrop Grumman technician puts finishing touches on the center fuselage section of the F-35 prior to delivery to F-35 prime contractor Lockheed Martin. (Northrop Grumman)**

helmet gives him "the choice of what I see, the choice of what to do. When I plug in my HVI [helmet vehicle interface] cable, I truly become one with the aircraft."

The system provides a lightweight HMD, with optimized center of gravity and maximum comfort for reduced pilot fatigue. Everything about the F-35 Gen III HMDS is designed to enhance the fighter pilot's precision, efficiency, and safety, while reducing the overall cost of the program, says Rockwell. The Gen III design includes improved optics, image device and backlight, along with enhanced head tracking capability and the next-generation Night Vision Camera, providing equivalent performance to ANVIS-9 NVGs (night vision goggles).

Norman said the system eliminates the need to decide when or if to wear NVGs, "turning night into day. It's like having six eyeballs [due to the plane's six cameras]. Everywhere I am I have my symbology with me." He added that pilots can use either the stick or the touch-screen glass to change the option of their view and amount of information from the helmet.

Rockwell Collins was responsible for the overall HMDS performance and the helmet-mounted display components, and Elbit was responsible for the night vision cameras, helmet tracking, and display processing components.

To date, more than 160 HMDS units have been delivered to Lockheed Martin. The HMDS generations have logged more than 15,000 hours of test flights on the F-35.

**Jean L. Broge**

## Regulations/Standards

# New SAE standard focuses on manufacturing management

A soon-to-be-published **SAE International** standard, AS6500, is designed to encourage suppliers and OEMs to put more focus on manufacturability during the early phases of a product's life cycle. The objective: more reliable, affordable, and on-schedule weapons systems.

"The standard will help achieve that by requiring certain activities to be accomplished and certain assessments of manufacturing maturity to be done early in the life cycle," the sponsor of the standard, David Karr, told *Aerospace Engineering*. "It applies all the way through development and production—and even in the sustainment phase, so when major modifications to weapons systems are being done, it will also cover those major modifications."

From a Quality Management System perspective, the industry is well covered by **ISO** 9000 and AS9100, Karr said. "But there was a gap in the manufacturing management area for which there were no government or commercial standards available."

"AS6500–Manufacturing Management Program" will cover that gap. The standard

**TECHNICAL WEBCAST SERIES FROM THE EDITORS OF SAE: SIMULATION FOR SAFETY**

Tuesday, September 30, 2014, Noon U.S. EDT

**You're invited to attend this FREE live, interactive 60-minute webcast!**

Design tool suppliers are helping design teams meet demanding safety requirements by making it easier to spot potential problems earlier in the design phase when it's less difficult to change them. Modeling and simulation have become important tools in the race to get sophisticated aircraft to market quickly while meeting safety requirements and other regulations.

**In this 60-minute webcast, attendees will:**

- **Explore how these tools are handling more functions, helping design teams mesh mechanical, electronic, and software components while also ensuring that standards and guidelines are met**
- **Learn how updated tools are also letting developers handle larger simulations**
- **Discuss some of the latest technological breakthroughs in design tools and challenges facing engineers tasked with ensuring that systems, software, and mechanical elements work together seamlessly**

***Webcast attendees are also invited to interact with the experts during the program's LIVE Q&A segment***

**Industry Expert Participants:**



**Bill Chown**
Product Line Director, Systems Life Cycle Management, System Level Engineering Division, Mentor Graphics



**Jace Allen**
Lead Technical Specialist for Simulation and Test Systems, dSPACE Inc.



**Noah Reding**
Automotive and Aerospace Product Manager, National Instruments

**Registration: www.sae.org/webcasts**

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is currently in the balloting process and is expected to be published in Fall 2014.

The geographical origin of AS6500 is Wright-Patterson Air Force Base in Dayton, OH, where Karr works in the Air Force Life Cycle Management Center as Technical Advisor for Manufacturing & Quality. The contextual origin is MIL-STD-1528, a military document that described manufacturing management requirements. "That document was written in the 1970s," Karr pointed out. "We've come a long way since then. We've learned a lot of things and have a lot of new practices, so this is a significant update to that standard."

Something else happened in the intervening years: MIL-STD-1528 and related documents became casualties of a war on standards.

Karr tells the story: "From the mid-1970s to the mid-1990s, we had a lot of military specifications and standards governing... quality and manufacturing management that we would put in contracts to explicitly lay out what our requirements and expectations were relative to manufacturing management. In the mid-1990s we went through an initiative called Acquisition Reform, and that did away with all those specs and standards. The result was a lack of standardization which resulted in a significant amount of variability in how each program managed its manufacturing operations. The result of that was just as much variability in outcomes; some programs might have done OK, some programs might have had a lot of problems."



**G-23 Committee Co-Chair David Karr is based at Wright-Patterson Air Force Base and serves as Technical Advisor for Manufacturing and Quality, AFLCMC/EZSM, Manufacturing and Quality Branch, Engineering Services Directorate, Air Force Life Cycle Management Center.**

Elaborating, Karr recalled that industry was asking for less regulation, "So the **Department of Defense** said, 'OK, we'll get rid of all of those standards, give you free rein, and open things up for a lot more creativity and more opportunities for industry to do things smartly. Unfortunately, that just didn't always work out."

Cost overruns and quality problems associated with weapon systems became evident not only in news reports, but also in reports from the **U.S. Government Accountability Office**. The Mil Standards retreat contributed to the problem, Karr said: "At least on the **Air Force** side of things, I'd say that we've really not been good customers because we didn't explicitly spell

out our manufacturing requirements in Requests for Proposals"

Another DOD philosophy that has contributed to the current state of affairs is a greater tolerance for risk as it relates to manufacturing maturity—"especially compared to how the commercial industry does things," Karr said. "Commercial industry spends a lot of time, effort, and money making sure its manufacturing processes are stable and capable and mature before they go into production. Unfortunately, we don't mirror some of the commercial industry's practices when it comes to maturing our production processes."

It eventually became clear that a plan was needed to improve manufacturing standardization within DOD. In December 2012, the DOD created a working group to carry out that effort. Karr was appointed lead. In addition to drafting a working document, the group also was directed to select an outside organization to create a commercial, vs. military, standard. In September 2013, SAE International was selected for that work. A new SAE committee, G-23 Manufacturing Management, was formed. Consisting of approximately an equal number of DOD officials and industry (including representation from **Lockheed Martin**,

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**Boeing**, **Raytheon**, **BAE**, **GE**, and **Northrop Grumman**), the roughly 40 G-23 members in 2014 reviewed and revised the initial draft standard.

Among the manufacturing management tools required by the standard is Manufacturing Readiness Levels which, Karr said, "are quickly becoming the generally accepted approach, at least within the DOD industry, and even in some other industries, for measuring your manufacturing maturity and level of risk. It's a tool that the standard imposes that's widely recognized and has a common language that everyone understands. The standard addresses the use of that tool very early on in the life cycle so that early on we understand where our manufacturing risks are and we can start addressing them."

Producibility Analysis, Process FMEA, and Key Characteristics are among other tools.

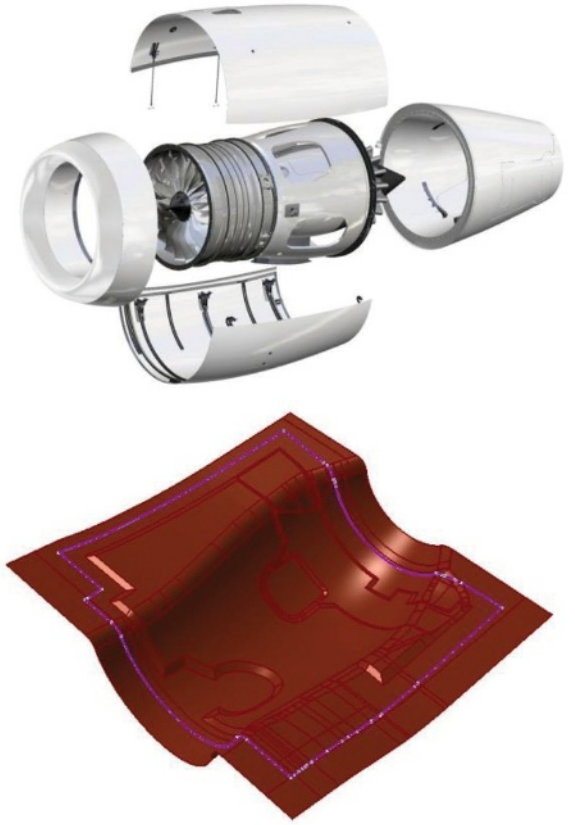
Karr noted that the standard is designed for application across military and commercial sectors, and for customization such as for build-to-print shops that do not deal with initial product designs. The standard can serve as a reference for everyone from the vice president of manufacturing operations "all the way down to the factory manager, and the manufacturing engineers."

The standard will be incorporated into new Air Force contracts soon after it is adopted, Karr said. It may be applied in its entirety or tailored to each program's specific needs.

**Patrick Ponticel**

**Materials | Simulation**

## Composites design optimization for automated fiber placement



**Coriolis Composites and SAFRAN Aircelle worked together on a thrust reverser component demonstrator made with CFRP material and an AFP process (top). This component is an inner fixed structure (IFS), made of two monolithic carbon skins and a core (bottom).**

Complex composites structures are becoming more common, especially in aeronautics. Composites preforms can now be manufactured by automated processes, such as automated fiber placement (AFP) and automated tape laying (ATL), to achieve the ex-

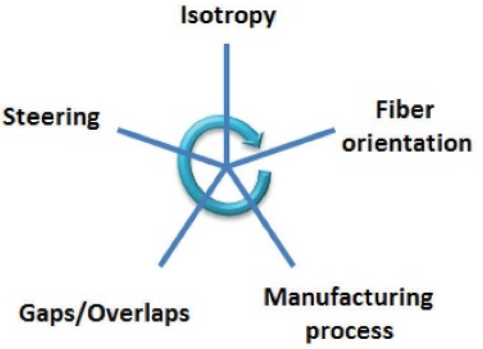
pected production volumes.

The AFP process is the most interesting since it can address complex double-curvature layup surfaces with good productivity rates and low material scrap, according to **Coriolis Software**. The main advantages of this technology are that material can be steered to address the problem of curvature, and fiber angular deviation from the engineering rosette can be easily managed. This opens interesting possibilities to optimize the design of composites structures and to change the current traditional "black metal" approach of design offices.

But these benefits also induce new problems to solve in terms of potential manufacturing defects, such as wrinkles, bridging, gaps, and overlaps. The off-line programming system used to build the tape courses over the layup surface should be able to predict these defects, but also help find an optimal draping strategy.

These systems should integrate all the programming features at the design stage, allowing the design engineers to make smart proposals to NC programmers, validated by stress analysis, and hence eliminating useless loops and trials.

Researchers from Coriolis used an aerospace use case to illustrate the required software features for optimal fiber-placement programming. Through the collaborative research project "Defi Composite," **Coriolis Composites** and **SAFRAN Aircelle**

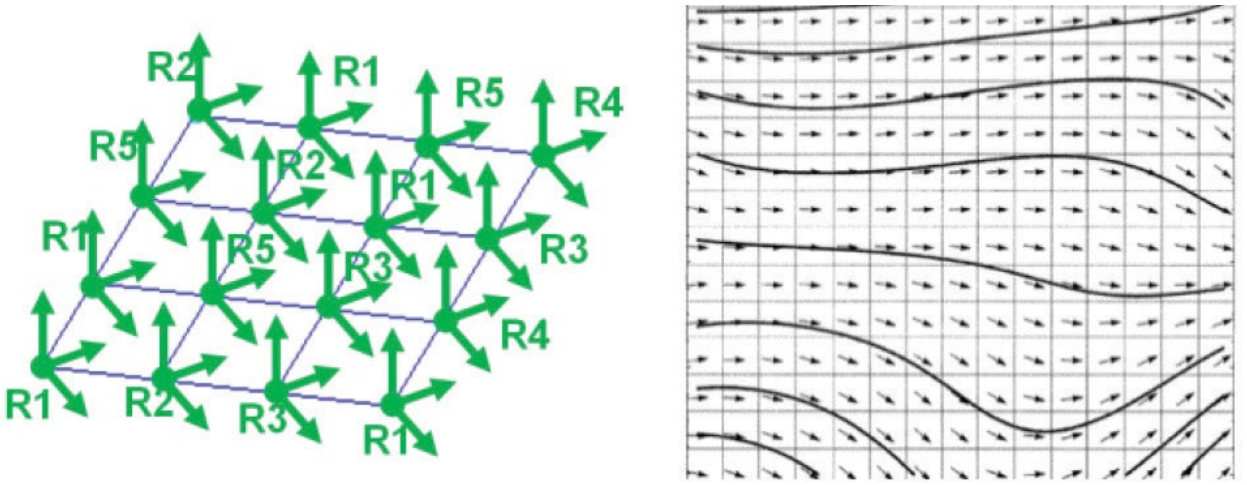



**Major constraints for optimal design with AFP process.**

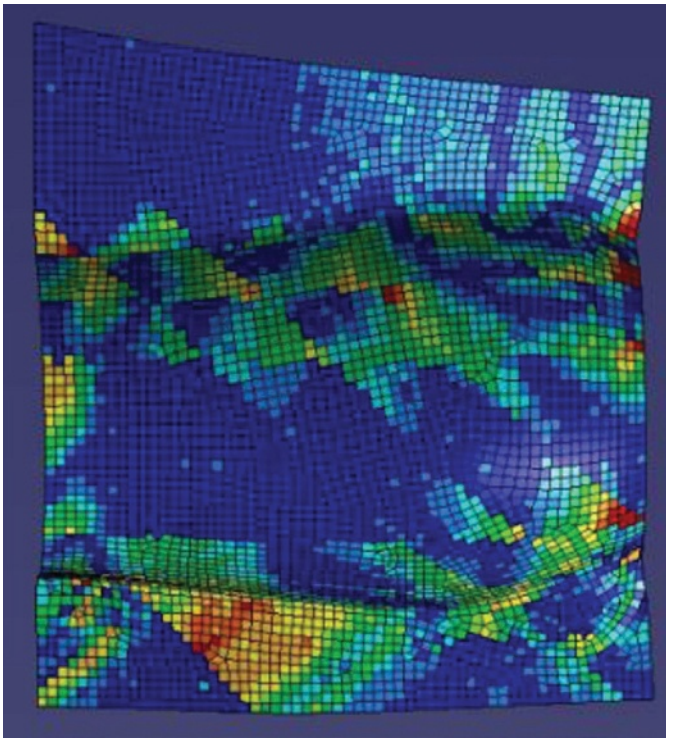
worked together on a thrust reverser component demonstrator made with carbon-fiber-reinforced plastic (CFRP) material and an AFP process. This component is an inner fixed structure (IFS), made of two monolithic carbon skins and a core.

The goal of this project was to highlight






**Example of a grid mesh and rosette axis vectors (left), and a resulting vector field with generated tape streamline paths (right).**



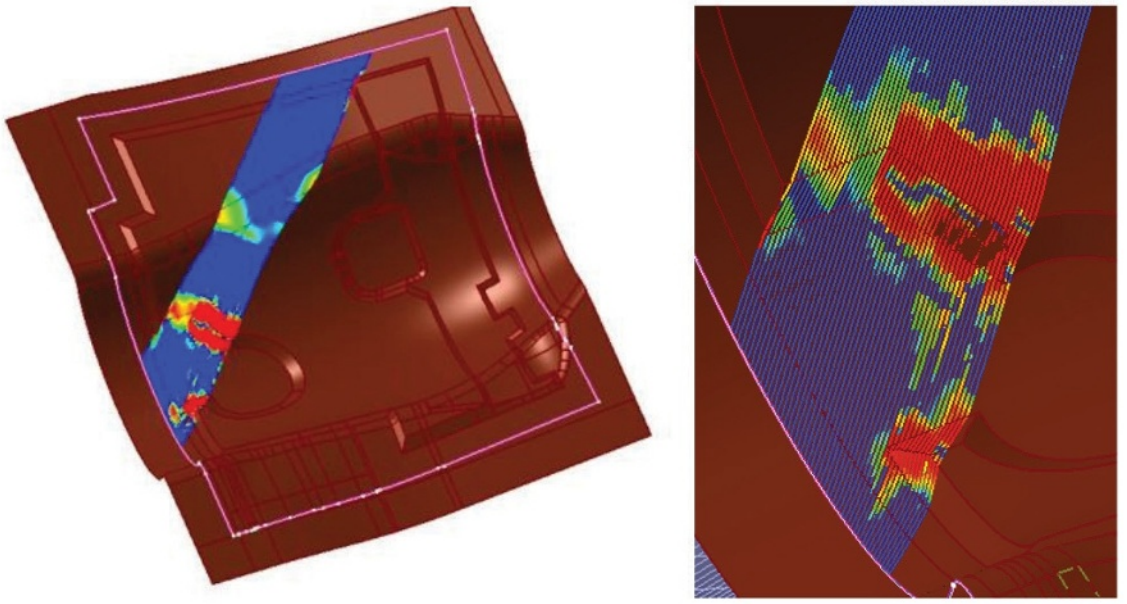
**Example of isotropy image based on realistic composites shell properties exported from fiber-placement programming data (red areas: largest fiber deviation angles).**

the benefits of an AFP process compared to manual hand layup, in terms of layup quality and productivity rate.

## Multiple constraints for optimal design

The most important thing to understand with AFP programming is that both engineering and manufacturing specifications need to be managed, and are often in contradiction. That's why the software system should be designed to address not only NC programmers, but also composites designers, project leaders, and stress engineers.

Five constraints are identified with a key role for optimal design with an automated manufacturing process: fiber orientation, isotropy, fiber steering radius, fiber gaps and overlaps, and the manufacturing process. Coriolis presents an implemented solution for each constraint.



**Fiber steering radius analysis over honeycomb ramp edges.**

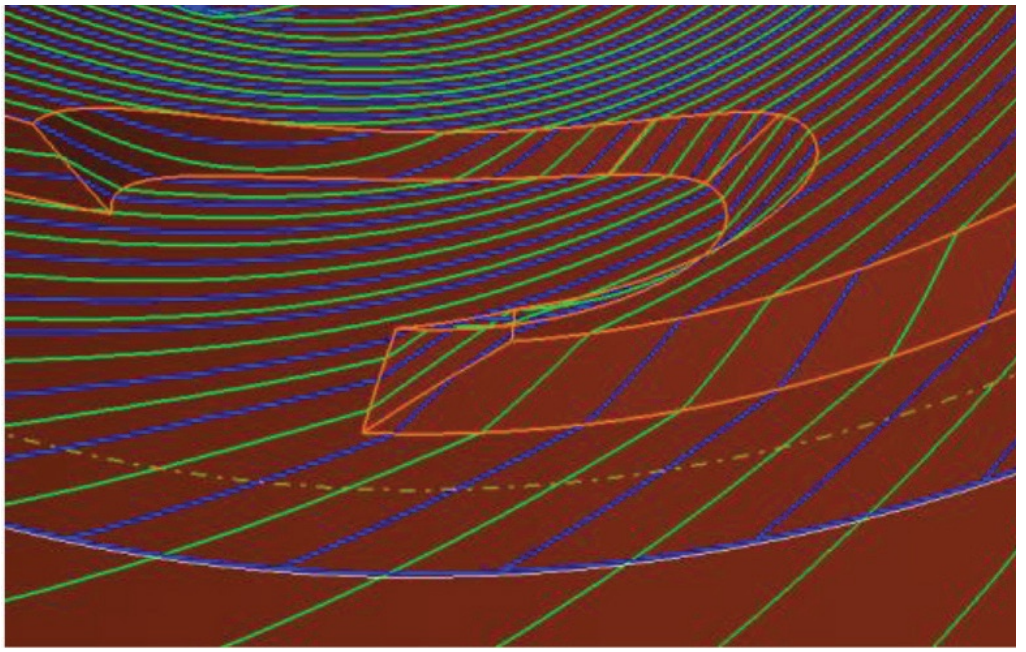
For example, the off-line programming system offers the possibility to analyze isotropy, since the maximum fiber deviation constraint alone can be too restrictive. Isotropy is the measure of the relative fiber angle between two layers at a same measurement point, for example between a 0° and a 90° ply.

A specific development was done to export fiber angle deviation for each layer from the programming courses, in order for the stress engineer to validate fiber orientation and isotropy. This software add-on is integrated on top of the off-line programming system to ease communication between designers and stress engineers.

The main steps for capturing the fiber deviation and isotropy for structural analysis are: 1) Mapping of fiber centerlines on FE shell mesh, 2) Core sampling at finite element centroid point, 3) For each layer of the stacking sequence, get the closest fiber direction and evaluate angle deviation from the cartesian rosette, 4) Writing of a composites shell property with "true" material angle, for each mesh element, and 5) Factorization of stacking sequence using a custom angular tolerance, to minimize the number of composites properties.

Concerning fiber steering radius, the constraint is mainly caused by fiber in-plane curvature and material width, and may lead to wrinkles and tow buckling. This kind of defect is not perfectly well understood in terms of direct impact on structural strength.

Fiber steering is very complicated to interpret, since it depends on other parameters such as material tackiness, compacting pressure of roller, layup velocity, heating power, and intermediate vacuum bagging. For this reason, fiber steering radius analysis at the design stage should always be correlated to real sample tests to get the empirical



**Ply automatic splicing result on IFS core skin. Sector closed contour with guide curves (tape course centerlines).**



**Final layup of cover skin of IFS demonstrator using the Coriolis Composites AFP robot.**

knock-down factors.

The software system is able to detect this problem at least through a geometrical analysis of the in-plane curvature of tow centerline curve, in order to highlight critical areas. The designer can also easily do "what if" scenarios with different material widths (1/4 in or 1/8 in) or types (thermoset, dry fiber).

Steering issues can be solved at the design stage by either using a geodesic path approach—for example, through a complex rosette transfer—or by locally decreasing the layup velocity. This can be achieved by defining a local "process contour" in the software system (also called manufacturing strategy), after identifying the highly steered areas over the surface, and then applying a lower nominal machine velocity.

Experimental trials showed that it can significantly improve the final layup quality.

## Automatic ply boundary splicing

To optimize the design for AFP, one solution is to split the ply boundary in several pieces, called sectors or regions. This task can be manually achieved, but it is time consuming, and more important, it will not

be easy to obtain an optimal result.

The optimal result of the problem is to minimize the number of sectors and tape courses within the ply and to avoid too many material feeds and cuts (leading to slow layup velocity).

A specific software module was implemented in that way, to automate the sector and guide curves creation, starting from the following initial conditions: geometrical layup surface, engineering rosette axis, ply contour, initial seed-point, material width, maximum number of tows by course, maximal angular deviation, and minimum steering radius.

The system is based on an iterative algorithm, building a fixed angle path and parallels, and then cutting the ply boundary if the parallels present excessive angular deviation. The output result is a list of sectors, each made of a closed contour and one or several guide curves.

After many trials and experimental validations, the system was improved to integrate the following specifications:

- Avoid ply cuts and tow drop-off located in a specified zone (example: stringer bonding area)
- Adjust the tape width (number of tows) if roller conformance is not compliant (excessive crush or fiber bridging defects)
- Minimize the gap between adjacent tape courses
- Management of sequence of several plies in the same layer (patch areas).

Compared to a traditional approach (ply with one single guide curve) or a manual ply sectors method, the automatic method proposal provides significant benefits. The major benefits include the programming time (limited required skills, possibility to manage iterative design loops) and the convergence to an optimal result, very difficult or impossible with other methods because of the large number of parameters and constraints.

A solution was successfully implemented on a complex aerospace case, with competitive results compared to a manual hand layup process in terms of structural strength, layup quality, and productivity rate. Improvements will be made for extending the automatic method to manage geodesic path as sector guide curve, and control the staggering distance of tow drop-off areas.

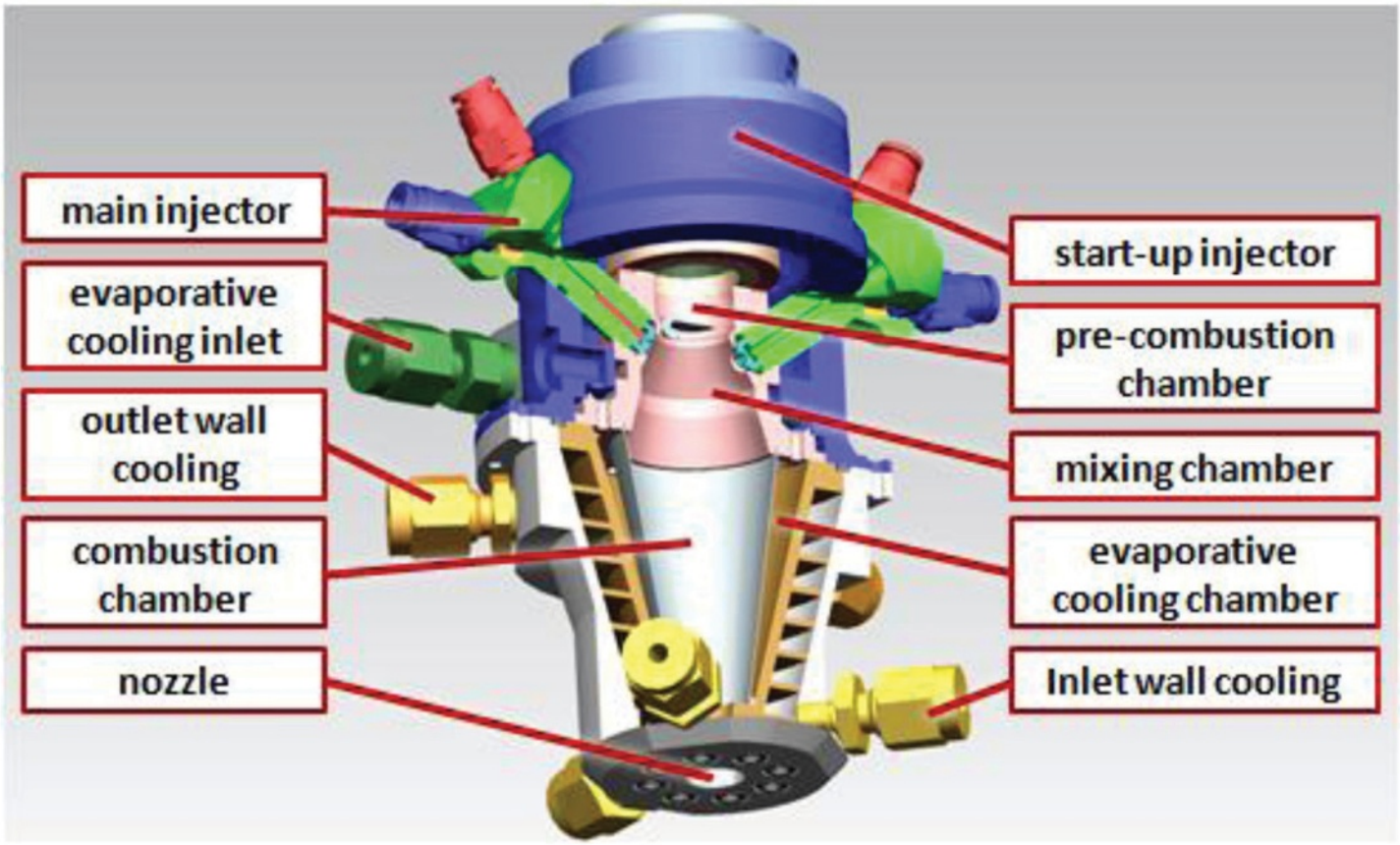
**This article is based on SAE International technical paper 2014-01-2261 written by Yvan Blanchard of Coriolis Software. The paper is part of the "Manufacturing/Materials/Structures – Product Design and Manufacturing Integration" session taking place at the SAE 2014 Aerospace Manufacturing and Automated Fastening Conference & Exhibition.**




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# START-UP ABILITY OF UAVs ON TASK

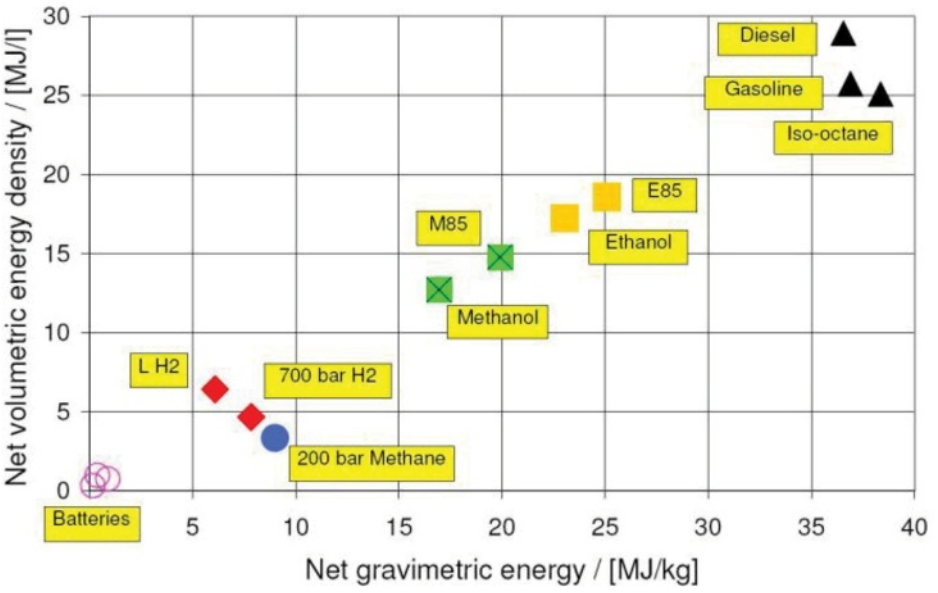
**Besides low cost, easy manufacturability, light weight, long operation time, and high durability, miniature UAVs need restart capability during flight.**




**Cross section of the prototype engine TRe-1.10 from Ghent University, with the most important parts of the engine indicated.**

Small unmanned air vehicles (UAVs) are today extensively used for a wide range of applications, from amateur to military applications. Many UAVs use electrical energy for the thrust generation, making them flexible, simple, safe, and quiet. The main drawback of this traction strategy is the low energy density of batteries compared to energy stored in the liquid form, as well as the speed and flight range of the vehicle. This is the point where turbines make their entrance.

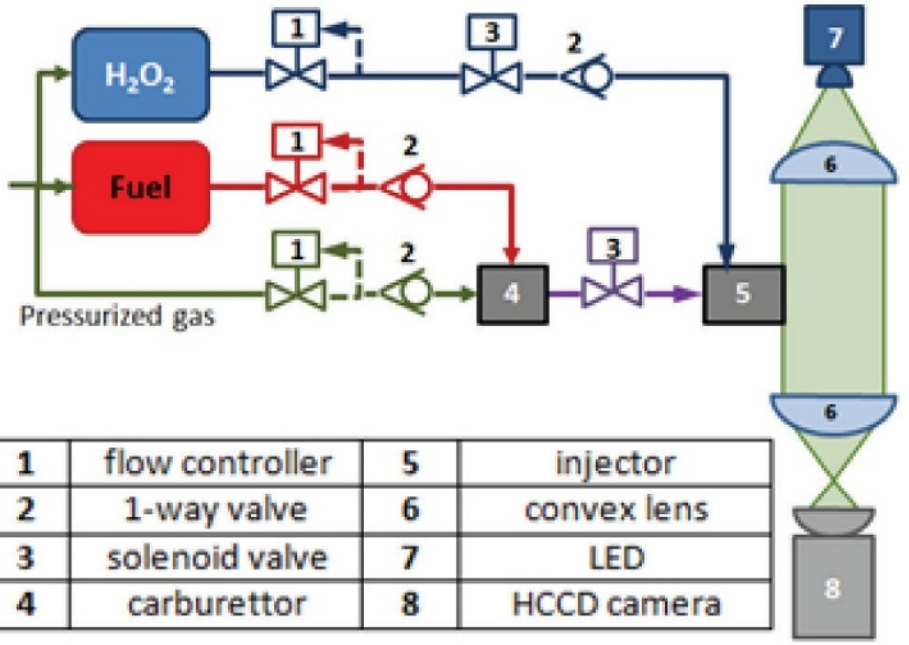
However, micro turbines used for the bigger UAVs are complex and expensive. The small dimensions require small clearances to maintain reasonable efficiencies. On the other hand, the rotating parts should be able to expand due to the high temperature. As the scale of turbo machinery is reduced, the compressor efficiency decreases and, therefore, the efficiency non-linearly drops with its size when it is utilized in a micro-propulsion system, resulting in efficiencies of about 30 to 50% lower than for big turbines.




**Energy densities of common fuels.**

Other solutions for propulsion systems have been studied for both amateur and professional applications. Pulsejet engines are mainly used for their simplicity. They consist of a combustion chamber, in which combustion periodically occurs in a long tube. There is simultaneously an acoustic wave propagating down the exhaust duct, reflecting off the exhaust exit, travelling back up to exhaust duct as an expansion wave. The expansion wave reflects off the inlet and travels back down the exhaust, reflecting off the exhaust exit, now as a compression wave, and propagating back to the combustion chamber. When the reflected wave reaches the chamber, the combustion chamber pressure increases again and the process repeats itself.

Low chamber pressures (~1.2:1 as a compression ratio, while turbojets can achieve 25:1 or more) and high heat losses strongly limits the efficiency of these type of engines: efficiencies can be up to 10 times lower than for turbine propulsion. The length of the tailpipe is optimized for a certain working




| | | | |
|---|---|---|---|
| 1 | flow controller | 5 | injector |
| 2 | 1-way valve | 6 | convex lens |
| 3 | solenoid valve | 7 | LED |
| 4 | carburettor | 8 | HCCD camera |

**Overview of the complete experimental setup, which can be used for both the start-up and main injectors.**

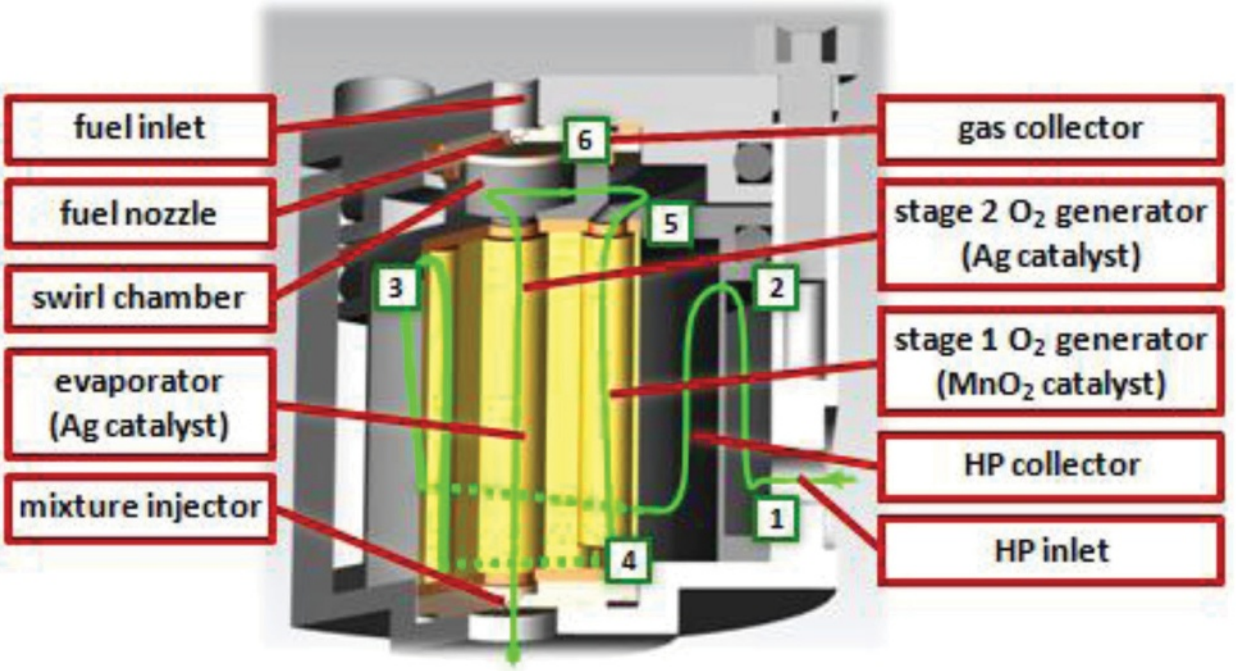
condition, which results in a very narrow operation range. Together with the noise problem generated by the thermo-acoustic working principle of the engine, it is mainly used for amateur applications for small thrust, where additional equipment and complexity would make the thrust-to-weight ratio too small.

A fourth commonly used propulsion mechanism is the rocket engine. Rocket engines are available in a broad range of types, each with their optimal application. Micro-rockets usually use monopropellant or solid fuel technologies. Solid fuels are rarely used for UAVs with motion control ability since the thrust of these engines depends mainly on the burn rate of the fuel and combusts till it runs out of fuel. Monopropellant systems using hydrogen peroxide (HP) have become very popular lately and are considered a green propellant.

When the start ability or ignition needs to be countered with little additional components, hypergolic fuels are commonly used. These fuels self-ignite when mixed with a carefully chosen oxidizer. Well-known examples are hydrazine/nitrogen tetroxide, monomethyl hydrazine/nitrogen tetroxide, and unsymmetrical dimethyl hydrazine/nitrogen tetroxide. However, most of these fuels and oxidizers are highly toxic and unstable.

HP is often also considered as a hypergolic fuel (or oxidizer) when a catalyst is used for the decomposition. Since HP is available in water solutions, the hypergolic properties mainly depend on the HP concentration. When the concentration is high enough, enough heat is produced to ignite an added fuel.

Researchers from Ghent




**CAD drawing of the start-up injector with its different components and indicated flow of the hydrogen peroxide (HP). The dotted green lines indicate the invisible path.**

University undertook a UAV engine development project that combined features of common rocket engines and turbojets. Apart from the simple operation principle, fuel supply, ignition, and cooling are state-of-the-art challenges for combustion engineers.

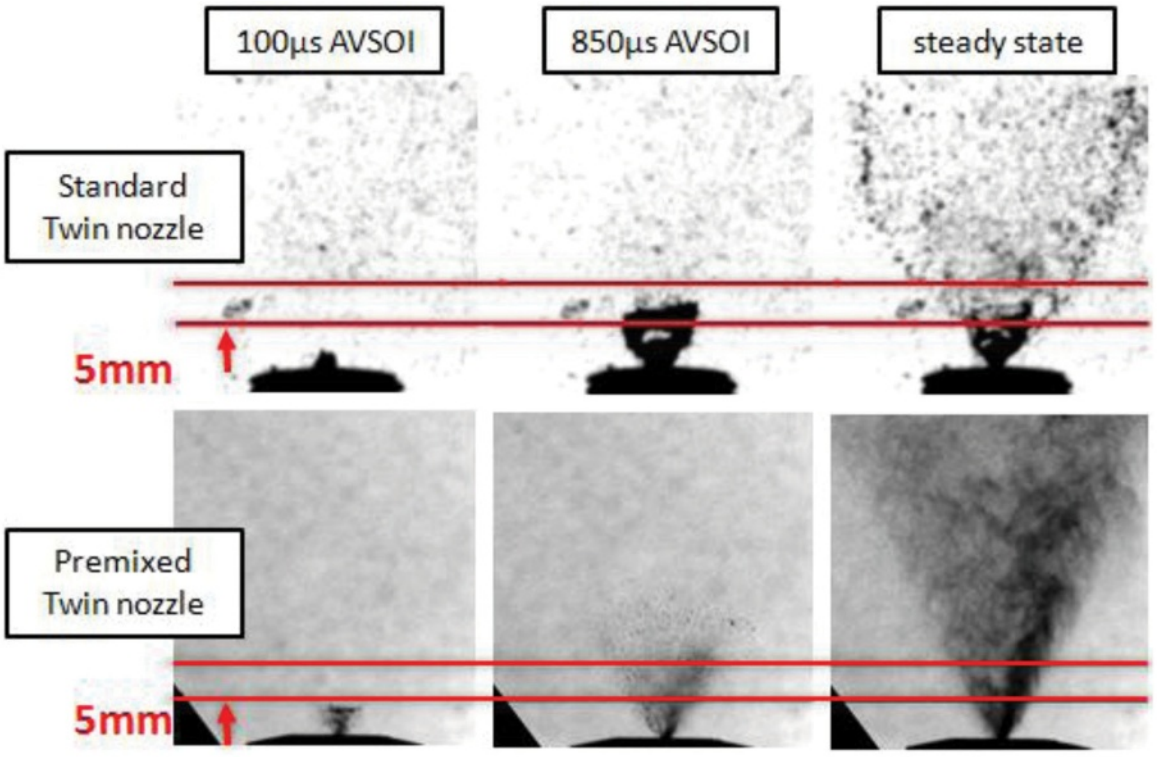
## Engine targets

There were several project goals identified in the initial UAV design, including: cheap and easy to (mass) produce, efficient and low weight, a mid-range UAV with relative low power (30-500 N thrust), a broad power operation range (fast acceleration and gliding mode), restart ability during flight, a low-pressure fueling circuit, and high durability.

Such desires seem to need "the" perfect engine, with a lot of contradictions. This is the point at which design for optimal operation and trade-offs pops in. A lot of attention was paid to affordable manufacturing and durability, rather than it being the best among all engines in its application area.

A main challenge in this design is the low pressure available for the fueling circuit. Due to the micro-application, commercially available piping, valves, etc., have limited operation pressures around 10 bar. As a result, this also limits the combustion chamber pressure.

It was expected that mid-range distances would be covered (~1-10 km). Some applications require UAVs to get fast to a checkpoint and then to glide around in the area for observation or measurements. These types of




**Upper row: the standard twin nozzle spray. Bottom row: premixed twin nozzle spray at three different timings after visual start of injection (AVSOI).**

trajectories do not require a constantly powered engine and to save fuel/energy, the UAV might switch to a glider mode, shutting down the engine. Propulsion systems such as pulsejets and turbojets are not optimal for such start-stop operation without additional equipment; start-up is not easy and takes time to reach the nominal working point.

For the turbine during start-up, thermal stress and engine resonance may significantly reduce its lifetime. Additionally, the operation range is narrow since the design dimension mostly defines the operation point.

The major drawback of common rocket engines for this type of application is that rocket engines are designed to generate high impulse and for short burn operation. The heat-resistant material and wall cooling of the nozzle and chamber are sufficient enough for this operation strategy. However, for long operation times, the wall cooling might not be effective enough due to low fuel flows, and the need for heat-resistant material would be in conflict with the desire to have an affordable design with easy manufacturing.

A monopropellant hydrogen peroxide rocket engine might be a better solution: the exothermic decomposition generates less hot gasses (less than 1000 K, depending on the HP concentration) and just 1 tank is

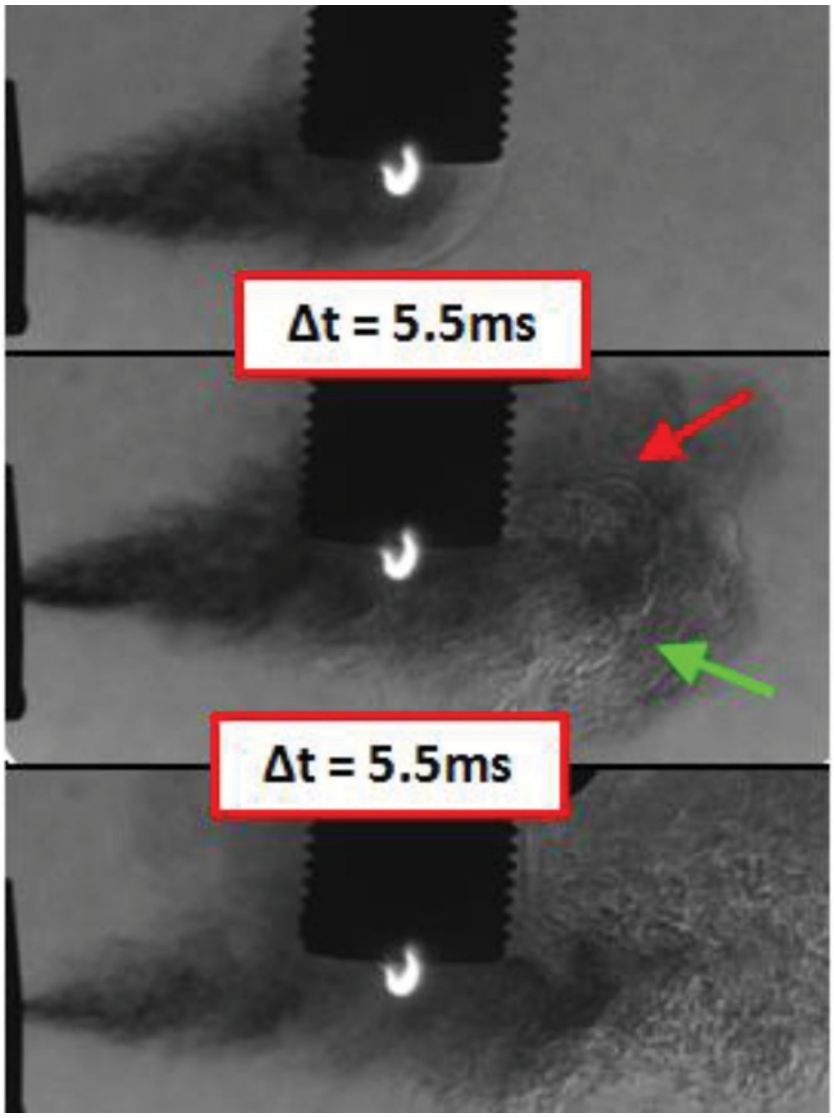
necessary since no oxidizer tank is required. The main challenge is that the catalyst, required for the low-temperature decomposition, needs to be properly designed. Low-cost catalysts such as manganese dioxide are widely and cheaply available, but to have an efficient and controlled decomposition, a highly purified propellant grade HP solution (>80wt%) and elevated temperature are preferred.

## Injector types

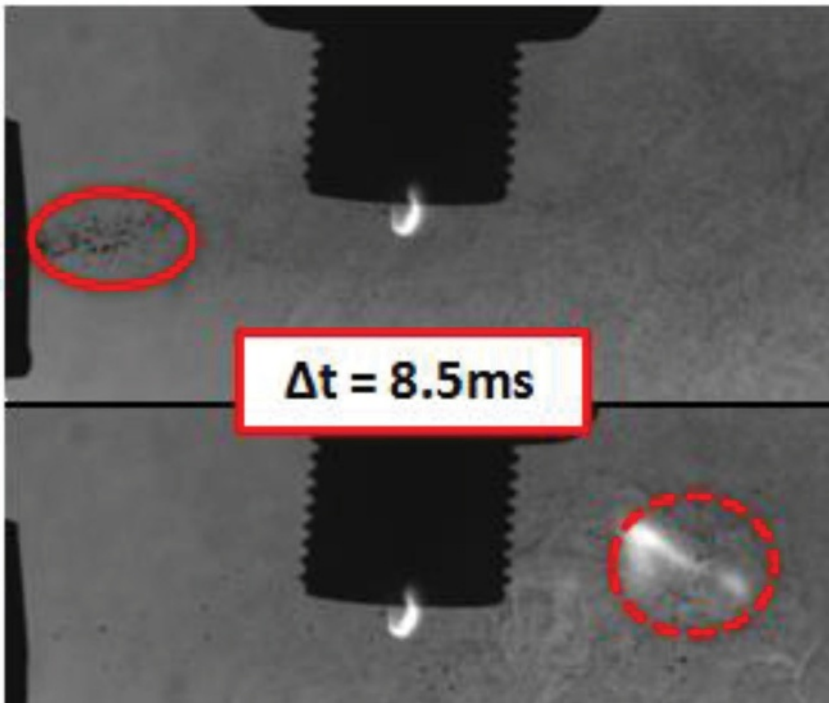
One of the hardest tasks in the design of a miniature liquid-fuelled rocket engine is a repeatable initial ignition of the fuel-oxidizer mixture at low injection pressures in atmospheric conditions. Since pyrotechnic mechanisms only work once, other techniques are needed. Once the engine is fired, the heat from the combusted mixture can act as an ignition source for the injected mass. Active preheating systems for both fuel and oxidizer are avoided if possible due to weight and power consumption issues.

A first step to easy ignition combustion is the proper design of the injection system. The fluids can be injected in three different ways: both fuel and oxidizer as a liquid, one as a liquid and one as a gas, or both as a gas.

Liquids are very easy and dense to store, however proper atomization and mixing with the oxidizer is required.




**Results from high-speed imaging for gasoline. The hot gas produced by the combustion is visible through the schlieren effects indicated by the green arrow. It should be noted that the combustion area is completely downstream of the ignition source, even when the combustion seems to be stable.**




**Influence of end of injection on the spray combustion. The solid circle in the upper image shows the bigger droplets at the end of injection, the dashed circle shows the soot produced by these droplets. The illumination of the soot is clearly visible near the ignition source whereas no visible soot was detected within the camera frames for the main injection. Further downstream, however, soot was seen since the unburned fuel-air ratio became lean and no complete combustion could be established.**

If a gas and liquid are both injected through the same nozzle, the atomization is suddenly completely different. This type of injection can be most likely a liquid fuel with a gaseous oxidizer or mixture of a liquid fuel and oxidizer with an additional gas (e.g., the working gas for the pressurizing the tanks).

Injecting both as a gas would cancel the atomization and evaporation problem and only the right mixture ratio and ignition energy is required. However, storage of gases is difficult and requires cryogenic or pressurized storage technology. A better possibility would be to convert a liquid into a gas prior to injection.

At atmospheric conditions there is barely back pressure that provokes the atomization of the liquid jet. In this case atomization needs to be induced by the nozzle itself rather than the interaction with the surrounding atmosphere as is the case for automotive direct injection engines.

Furthermore, the low atmospheric conditions do not evaporate the fuel, which makes ignition even more difficult. Near nozzle breakup can be mechanically introduced by impinging two or more jets into each other.

## Design conclusions

From the initial nozzle strategies, it was found that even with one of the injected components being a gas, ignition at ambient conditions was very hard to realize within the dimensions of the considered engine size. With realistic storage possibilities in mind, conversion of a liquid-into-gas fluid prior to injection was the most suitable solution. The exothermal catalytic decomposition of hydrogen peroxide had this capability, and an

injector was designed to perform this task.

Fast atomization at low injection pressures could be obtained through the injection of both the fuel and a gaseous fluid through the nozzle. Collision of the mixture flow spray (e.g., twin or triple nozzles) improved the spatial distribution of the mixture, enhancing the ignition. This strategy, however, was not able to fulfill the needs for the start-up at ambient condition, but could be feasible for the main injection.

Among strategies for power control, burst injection seemed to be the most promising in terms of atomization. However, soot formation at the end of injection is a problem to be tackled.

The surface-to-volume ratio between the catalyst and HP, together with the temperature, dominated the performance of the start-up injector.

Current start-up time was still too long for the application (3-10 s) but can be improved by higher flow, elevated body temperatures, and better design of the catalytic bed. The delay is mostly due to the time needed to fill the collector. ■

**This article is based on SAE International technical paper 2013-01-2305 by Jonas Galle and Sebastian Verhelst, Ghent University.**



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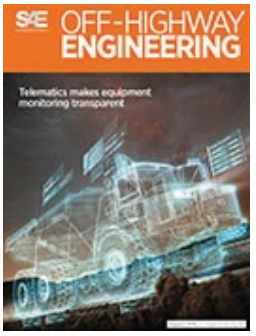
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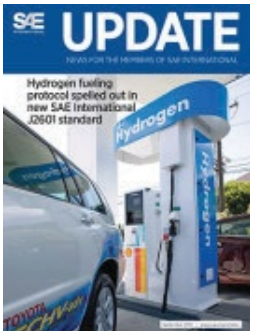

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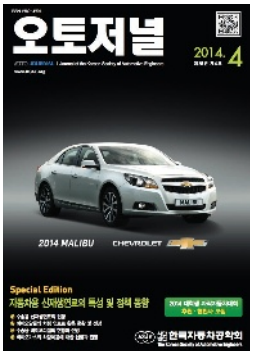

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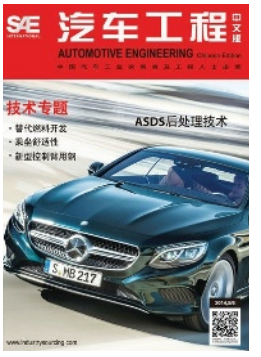

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