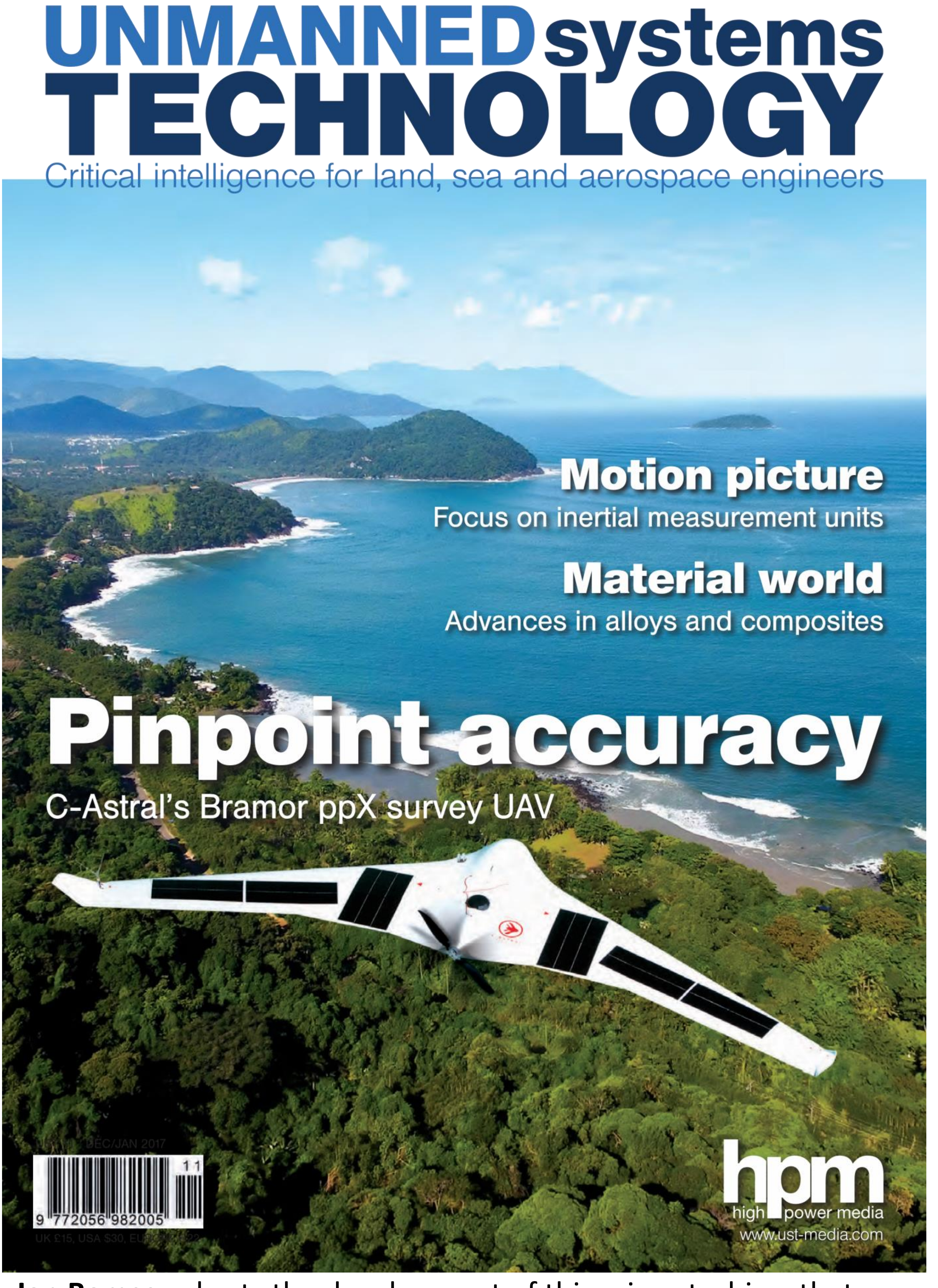


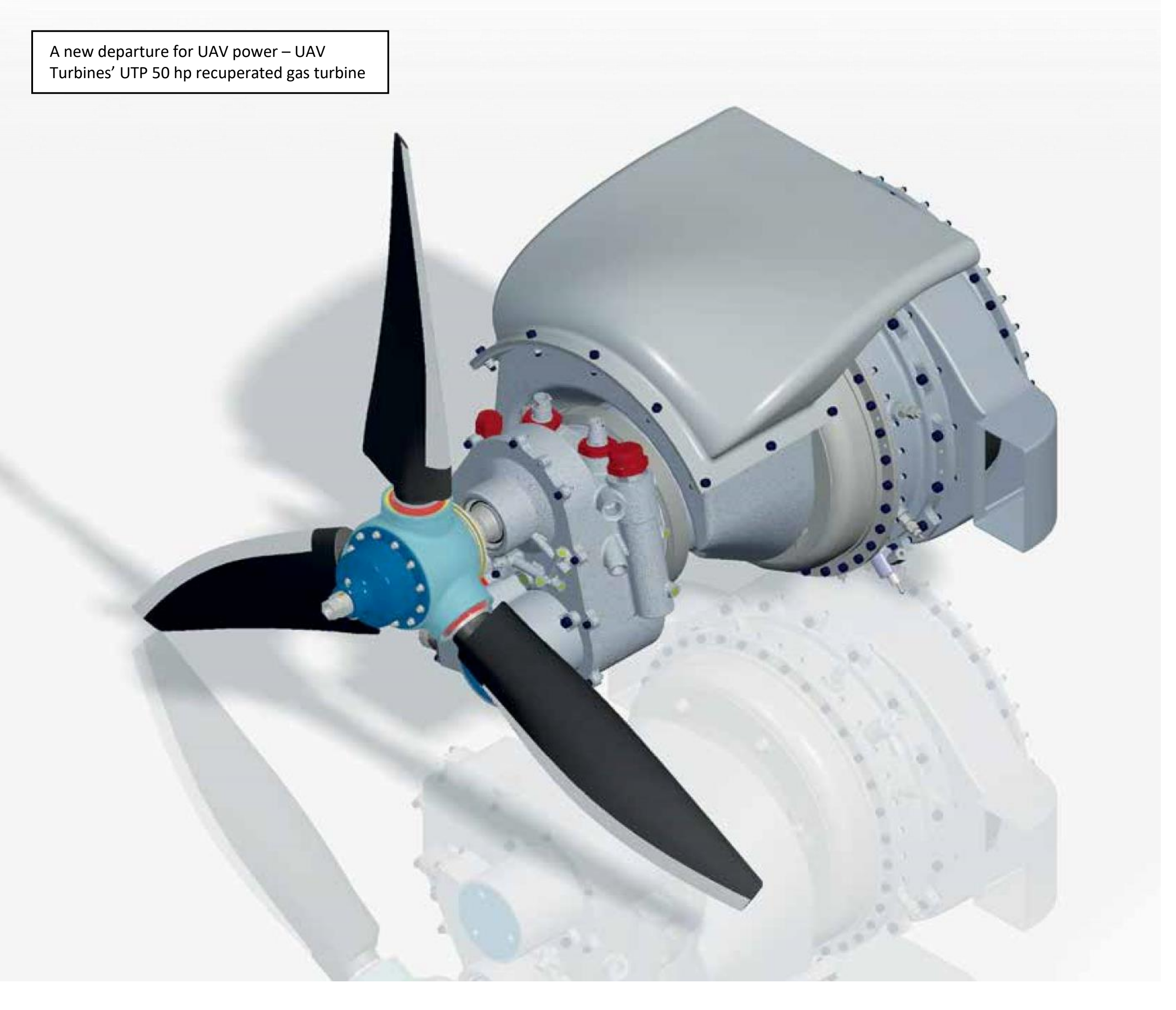
Ian Bamsey charts the development of this micro-turbine that looks to set a new standard in UAV performance

Small but perfectly formed

Small-displacement internal combustion engines for UAV propulsion are invariably piston or (Wankel-type) rotary units, but UAV Turbines aims to change that. The company has developed micro-turbines for the likes of robotics and power generation, and is now demonstrating the merit of its technology for small and medium-sized UAVs.

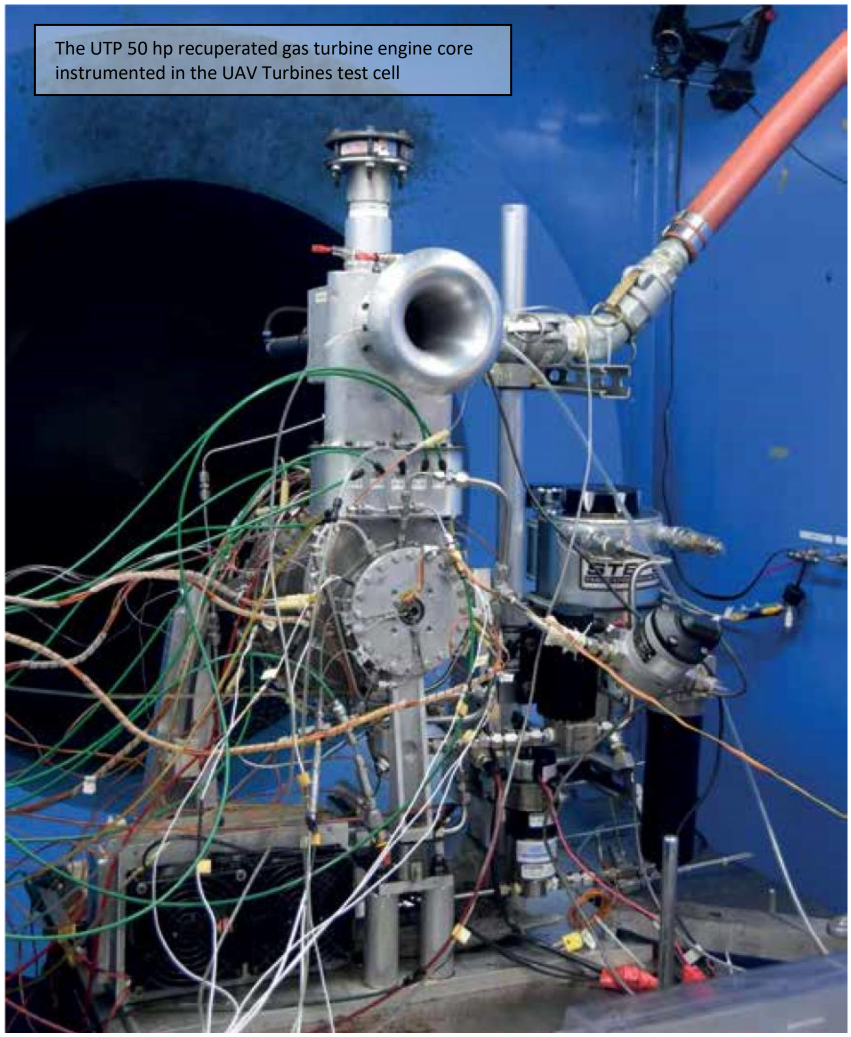
"Our gas turbine engines will increase reliability, flight duration, payloads and operational ceilings, while greatly reducing noise," says CEO Kirk Warshaw. That is a bold claim, prompting us to look in depth at the engineering behind its state-of-the art UTP50R 50 hp Class Recuperated Engine. In what respects can it promise to deliver technical advantages over established piston and rotary solutions?

A new departure for UAV power – UAV Turbines' UTP 50 hp recuperated gas turbine



The Challenge

UAV Turbines was conceived as a means of applying fundamentally simple, hence inherently dependable, light and cost effective gas turbine engine technology to applications at the other end of the power scale to normal aviation. Indeed, it was the use of a micro-turbine in a model aircraft that sparked the idea: why not apply state-of-the art aerospace engineering to make such a power plant relevant to small vehicles outside the hobby sphere, including UAVs?


The UTP 50 hp recuperated gas turbine engine core instrumented in the UAV Turbines test cell

UAV Turbines' engineering director Fred Frigerio says, "The turbojet is well suited to high-speed model aircraft; the problem comes when you want to make it more fuel-efficient and increase its life. If you are going to be flying slow, you need to make it into a much more efficient turboprop engine, and that is where it starts getting difficult.

"Gas turbines work on the principle that the speed at the tips of the turbine blades is extremely high. In the case of a small turbine, that implies a shaft speed of 100,000-plus rpm, and how do you reduce that to a 6000 rpm propeller speed? You need a gearbox of some kind, and that takes you out of the model aircraft arena. That gearbox is itself a significant challenge.

"The other problem we had was that existing model aircraft gas turbines were using compressors from automotive turbochargers, and the efficiency of those is not exactly what you need. What happens if you start trying to make your own compressor? Now you are moving into an area in which you need some serious knowhow, and it starts getting expensive."

This project began in 2000, and for the first ten years concentrated on developments funded by US government contracts. Only since 2011 has UAV Turbines concentrated on bringing its technology to the general UAV market.

Warshaw notes, “One thing about the initial development phase was that there was a feeling that this is established technology; we are just making it smaller – how hard can that be?”

As our research for this article revealed, the short answer is: far harder than anyone in the company suspected.

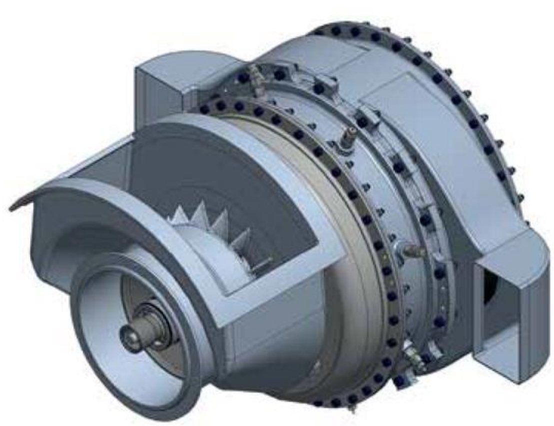
“At the start we thought combustion was going to be the biggest problem,” Frigerio recalls. “The conventional fuel delivery method was not going to work. Normally spray nozzles atomise the fuel into the combustion chamber, but that wasn’t going to work because our fuel flow is so low relative to regular turbines, and you end up with orifices in the nozzle that are so tiny they would clog up too easily.

“We did some work with different nozzles but in the end we solved it by going to a vaporiser tube; that is to say, you have a metal tube that you heat up. Instead of trying to make a spray of

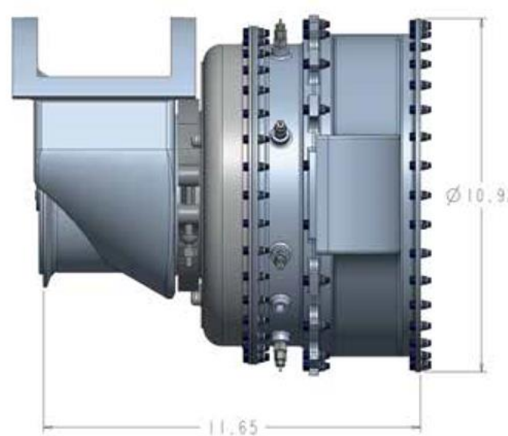
the fuel, you pass the fuel through that tube with the heat of the combuster itself warming it, and it passes out of the end of the tube perfectly vaporised.”

Warshaw adds, “Of course, there are all sorts of forms the tube can take. We didn’t get it right first time; it took a lot of effort, a lot of trial and error by very gifted and highly experienced engineers to make it work properly.”

The fuel supply pump is electrical and, operated by the engine control unit, is responsible for the fuel metering. It sends the fuel to a stainless steel manifold around the combuster, which directly supplies the vaporiser tubes set in a ring around the combuster to avoid the danger of hotspots in the turbine.



UAV Turbines’ UTP 50 hp recuperated gas turbine is very compact



Compressor impeller with integral cast turbine on the back

Frigerio says, "After about a year we had a working combuster. Then we did a lot more work on miniaturising it, and that is one of the technologies that we are very proud of – it is a very small, very compact combuster.

"After we got the combuster working, we had to find out how to start the engine without carrying propane [in addition to heavy fuel]. So we had to develop our own system for igniting heavy fuel, while to get the engine up to high speed for starting we needed to develop our own high-speed electrical starter/generator.

"We have developed our own patented ignitor using an electrical coil, which acts like a glow plug – albeit hotter than a glow plug – so that we get a 'pilot flame'. Once you have that flame you can bring in more air and fuel, and the combustion will get up to temperature and sustain itself. You then just have to manage the air-fuel mixture to ensure it doesn't get too lean or too rich."

The ignitor is located within the combuster: there are two at 180º apart. "That double-up is for redundancy," explains Frigerio. "We can operate on one, and you can shut down and restart this engine while the UAV is in the air, which can be an advantage."

The engine has a single-stage centrifugal compressor and a single stage radial turbine on a single shaft. In a single spool design such as this, (see sidebar: Gas turbine basics) normally that shaft will have one bearing at the front, ahead of the compressor, and one at the rear, usually behind the turbine. The problem then is that the rear bearing is on the hot side.

As Frigerio points out, "That is a difficult bearing to keep alive. It is hard to get oil to it and it lives in a very high temperature environment. In our case, both of our hybrid [ceramic ball/ metallic race] angular contact bearings are in front of the compressor. Thus the compressor and the turbine are cantilevered, which gave us issues of rotating assembly dynamics to overcome, but it means both bearings are well lubricated and located in a single cool compartment.

"That was a major challenge. It ended up requiring a very holistic-type approach to it – it wasn't one 'magic' thing that solved it."

Warshaw adds, "You solve one problem and find another, and again and again. It was lots of little things – ten years of trial and error, with some of the best engineering minds in the world applied to it."

"Yes," agrees Frigerio, "it was a very difficult nut to crack, but we can now predict what we are going to see from a rotor dynamics point of view, so we have really come to understand that in the context of these small engines. We now have a very reliable bearing system, and have engines running for 1500-plus hours. "But operating at 100,000-plus rpm, we also had to develop our own gearbox. And normally small UAVs have fixed pitch propellers so we had to develop our own variable-pitch propellers as well – a variable-pitch propeller being critical in a single-spool, constant-speed design where the propeller has to operate within a small range of speeds."

The recuperator

We asked: in the case of a micro-turbine is the efficiency inherently less than that of a larger version because the clearances and consequent blade tip leakages are proportionally larger?

"That is true," Frigerio says. "As you get smaller, the clearances don't scale down accordingly. The implication of that is in terms of fuel efficiency, and that is where the recuperator comes in."

UAV Turbines' recuperator is an air-to air heat exchanger designed to exploit the waste heat of the exhaust to raise the temperature of the charge air exiting the compressor, ahead of combustion. The two flows don't mingle; the exhaust runs over passages carrying the charge air from the compressor to the combuster, thus heating the air.

The UTP 50 hp recuperated gas turbine seen from below

"In the recuperator you are transferring heat from something that is hot to something that is cool, and the bigger that temperature difference is, the easier it is to move that heat in the direction you want," Frigerio notes.

The exhaust from the turbine is split into two passages, each travelling in the opposite direction at 90º from the turbine axis, and there is a heat exchanger each side.

Frigerio says, "The way you get more efficiency from your simple turbine cycle is by raising your pressure ratio. The higher the pressure ratio, the higher the efficiency – up to a point. But you can't do that with a small engine because of the clearances and difficulty in cooling the hot parts.

"We can run an efficient compressor at a low pressure ratio, but the disadvantage is that the air comes out of it relatively cool – in the region of 400 F (200 C). If you could run a higher pressure ratio, the air would instead be coming out at about 600 F (315 C). Then in burning fuel with it, you would get its temperature to 1800 F (980 C). When you heat air it wants to expand, and that expansion happens through the turbine, to drive it, the compressor and the propeller through the gearbox.

"However, with the recuperator you can recover some of the waste heat from the exhaust gases back into the air coming out of the compressor. And since you kept the temperature of the air leaving the compressor low, and the exhaust temperature is around 1400 F (760 C), you have a very big delta temperature, and it is easier to transfer energy back into the cycle.

"So the charge air, is taken from about 400 F (200 C) as it exits the compressor up to about 1100 F (600 C) entering the combuster. You still have to get it to about 1800 F (980 C), and you can do that with fuel. But instead of having to burn enough fuel to heat the air up from 400 F (200 C), you are only doing it from 1100 F (600 C). That means you burn roughly 40% less fuel.

"Of course, you will lose a small amount of pressure going through the recuperator, so that is a loss. Also, you want the recuperator to be as efficient as possible, but that implies heavy weight, so the challenge is to make it as light as possible while still withstanding the operating pressures and temperatures.

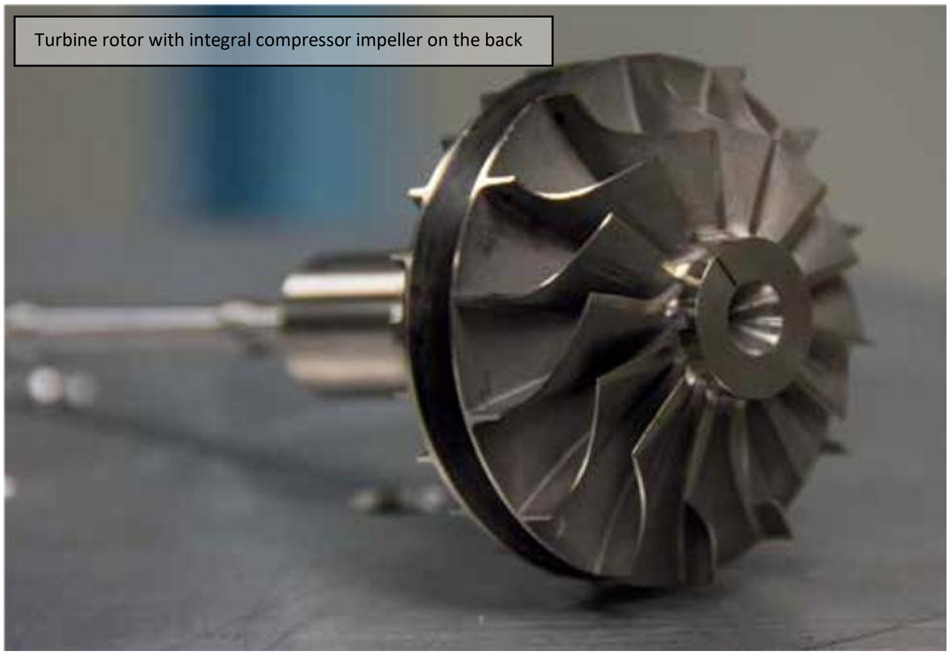
"Our recuperator is essentially a radiator composed of many very thin plates of high-temperature alloy; it is a micro-channel recuperator design. On a regular radiator the passages will have turbulent flow, but when you go to a very tight micro-channel the flow is laminar, which is better for heat transfer, as is the additional surface area for a given volume. That minimizes the size and weight of the recuperator by achieving the highest possible value of heat transfer per unit of volume.

"But if you think about the passageway for the air from the compressor, through the recuperator to the combuster, that is quite convoluted. It was quite a design challenge to get the air to go through the recuperator as efficiently as possible. You can't just do that with computational fluid dynamics, you have to make physical parts to rig test, redesign and re-test."

Another gain of the recuperator, according to Frigerio, is that "it works like a muffler, taking some of the exhaust noise out. The exhaust has no silencing, it simply comes out at the sides. Our turbine makes a high-pitched sound, which attenuates really fast in the atmosphere, especially at high altitude, and is quieter than a piston engine, but the loudest thing is always the noise of the propeller."

Materials

The engine uses no advanced coatings but a variety of materials, although not for the rotating assembly. Frigerio reports, "We ended up with a single spool with the compressor, shaft and turbine as one integrated casting, thus using the same material throughout.



Turbine rotor with integral compressor impeller on the back

"Normally you wouldn't do that, as the weight of the compressor is a significant element of the overall weight of the engine. But once you get down to a micro-turbine it is less crucial, and the trade-off versus making the various elements as different castings wasn't worthwhile. We eliminated a lot of cost and complexity by having just one casting.

"The material we use is a high temperature nickel-based superalloy. Although it's an established superalloy, we don't want to be precise as to its specification. It is difficult to machine, and our part is very complex and is cast rather than machined from solid, so there is very little machining required of the casting."

But isn't the cost of a high temperature material to cope with the demands of the turbine adding expense? "Yes, but overall it is less costly than making the compressor as a separate element," Frigerio says. "Plus that makes the compressor more durable too – if a little heavier!"

The gearbox is at the front of the engine, thus in a cold location, so its case is cast aluminium for minimum cost. The engine bearing housing immediately behind it is likewise cast aluminium, and this second section transitions into the engine intake.

Behind that is the compressor housing, which is titanium, machined from solid. At the rear is the combuster housing and the turbine-recuperator-exhaust section, both of which are made from a nickel based superalloy, cast and machined.

The various sections are attached using flanges with bolts or clamps, according to requirement. Careful design overcame the problem of the differential in expansion of the various materials, Frigerio reports.

Drivetrain

The engine is connected to the front of the rotating assembly shaft via a gearbox. The gearbox's first-stage drive arrangement is a derivation of a planetary geartrain. In this case there is no ring gear.

Frigerio says, "The high-speed input pinion drives planet gears in opposite directions; these gears are straight cut. As in a planetary gearbox, the radial component from the gears meshing is offset by the component on the other side. They cancel each other out, and you don't have a side force, just torque."

There is a more traditional reduction stage at the output to further reduce the shaft speed to the 6000 rpm output shaft speed. The gearbox – which contains a dozen bearings (all ball aside from one roller) – and the shaft bearing compartment share the same oiling system using a pump to scavenge oil from the bearing compartment.

Another view of an engine core instrumented in the UAV Turbines test cell

Suppliers to UAV Turbines include

Compressor/turbine castings: Precision Castparts Corp
Compressor/turbine: Bogue Machining
Housing castings: Uni-Cast/Vaupell Rapid Solutions
Housing: Giuliante Machine Tool
Shafts: Sirois Tool
Gears: Delta Research
Bearings: GRW, Barden, Cerobear
Seals: JetSeal
Threaded components: McMellon
Gaskets: in-house
Ignition system: in-house
Fuel system: in-house
Engine management system: in-house
Starter/generator windings: Motorsolver
Data acquisition: National Instruments
Pumps: Parker
Oil filter: Pall
Air filter: Pall
Fluid lines: in-house
Wiring loom: in-house
Heat exchangers: undisclosed
Fuel pump: undisclosed
Valves: The Lee Company

That is the only scavenge pick-up; the gearbox is wet sump. The oil pump combines one scavenge and one pressure stage, both of the gerotor type.

The oil pump is run off one of the two planet gear-shafts, the permanent magnet starter/generator running off the other one. The oil pump runs at a fixed ratio of the rotor shaft speed, and the supply of oil from the pressure stage is split between the engine bearings and the gearbox bearings. The oil pressure is

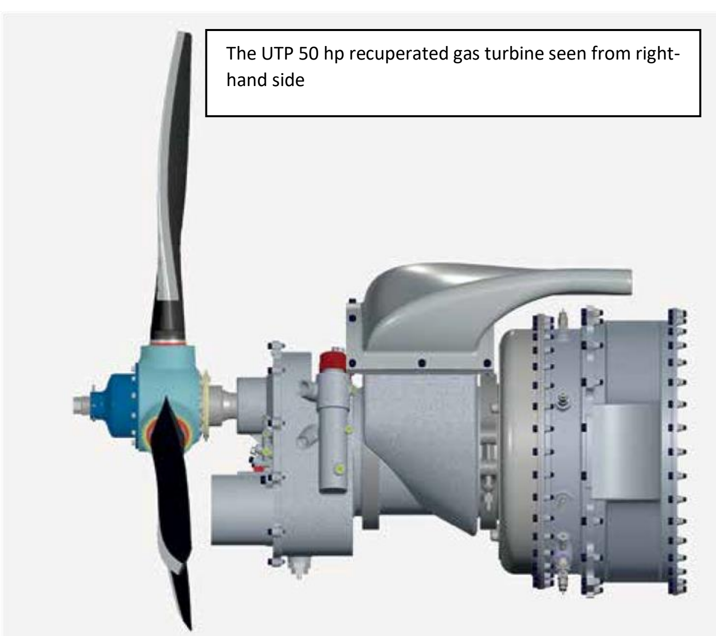
about 200 psi owing to the requirement of the variable propeller, which exploits the same system. The lubrication side runs at about 20 psi.

The gearbox provides a reduction from the 106,000 rpm of the output shaft to the 6000 rpm of the propeller, its exact speed set according to customer requirement. The slower the propeller, the more efficient it is, but the slower it turns the bigger it needs to be, so there is a tradeoff according to the individual installation.

Conventional variable-pitch propellers have an electromechanical operating mechanism, whereas UAV Turbines has developed a fully electronic system which is less complex, reducing cost and weight as well as enhancing reliability.

“We have two solenoid valves under the command of the engine management system,” explains Frigerio. “These regulate the oil going in and out of the system, and that eliminates a lot of the complexity in a regular constant-speed, variable-pitch control system. Essentially you are relying on modern computer controls to govern it, rather than having a 1960s electromechanical system.”

This approach provides a full-authority integrated propulsion control system, governing both engine speed and propeller pitch as an entire system.



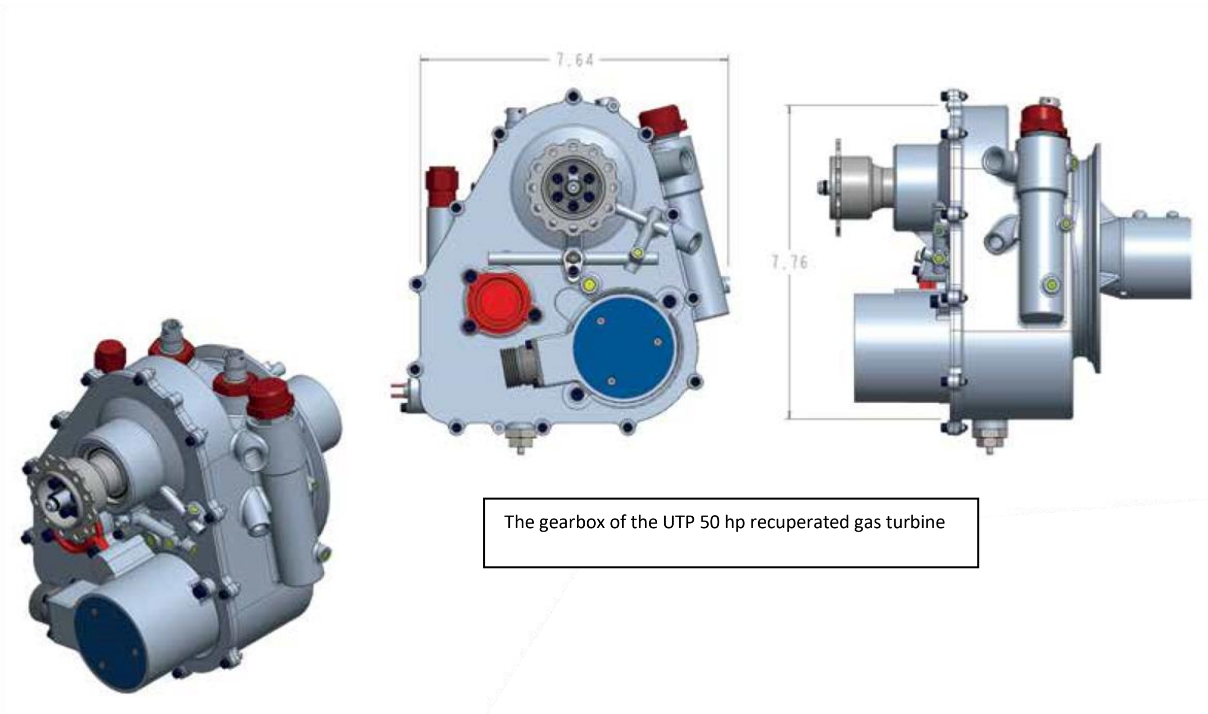
The UTP 50 hp recuperated gas turbine seen from right-hand side

Engine control

Frigerio explains that engine control is done via an ECU operating the fuel pump and the propeller. “If the rotor shaft starts slowing you need more power, so when that happens the ECU commands the pump to go faster to put more fuel into the engine,” he says. “When that happens the turbine inlet temperature is higher, so you are expanding the air from a higher temperature, so the power output of the engine goes up and the shaft speed goes back up.

“The opposite is also true. If you start over-speeding, the ECU slows the pump and the turbine inlet temperature goes down, and the engine slows until the required operating speed is regained.”

In operation, the ECU controls the fuel pump’s speed and the two solenoids governing the variable-pitch mechanism. During the start it also controls the starter generator and the ignitor, ensuring a safe reliable start. The starter/generator switches from a motor to a generator during normal operation, and its output is controlled by the power control unit, according to the electrical requirements of the vehicle. The ECU knows what the generator is doing so it can take that into account, but it doesn’t control it. The key inputs to the ECU are the electrical power requirement and the conditions of the engine – shaft speed, intake air temperature and density, and exhaust gas temperature. It also monitors basic health conditions such as oil pressure, temperature and vibration.



The gearbox of the UTP 50 hp recuperated gas turbine

Performance

The engine air intake is on top to avoid pick-up from underneath on take-off or landing. “There is an air filter in it so we can operate in dusty environments. There isn’t much danger of compressor erosion because of the material it’s made from, but the air filter stops dust clogging the recuperator passages,” explains Frigerio.

The only items that require cooling are the oil system and the electronics, and both are isolated from the hot side, consequently aerodynamic drag inducing air cooling flows are minimal. The engine, which weighs only 70 lb dry, is just 21 in long by 11.5 in in diameter, making it relatively easy to package.

Gas turbine basics

The heart of a single-stage gas turbine engine is an assembly through which the charge air travels, and consists of an upstream compressor that is coupled mechanically to a downstream turbine, with a combustion chamber between those two components. The chamber, which is the stage where the fuel is directly introduced, is often referred to as the combuster.

The compressor and turbine wheels rotate on the same shaft, with the turbine driving the compressor. The compressor raises the pressure and the temperature of the incoming air, which it sends into the combuster. There, combustion further raises the temperature of the charge, which continues its passage forward to drive the turbine.

In the case of a turbojet engine the expanding gas passing through the turbine is directed through a propelling nozzle, where it is accelerated to high speed to provide thrust. Of the energy in the fuel that is converted to kinetic energy to drive the turbine, only an amount sufficient to drive the compressor is extracted, the balance going towards creating jet thrust.

In the case of a turbofan engine, the turbine/compressor shaft directly drives a fan inside the engine, which is the main source of thrust. This is often considered a hybrid in that the exhaust from the turbine contributes some jet thrust to augment the work of the fan.

In the case of a turboprop engine, all the work done by the turbine is fed to the shaft driving both the compressor and, via a gearbox, the propeller; the exhaust gas does not contain enough residual energy to create significant thrust. UAV Turbine's UTP50R is a turboprop engine.

The gas turbine engine has constant combustion, and the rotating assembly is designed to operate (as near as possible) at constant speed. The propeller is coupled through reduction gearing that converts the high rpm, low torque of the turbine-powered driveshaft to low rpm and high torque.

Normally the gear ratio is not variable; instead the constant-speed propeller exploits the controllable pitch of its blades. The blades are rotated around their long axis to vary pitch, allowing the propeller to be adjusted to different air speeds and levels of thrust without the need to alter its rotational speed.

A clear advantage of a turbine is its multi-fuel capability. "In the combuster you are heating the compressed air to more or less the same temperature regardless of the fuel," notes Frigerio. "The trick is to ensure that you have the conditions in the combuster such that you can burn any fuel, that you can combine it with the air in the correct proportion.

"That is a lot easier to do with a continuous combustion than it would be when you are trying to control the combustion events in a piston engine. We don't have to worry about detonation: so long as we can keep it lit, it will work. With our continuous combustion you can run on almost anything – propane, diesel, jet fuel and so on."

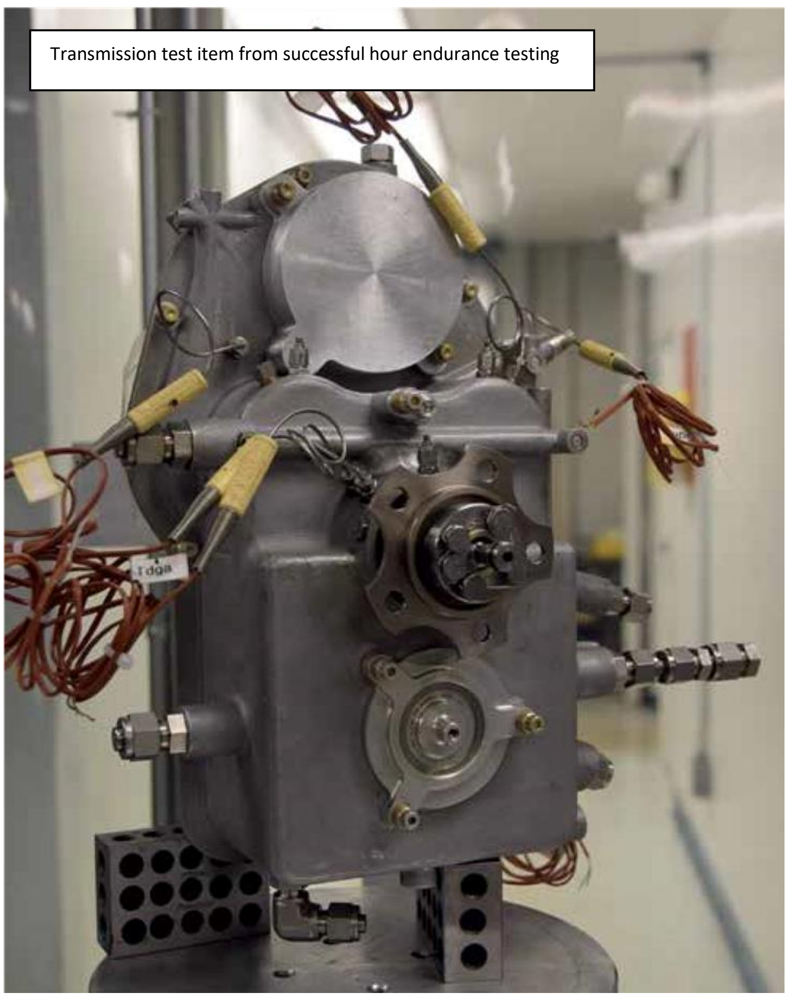
The engine has been designed specifically for UAVs requiring around 50 bhp with a fixed-pitch propeller. But, says Warshaw, "Remember that aircraft don't fly on horsepower, they fly on thrust, and with the variable-pitch propeller we are very efficient at turning horsepower into thrust. In other words, we need less horsepower for a given amount of thrust.

"It is like in the car industry, comparing an engine with a gearbox to one that is direct drive, with only a clutch – using a gearbox is a more efficient means of getting up to speed. Using a variable-pitch propeller is like having a continuously variable transmission. In theory you could put a variable-pitch propeller on a piston or rotary engine but the inherent engine technology is still less efficient.

"This engine for the 50 hp class is starting off at 39 bhp, and we intend to grow it from there. With our high-efficiency propeller we can attain 30% more [takeoff] thrust than a regular fixed-pitch prop so we don't really need the extra horsepower. Nevertheless, we intend to grow the power output by about 25% over time. By introducing the engine at 39 bhp we are leaving ourselves room to grow. "Once we fully understand where the life requirements are, where we need to improve, we can push the envelope in terms of temperatures and flows, and first of all get more power from the same airflow. Then we can increase the rpm a bit and increase component efficiency, and that is where that extra power will come from, not from any fundamental change."

Frigerio adds, "This engine is designed for high-altitude use. Most UAVs this engine will power fly at between 9000 and 18,000 ft for most of a mission, and that is what our engine is optimised for. If you look at sea level standard data, we could be more efficient in that condition, but the trade-off would be that we wouldn't be so efficient at altitude. Or we would be carrying more engine weight. So at take-off we aren't as efficient as we could be, but that is a small price to pay.

"Our gearbox is sized for the engine, and we have left ourselves room to grow in power [using that same box and making only small changes to the gears to handle the additional torque within the same unit]. It's the same with the starter/generator – we have sized that for what current UAVs require, but we can replace it with a larger, heavier unit if that is required for a specific application.


Transmission test item from successful hour endurance testing

"The upshot is that we can supply a propulsion system that is more powerful in terms of thrust and electrical energy than is normal in the 50 hp category, if that is what a customer wants. We suspect that is what the next generation of UAVs will require though."

Warshaw notes, "Many existing UAVs are failing for various reasons, most of which are related to the propulsion system. The fact is that UAVs generally need more reliable propulsion systems.

"We think our product will be heavily in demand by the military for various applications. Also, the FAA is looking to what is acceptable to fly over populated areas – do you want a reciprocating engine that might fail, or a turbine?

"There isn't much to fail in a gas turbine. The only moving part is the rotating assembly, and it goes in one direction only – that is why it is so reliable.

"Our engine is designed for 3000 hours between overhauls. The wear is first in the bearings. The gears are designed for 5000 hours, and even the static hot section should run for 10,000 hours between component replacements.

"In terms of brake-specific fuel consumption, we are in the 0.4-0.5 lb/hp/h (240-300 g/(kW h) range. Compared to existing UAV internal combustion engines in a given vehicle, in terms of fuel efficiency we are in some instances the same, in other instances better. In particular, the higher we fly the better we get relative to conventional engines. That is inherent in the use of gas turbine technology.

"We have a highly efficient propeller system and a highly efficient engine with the recuperator. We also have the efficiency advantages of our gearbox and electronic controls. Our engine is a significant step forward but we had to overcome a lot of challenges to obtain these gains," Warshaw says.


Subscribe today
UNMANNED systems TECHNOLOGY
Critical intelligence for land, sea and aerospace engineers
Motion picture
Focus on inertial measurement units
Material world
Advances in alloys and composites
Pinpoint accuracy
C-Astral's Bramor ppX survey UAV
ISSUE 11
December/
January '16
LAUNCH ISSUE Winter '14
ISSUE 2 Spring '15
ISSUE 3 Summer '15
ISSUE 4 Autumn '15
ISSUE 5 December '15/ January '16
ISSUE 6 February/ March '16
ISSUE 7 April/ May '16
ISSUE 8 June/ July '16
ISSUE 9 August/ Sept '16
ISSUE 10 October/ Nov '16
4 ways to subscribe
to guarantee a personal copy
1) Online at www.ust-media.com
2) Telephone +44 (0)1934 713957
3) Fax to +44 (0)208 497 2102
4) Email chris@ust-media.com
Subscription prices
1 year subscription: The next 6 issues
UK £90 £75
Europe £108 £90 (~125€)
USA/Canada £112.50 £93.75 (~$150)
Rest of World £117 £97.50
2 year subscription: The next 12 issues
UK £180 £135
Europe £216 £162 (~225€)
USA/Canada £225 £168.75 (~$270)
Rest of World £234 £175.50
To enquire about advertising with us, email simon@ust-media.com
High Power Media Ltd, Whitfield House, Cheddar Road, Wedmore, Somerset, BS28 4EJ, UK.
Tel: +44 (0)1934 713957 Fax: +44 (0)208 497 2102 E-mail: chris@ust-media.com www.ust-media.com
hpm high power media