THE PRIDE WITHIN

DSO NATIONAL LABORATORIES

1972-2012

THE PRIDE WITHIN

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IN OUR RELENTLESS PURSUIT.

INSPIRING US,

TO PUSH FURTHER, THINK DEEPER.

CHALLENGING US,

TO UNLOCK THE MAGIC OF SCIENCE, THE WONDERS OF ENGINEERING

SERVING THE NATION FOR 4 DECADES,

THE PRIDE WITHIN

CHAIRMAN'S MESSAGE

One of Singapore's forefathers, the late Dr Goh Keng Swee, was clear that a nation must be able to defend itself in order to protect its sovereignty and its people. He believed that a country could not prosper without a strong defence force.

As Singapore faced strategic vulnerabilities such as its small population and geographic size, Dr Goh also believed that the key to overcoming these vulnerabilities and building a formidable defence force was technology.

In 1972, he established DSO with only three young engineers, and gave them a critical mission – to research and develop technological surprises that would provide the Singapore Armed Forces with the critical edge in the battlefield.

Today, DSO has grown, but its mission remains clear and unchanged. Over 1,200 research scientists and engineers constantly strive to fulfil this mission by staying at the forefront of technology, and looking beyond the horizon to develop game-changing defence solutions.

To achieve something that is seemingly impossible requires more than just acquiring and applying knowledge. It takes passion, commitment and grit. It requires the hunger to explore the unknown and make the impossible of today, possible tomorrow.

This year, as DSO celebrates its 40th Anniversary, we are reminded of this unique DSO spirit that has been guiding us in our quest to achieve our mission and vision. Our quest has been helped by our partners in the Singapore Armed Forces, in academia and in industry, both local and global.

Looking to the future, DSO will continue to pursue its mission relentlessly as it continues to push the boundaries to reap the possibilities that technology can offer in furthering our defence capabilities.

Dr Tan Kim Siew
Chairman
DSO National Laboratories

DE
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OUR EVOLUTION IN THE FIRST 30 YEARS

1972

Dr Goh Keng Swee, then Minister for Defence, handpicks three newly graduated engineers to study Electronic Warfare (EW). The group calls themselves the **Electronics Test Centre** (ETC) and undertakes the critical mission of building up secret-edge defence technologies for Singapore.

1976

ETC grows to 20 staff and moves to new premises in Marina Hill.

1977

The **Defence Science Organisation (DSO)** is formally established with a staff size of 50 engineers.

1986

The Ministry of Defence (MINDEF) forms the Defence Technology Group (DTG). The DTG unites the technology and logistics groups in MINDEF, and establishes DSO as the centre of R&D for the Singapore Armed Forces (SAF). DSO continues to focus on EW as well as Guided Systems and Cryptography as its key research thrusts.

1989

With the opening of its new building in Science Park, the existence of DSO and its work is publicly acknowledged for the first time. The organisation also bags the inaugural Defence Technology Prize in the individual and team categories.

1991

The Gulf War reinforces the role of superior technology as a game changer in the battlefield. In the same year, DSO becomes one of the first Executive Agencies in MINDEF, gaining partial financial and operational autonomy.

1997

DSO is corporatised and is renamed as **DSO National Laboratories** (DSO). The organisation begins a total revamp of its systems and procedures to embrace the best commercial practices to recruit and retain talented people, and set new levels of service for its customers.

1998

DSO expands its premises with a second building at Marina Hill containing state-of-the-art research facilities. In the same year, DSO organises its first international symposium - the Singapore International Symposium on Protection Against Toxic Chemicals (SISPAT).

DSO IN THE NEW MILLENNIUM

2002

As part of its 30th Anniversary celebrations, DSO releases its first commemorative book, unveiling a glimpse of its R&D in Electronic Warfare and Guided Weapons publicly for the first time.

In response to asymmetric threats that could be conducted by non-state perpetrators and against targets that are not necessarily military or physical, DSO announces its new mission to include the protection of Singapore's critical infrastructure and information network. Defence R&D will continue to remain as its primary focus.

2003

The integration of Defence Medical Research Institute into DSO to form the Defence Medical and Environmental Research Institute expands DSO's research to include human sciences.

DSO achieves its first Organisation for the Prohibition of Chemical Weapons (OPCW) Designated Laboratory status, a reflection of DSO's chemical verification capabilities being on par with some of the world's best.

During the Severe Acute Respiratory Syndrome (SARS) crisis, DSO provides diagnostic support for clinical samples, and joins the Singapore Clinical SARS Consortium to jointly develop and validate a diagnostic kit to detect the virus.

2004

DSO's TV-guided bomb is showcased to the public for the first time in the 3rd Gen SAF TechX exhibition, 20 years after its initial development as a technology demonstrator.

DSO and other collaborative partners, namely, the National University of Singapore (NUS), Supelec and ONERA of France come together to form SONDRA, a joint research laboratory set up in France with a mission to conduct basic research in the areas of advanced electromagnetism, radar and signal processing.

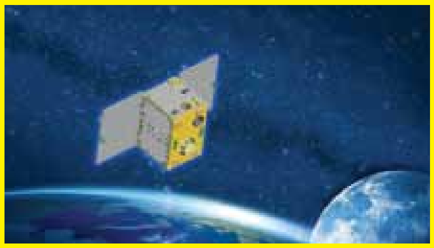
2006

Leveraging on DSO's and Singapore Technologies Kinetics' (STK) expertise in advanced material, the Advanced Technology Research Centre (ATREC) is established to bring together R&D personnel from both entities, to further enhance the level of research, experimentation and technology development.

2009

DSO marks its 20 years of research in chemical defence, and publishes a commemorative book, "Unveiling the Face of Progress", providing a rare insight into the programme's capability built up over the past two decades.

2011



Singapore Technologies Engineering, DSO and the Nanyang Technological University (NTU) establish ST Electronics (Satellite Systems) in a joint venture to develop advanced earth observations satellites. This comes after the successful launch of X-SAT, Singapore's first indigenously built microsatellite by NTU and DSO.

2012

DSO is the oldest and largest local R&D institute with more than 1,200 research scientists and engineers. Its expertise spans across the spectrum of land, sea, air and cyberspace, and has won more than 70 Defence Technology Prize awards since its inception.

Delivering Systems

In support of the Singapore Armed Forces' (SAF) transformation into a 3rd Generation networked fighting force, DSO's mission is to deliver systems and technologies that sharpen its edge in the battlefield, and makes potential threats irrelevant.

UNMANNED AERIAL VEHICLE DEVELOPMENT

The increasing use of Unmanned Aerial Vehicles (UAVs) for military applications has received much attention in recent years. As demonstrated during the Afghanistan and Iraq war, UAVs have proven to be a formidable asset for superior battlefield surveillance and comprehensive situation awareness.

In 2010, the SAF received its first fleet of indigenously built UAVs - the Skyblade III - which was developed by DSO, in collaboration with Singapore Technologies Aerospace (STA).

Since the successful transition of the Skyblade III into SAF operations, DSO and STA have moved on to jointly develop a bigger class of UAV, the Skyblade IV, with longer range and higher endurance capability.

In the following pages, two DSO-developed capabilities used to support advanced UAV development are highlighted: a UAV system integration and reliability testing methodology, and a special two-dimensional braiding machine to fabricate complex composite shapes.

Also highlighted in the section on Emerging Technologies are several technologies currently under development in DSO that could enhance the capabilities of UAVs. These include a Hybrid Power System (page 118), research on Tornado-Like Jets Technology (page 122), and Hyperspectral Technology for UAVs (page 126).

UNMANNED AERIAL VEHICLE SYSTEM INTEGRATION RELIABILITY LABORATORY

The continued increase of Unmanned Aerial Vehicles (UAVs) operating in civilian airspace for a broad range of civil and military applications has led to an increasing demand for high reliability in UAV system design. To ensure reliability, extensive UAV system flight testing has to be conducted during the system development phase.

UNMANNED AERIAL VEHICLE SYSTEM INTEGRATION RELIABILITY LABORATORY

However, with Singapore's limited airspace and concerns regarding airspace safety, it is almost impossible to carry out local flight trials for UAV system development. As such, ensuring UAV system reliability requires an alternate innovative test approach. DSO's UAV System Integration Reliability Laboratory (SIRL) facility has been set up to meet such a requirement, enabling UAV development teams to achieve a high level of reliability in their UAV system with a much reduced number of airborne flight trials.

The SIRL facility provides extensive UAV system testing on the ground in order to characterise and sieve out potential UAV system weaknesses prior to flight. This helps to mitigate flight test risk, shorten development cycles and improve system reliability. In the past, these could only be achieved by extensive flight test programmes.

The SIRL facility setup consists of a UAV simulator station integrated with a UAV Unit-Under-Test (UUT) housed in a custom-designed test jig. The UAV simulator station runs real-time UAV flight dynamics and environment simulation to emulate actual UAV mission flight profiles. The signal outputs from the UAV simulator station are sent to the UAV UUT on the test rig so that it will exhibit similar responses as if it were in flight. This enables the actual avionics hardware on the UAV UUT, as well as the software in its ground control station, to be tested realistically through various mission profiles.

Several challenges were presented in the development of the simulator station. A high fidelity UAV flight dynamics model was essential for the UAV simulator station to simulate and predict UAV flight motions within the simulator flight environment. As such, Computational Fluid Dynamics (CFD) analysis, wind tunnel experiments and flight test system identification works were carried out to support the flight dynamics model development.

In addition, sensors data from actual physical sensors used during airborne flight had to be emulated accurately by the simulator station. The physical sensors to be emulated included inertial measurement sensors, air data sensors and Global Positioning System (GPS) sensors. To achieve this, detailed sensor dynamics modelling and signal interface emulation to the UAV UUT were carried out during the simulator station development. The ability to simulate and emulate each sensor in the simulator station environment provides the ability to simulate or inject different critical failures modes during SIRL testing such as the loss of GPS signal conditions or airspeed sensor failure.

The test jig that houses the UAV UUT is designed to support different sizes of UAVs for reliability programme testing. Instead of hard-mounting the UAV UUT to the test jig, the UAV UUT is suspended using multiple bungee slings in order to create free suspended flight conditions. This helps to damp UUT airframe vibration propagated by the UUT propulsion system, creating an almost similar isolated vibration damping condition experienced during actual airborne flight. Each bungee sling is suitably sized to withstand UUT testing and provides adequate safety from breaking, while still providing good damping of free flight conditions. To ensure the overall stability of the test jig during SIRL testing, a high safety margin using maximum thrust conditions as a base has been designed into the test jig.

Other features of the test jig include airflow blowers to provide cooling based on flight airspeed, as well as to support continuous engine propulsion on the ground. The airflow blowers also help to create a realistic thermal environment that enables the testing of the UUT thermal management system.

In order to support reliability test plans for the UUT servo actuators, load profiles representative of the actual aerodynamics forces acting on the UAV control surfaces (aileron, elevator and rudder) during flight can be applied on the UUT servo actuators that drive the control surfaces.

UNMANNED AERIAL VEHICLE SYSTEM INTEGRATION RELIABILITY LABORATORY

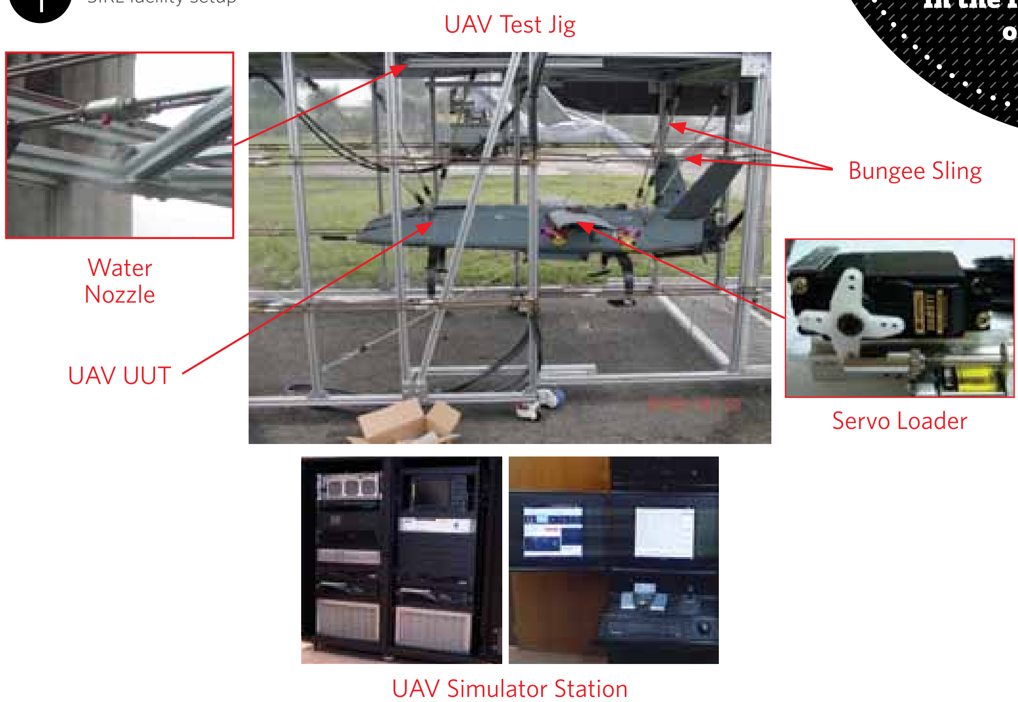
As a unique design feature, multiple water nozzles have been integrated on the sides and top of the test jig. This enables environment qualification testing for rainy weather conditions - especially prevalent in the local operating environment. The intensity of water sprayed on the UAV UUT is determined in accordance with military standard rain test specifications. Such testing enables the validation of the UAV UUT design for water tightness and can be used to identify potential weaknesses in the UAV airframe design and fabrication.

To date, DSO and Singapore Technologies Aerospace have worked together to undertake SIRL testing of the Skyblade UAV. Through extensive SIRL testing, many safety-critical bugs were discovered and rectified even before actual flight testing, giving the development team greater confidence in the functional reliability of the platform.

DSO is currently working on enhancements to the SIRL facility ground testing technologies in order to expand its capability beyond reliability testing. One area of enhancement is the use of virtual flight testing on the ground to augment actual flight testing. This represents a great payoff for UAV development programmes as it will reduce the need for actual flight testing and alleviate the constraints of Singapore's limited airspace.

Through extensive SIRL testing, many safety-critical bugs were discovered and rectified even before actual flight testing, giving the development team greater confidence in the functional reliability of the platform.

Figure 1 SIRL facility setup



TWO-DIMENSIONAL BRAIDING TECHNOLOGY

Braiding is a simple interlocking of two or more fibres or fibre bundles to produce a near net-shape fibrous preform (see Figure 1 overleaf).

TWO-DIMENSIONAL BRAIDING TECHNOLOGY

With an integrated network of structural cells in bi-axial or tri-axial configurations, the braids or textile structures provide a mechanism for structural toughening of composites. The fully integrated preform structure facilitates the processing of composites into near net-shape structural parts, thus simplifying the processing steps and bridging the gap between the material and the final product. Virtually any fibre with a reasonable degree of flexibility and surface lubricity can be braided over a shape-forming mandrel (see Figure 2) in a controlled manner to create a fibrous preform. Typical engineering fibres include aramid, carbon, ceramics, fibreglass and quartz.

Realising the potential of two-dimensional (2D) braiding technology, DSO collaborated with an overseas company to conceptualise the design of a multi-axis braiding machine capable of handling complex shapes with asymmetrical braiding. Based on a three-dimensional (3D) model creation of the perceived machine, DSO engineers worked closely with six local companies to assemble, test and commission the machine. These companies specialised in areas such as precision machining, mechanical assembly and electrical harnessing, drive-&-control technologies, and machine automation.

Figure 3 shows the partially-assembled multi-axis braiding machine.

The assembled seven-axis 2D braiding machine was finally integrated with an in-house developed proprietary Computer Aided Design/ Computer Aided Manufacturing (CAD/CAM) software to control complex-shape braiding.

Figure 4 shows the successful asymmetrical braiding of a curved-shape demonstrator with multiple step features.

Figure 1 Fibrous braids in the form of Bi-axial or Tri-axial configurations

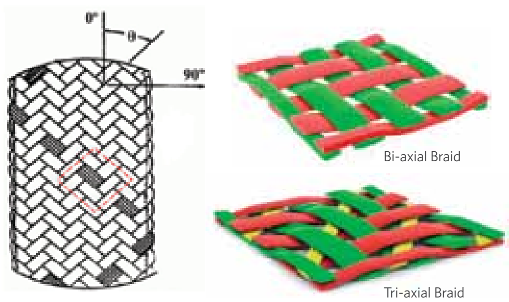


Figure 2 Creating a standard carbon braid

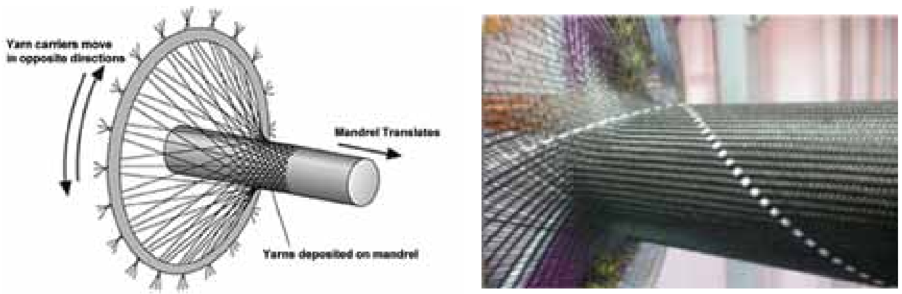


Figure 3 Partial assembly of a multi-axis braiding machine

Figure 4 Asymmetrical braiding of a curved-shape demonstrator

TWO-DIMENSIONAL BRAIDING TECHNOLOGY

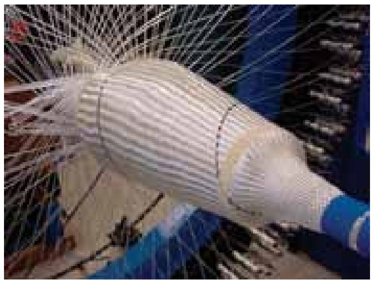
DSO's unique braiding machine is capable of continuous symmetrical and asymmetrical braiding over a wide variety of mandrel shapes and sizes. It has the ability to produce braids in single or multiple layers with tremendous hoop strength, as well as longitudinal strength and rigidity. Material in their raw fibre form can be readily turned into near net-shape braids. Using standard composites fabrication techniques, these braids can then be turned into structural composites. By virtue of its ability to conform to complex shapes, braids can be used in producing components such as fuselages, wings and frames for Unmanned Aerial Vehicles (UAVs).

By using carbon in its raw form, a braiding solution can significantly minimise wing fabrication cost. The seamless wing structure produced has also been found to possess superior bending strength and stiffness when compared to composite wings assembled by the traditional method using two half-woven skins.

In addition, fibrous preforms created using the braiding machine can readily be turned into composites by combining it with liquid infusion processes. Figure 5 illustrates the combination of braids with a Resin Transfer Moulding (RTM) process to produce a typical structural composite part.

DSO's 2D braiding machine opens up new R&D capabilities in the design, development and fabrication of multi-functional and smart composites through the utilisation of functional yarns in braid production. One such possibility is to embed optical fibres, conducting wires and coils, thermo-chromic fibres, and photovoltaic wires to produce smart composites with sensing, adaptive self-healing, structural health monitoring and temperature monitoring functionalities.

Figure 5 Combination of braiding and RTM process to produce a composite structure



Braiding on mandrel

Closed-mould RTM process

Release of moulded part

Final composite structure

TAKING FLIGHT

Dr Justin Teo Senior Member of Technical Staff Guided Systems Division Years in DSO: 13	**Paw Yew Chai** Senior Member of Technical Staff Guided Systems Division Years in DSO: 12	**Edward Pang** Senior Member of Technical Staff Guided Systems Division Years in DSO: 7

DSO's build up of indigenous UAV development expertise over the years has enabled the launch of the Skyblade III Mini-UAV, a crucial platform in the 3rd Gen SAF's network of sensors that help it see further, more clearly and in real time. Dr Justin Teo, Paw Yew Chai and Edward Pang are just three among those who have contributed to the build up of DSO's UAV development expertise. Each of them is also well aware of the trials and tribulations involved in the development UAVs.

Take us back in time. How did each of you get started in UAV development?

Yew Chai (YC): It started with my Final Year Project in university. At the time, there was a project offered by DSO to perform modelling and simulation for a small remote controlled helicopter. I took up the project and ever since then, I've been hooked onto UAV development. UAVs are a complex system requiring knowledge from different domains to develop. The technical complexity and the integration with different cutting edge technology make UAV development a highly exciting field to be in.

Justin Teo (JT): Back in my days as a polytechnic student, I built a micromouse with two other team mates for a competition. A micromouse is a small wheeled robot that is designed to find the most optimal path through a maze. I was responsible for designing the controllers that would keep the micromouse on its desired path at a specific speed. That was my first practical experience with controls for unmanned technology. Back then, it was for fun, but now I do it as a job. However, I must say that it's still fun!

Edward Pang (EP): In my case, I need to go back further in time to my childhood days. Back then, my favourite past time was playing with LEGO blocks. I think it was having the power to assemble the individual blocks into almost anything I wanted that got me excited. I suppose that was how I ended up as a mechanical engineer. Besides LEGO, I have always had a keen interest in aircraft. So here I am in DSO, a mechanical engineer working on UAVs!

Tell us a bit more about the work you do in UAV development.

YC: My work involves understanding and modelling the flight dynamics of UAVs, and developing the algorithms that enable the UAV to fly autonomously. Guys like Justin then design the physical controls that actually keep the UAV in the air.

JT: That's right. A simple analogy of my work is the humble toilet flush! Think of it as a control system that allows the tank to be filled with water to the 'right' level. UAV controls however, are more complex and involve the selection of actuators and sensors, controller design and implementation, as well as testing and verification. What's exciting to me is the idea that a highly erratic and complex system like a UAV can be tamed via controllers to behave as one would desire!

EP: As a mechanical engineer, I'm involved in almost the entire process of developing a UAV. This process ranges from conceptual design and fabrication, testing and qualification, right through to product evaluation. You could say that I have the unique opportunity of witnessing a UAV from birth to an actual flying platform!

Work sounds quite exciting for the three of you. But what's the most painful part?

YC, JT and EP: Flight trials!

YC: First, there are the logistics requirements and preparations which can take a long time. Then, we're in the field for long periods of time, sweating it out to achieve trial objectives. If all goes well, and the trial objectives are met, then we can move forward in the development process.

EP: But, if the prototype crashes during the trial, it's a different story altogether! When that happens, everyone scrambles to figure out why it happened. Being such a complex system, the cause for the crash could be due to mechanical, electrical, or software issues. It could even be a combination of all three. Sometimes, heated arguments do break out when trying to solve the problem, but in the end, we've always managed to get the prototype flying for the next trial!

YC: So whenever we manage to carry out a successful flight trial, we experience a great deal of satisfaction. Not to mention relief as well!

You've each been with DSO for a while. What is it about DSO that keeps you going?

JT: I remember when I first started work in DSO, I was shown a video of a proof-of-concept prototype built by DSO. At the time, I thought "Wow! This is science fiction!" I think that sums up what keeps me going: turning 'science fiction' into reality is a privilege unlikely to be available anywhere else in Singapore!

YC: I agree, no other organisation in Singapore offers this nature of R&D. Each project that I work on offers a new set of challenges resulting in quite a dynamic work environment. Thinking of solutions to overcome these challenges keeps me fresh. It also helps that I work with like-minded colleagues who all speak the 'engineering' lingo!

EP: Yew Chai is right. Working with the right people definitely keeps me going, and the team that I work in is great! Always willing to try out unconventional ideas, and pitch in to make these ideas work. It's my colleagues that make my work a pleasure!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FUSION ENGINES FOR COMMAND AND CONTROL

Real-time data fusion engines are important to the SAF as commanders need to make sense of a given situation through inputs from sensors, and make accurate time-critical decisions in the Command & Control (C2) systems.

FUSION ENGINES FOR COMMAND AND CONTROL

DSO has developed two key data fusion engines, namely the Identification (IDENT) and the Threat Evaluation and Weapon Assignment (TEWA) engines.

In order to determine the identity (friendly, neutral or hostile) and platform type (e.g. fighter or helicopter) of a target, the IDENT engine takes in multiple sources of input and updates the data on incoming evidence. At the same time, the TEWA engine continuously evaluates which targets pose a threat to friendly forces and then assigns the best weapon at the best time to engage them.

The IDENT and TEWA engines have been implemented in the Republic of Singapore Navy's (RSN) Frigate Combat Management System (CMS). To explain the science and technology behind the IDENT and TEWA engines, the Frigate CMS application will be used as an example.

Frigate CMS

DSO was tasked to design, develop and deploy the IDENT and TEWA fusion engines in the Combat Management System (CMS) onboard the RSN's stealth frigates.

These frigates are highly capable warships. They are equipped with advanced state-of-the-art combat capabilities, allowing them to perform a wide spectrum of missions and also deal with various threats in all the three dimensions of naval warfare - surface, air and underwater.

The CMS is an advanced computer program that is able to detect, track, identify and prioritise contacts, and assign weapons to engage enemy targets which are facing the ships. The many sensors and weapons on-board the frigates are integrated into this one command and control system, which simplifies the decision making process to fire the ship's missiles and other weapons. As such, less time is taken and a smaller crew is required to man the combat systems.

If the CMS is likened to the brains onboard the warships, then the IDENT and TEWA engines that DSO has developed are the intelligence that enables the frigate to do more and respond in a much shorter time.

IDENT Engine

The IDENT engine attempts to evaluate the identities and platforms of all air and surface targets detected by the ship's sensors such as radars and datalinks. On top of that, it also watches out for any suspicious behaviour, such as a neutral aircraft behaving like a hostile one.

To illustrate how the IDENT engine identifies unknown air tracks around the air space, two sample sets of data within a knowledge base are used: commercial flight routes and Identification Friend or Foe (IFF) codes. To get a clue or confidence value about the identity of an air track, the kinematics (flight path conformance) of the air track is checked against flight routes data. If the air track's movement resembles a flight route, the confidence level of the track being a legitimate one is high. Further analysis of the IFF code emitted by the air track allows the IDENT engine to confirm the track's identity.

Confidence value $C_1 = C\,(\mathbf{K}, \mathbf{S})$
Where Track's kinematics $\mathbf{K} = \langle heading, latitude, longitude, altitude, \ldots \rangle$
Waypoint $\mathbf{W} = \langle latitude, longitude, altitude \rangle$
Flight Plan $\mathbf{F} = \langle W_1, W_2, \ldots, W_n \rangle$
Flight Plans $\mathbf{S} = \langle F_1, F_1, \ldots, F_q \rangle$

Figure 1 shows an imaginary sample flight path of a commercial aircraft flying from Changi Airport to the airport of another country (T), as depicted by the black line with blue icons, and the actual flight record of an unknown track, depicted by the red line.

To generate an overall confidence value of a track's identity, confidence values of flight plan conformance (C_1), IFF-mode-3 conformance (C_2) and other confidence values can be combined using the Certainty Factors model. The Certainty Factors model is a method used to manage uncertainties in rule-based systems, which matches the engine's need to manage or address the track's identity. A simple two factors model is shown below:

Combined confidence value $B = C_1 + C_2 - C_1 C_2$

Taking a two factors model of flight plan conformance and IFF-mode-3 conformance confidences as examples, Figure 2 shows how the changes in any of the factor's confidence value will impact the overall combined confidence value. The IFF-mode-3 conformance confidence C_2 is weighed heavily in the example shown in Figure 2, and during the period when it dropped, the combined confidence value also plunged below the confidence threshold.

To qualify the identity of the air track, the combined confidence value has to be above a confidence threshold value (e.g. 0.85 or 85%). In Figure 2, the system would monitor variations of combined confidence values through time and may act accordingly, such as raising an alert.

Figure 1 Flight plan vs. air track

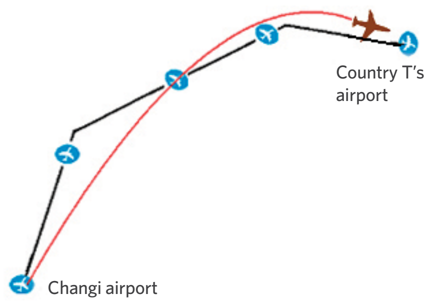


Figure 2 Combined confidence values vs. time step

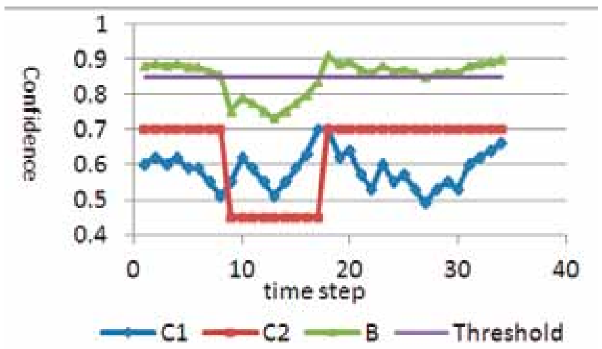
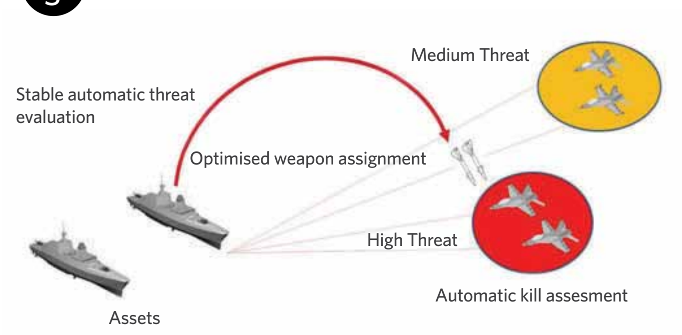


Figure 3 IDENT and TEWA engines in operation



TEWA Engine

While the IDENT engine continues to establish the identities of air tracks, the TEWA engine evaluates those that are threatening the frigates as well as the friendly ships that she is protecting, and recommends the best weapon to engage them.

Using a rule-based system, the TEWA engine quickly assesses all air tracks to sift out those that pose a threat to the frigates. These detected threats are then evaluated to determine their threat levels based on their kinematics, while taking into consideration other factors such as the presence, priorities and capabilities of our own forces. With a prioritised list of threats, the TEWA engine uses weapon models and real-time weapon status information to compute the effectiveness of its available suite of weapons against them. Using the information computed for every threatening air track, the TEWA engine then recommends a prioritised list of target engagements to optimise the use of weapons, while maximising the chances of survival of our own forces.

The results from the TEWA engine, such as the threat levels, are used to recommend target engagements. Associated details are then presented in a format that is intuitive to the ship's crew.

Figure 3 shows a typical operations scenario. While the IDENT engine evaluates the identities of the non-friendly air tracks, the TEWA engine in parallel, evaluates them to find out which ones pose a threat to our own forces and recommends specific weapons to engage them. All these are done continuously to assess the situation and help the ship's crew to take decisive actions quickly.

KEEPING THREATS AT BAY

John Sng Senior Member of Technical Staff Information Division Years in DSO: 10	**Dr Foo Shou King** Principal Member of Technical Staff Information Division Years in DSO: 15

For a small island nation like Singapore, it is crucial to identify friend or foe in the waters around us. Two DSO researchers - Dr Foo Shou King and John Sng – know this well. They were part of the team responsible for developing the Identification, as well as Threat Evaluation and Weapon Assignment data fusion engines for the Combat Management System onboard the Republic of Singapore Navy's (RSN) stealth frigates.

This was an enormous task given how a mistake in identification could have grave consequences. However, they met the challenge head-on and delivered a system that won them the 2007 Defence Technology Prize Team (Engineering) Award.

What was it about Data Fusion that gets you excited?

Shou King (SK): I started off in the area of Natural Language Processing but switched to Fusion Systems to experience something different. I'm someone who likes to see things work, and I want the projects that I work on to be used operationally. When I think of how we can help the users automate their work through the systems we design, I feel a sense of pride and excitement.

John Sng (JS): In this field, I build systems which are usually part of another larger system. This means that people from different areas of expertise will be involved. When I work with them, I get to see and be inspired by the amazing things that they do. The most exciting part of my work is the finale of a project. This is when all the different parts of the project have been integrated and works successfully. That feeling is priceless.

You had to work long hours out at sea for your project trials. Are there any horror stories to share from those experiences?

SK: Yes. Because of those long hours at sea, there were times when I suffered from bouts of sea sickness. These were times when the toilet became my best friend! On the whole however, I enjoy what I do, so a bit of sea sickness wasn't going to stop me.

JS: Unlike Shou King, I remembered to take sea sick pills when I went on trials, but the downside was that they made me sleepy! Once, I dozed off at my terminal while waiting for my part of the trial to start, only to realise that it was already over when I opened my eyes! Fortunately, my system worked fine as I had all my data logged in. After this close shave, I always made sure I had snacks on hand to keep me awake.

Define 'job satisfaction'.

SK: Simply put, to see our fusion engines working well. Once, I was told that one of our engines worked so well, the commander had to deliberately turn it off to ensure that his operators knew how to do their jobs manually. For me, that's 'satisfaction guaranteed'!

JS: I'll define it as the moment in time when you see the entire system work smoothly after years of development and countless sea trials. To witness the joy and relief on the faces of my colleagues – that was definitely job satisfaction, and more.

What is the one thing that you hope to achieve in your research?

SK: An engine that can infer or discover new trends from past knowledge. That's where we humans infer a lot of things from too – the past. To break new ground, we will need to build an engine that can do that as well.

JS: I hope to see our current work evolve into a new generation of decision support systems that will be able gather new knowledge from vast amounts of streaming data. I think that with a good mix of experience, fresh ideas, as well as rounds of unlearning and relearning, this hope is definitely achievable!

TACTICAL NETWORKING FOR THE REPUBLIC OF SINGAPORE NAVY

Integrated Knowledge-based Command and Control (IKC2) is vital in the Republic of Singapore Navy's (RSN) transformation into a networked 3rd Gen fighting force. It is a force multiplier that enables more to be achieved with less through the networking of naval assets both at sea and on shore.

TACTICAL NETWORKING FOR THE REPUBLIC OF SINGAPORE NAVY

Technological advances in wireless networking play a critical role in driving this transformation. DSO's research and development in the field of tactical Mobile Ad-hoc Networking (MANET) spans the design, development and validation of its suite of tactical MANET protocols for the RSN.

The design of the suite of tactical MANET protocols adopts a layered architecture approach. By adopting this modular approach, a complex networking problem is broken down into more manageable modules, allowing each layer to be independently designed, developed and upgraded. Similar to the Transmission Control Protocol/Internet Protocol (TCP/IP) model, this suite of tactical MANET protocols comprises four layers: the link, network, transport and application layers (see Figure 1).

Media Access Control (MAC) is a key function of the link layer that allows multiple nodes to share a common wireless transmission medium. The Time-Division Multiple Access (TDMA) protocol is a natural choice for tactical networking as it is robust in the dynamic MANET environment. However, it suffers from poor bandwidth utilisation when the network loading gets uneven due to its static bandwidth allocation. Bandwidth is wasted whenever a node is unable to fully utilise the allocated bandwidth in its assigned time-slot, even though there are other loaded nodes in the network. Furthermore, in the event of a light network load, a node still needs to wait for its assigned time-slot before it can transmit data, resulting in significant network access latencies. All these undesirable characteristics of the conventional TDMA protocol provided motivation to look for a better solution.

To better utilise the scarce radio bandwidth resources, DSO designed a MAC protocol that allows a node that is unable to fully utilise the allocated bandwidth in its assigned time-slot to dynamically re-allocate the unused bandwidth to a loaded neighbour. This is done via token-passing, as shown in Figure 2. In the event that the recipient of the token is unable to fully utilise the bandwidth in the same time-slot, it can 'token-pass' the unused bandwidth to another loaded neighbour. This token-passing process continues until all the bandwidth within the time-slot is fully utilised. The scheme adapts well to varying levels of traffic at each node and achieves better utilisation of the bandwidth than a conventional TDMA scheme.

Routing is a key function of the network layer that allows data packets to be exchanged seamlessly between any two nodes in a multi-hop network. For tactical networking, proactive routing protocols are preferred over their reactive counterparts due to their lower path set-up latencies. Proactive routing protocols can be further classified into Link-state (LS) and Distance-vector (DV) routing protocols. LS routing enjoys fast route convergence but suffers from high routing overheads as link state updates are regularly flooded throughout the network. Conversely, the routing overheads for DV routing are significantly lower but route convergence is slower as nodes only exchange distance vectors with their immediate neighbours. Hence, both the conventional LS and DV routing protocols are unsuitable for tactical networking using narrow-band radios.

Figure 1 Layered architecture approach

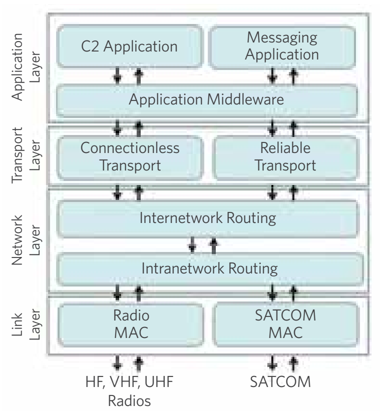
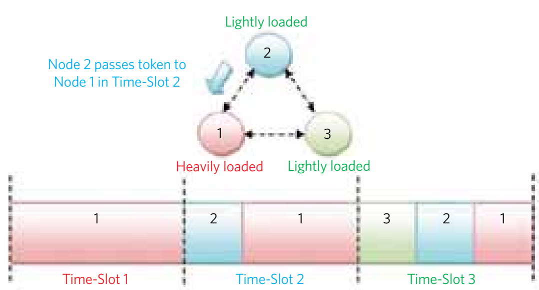


Figure 2 Token-passing within time-slots



Driven by the insight that a node communicates more frequently with neighbours within its 2-hops neighbourhood, and only occasionally with nodes further away, DSO developed a routing protocol that was inspired by how the eye of a fish works. The eye of a fish captures pixels nearer its focal point with higher resolution, and pixels further away with lower resolution (see Figure 3). The scheme which uses a hybrid of LS and DV, achieves fast route convergence for destinations within a node's 2-hops neighbourhood and yet, significantly reduces routing overheads. This is due to the fact that routing updates are no longer regularly flooded throughout the network, which is achieved by using compression techniques to reduce the size of routing update packets. All these result in a very light-weight routing protocol that is suitable for tactical networking using the narrow-band radios.

End-to-end reliability is a key function of the transport layer that allows any source-destination node pair in the network to communicate reliably. Traditionally, in wired networks, it is sufficient for only the source to retransmit messages that it did not receive acknowledgments for. However, due to the unreliable nature of wireless links and the dynamic nature of MANETs, this technique of ensuring end-to-end reliability is no longer adequate. For example, in a typical wireless environment, the probability of a successful transmission per-hop of a larger message packet is 0.7, while such a probability of a smaller acknowledgment packet is 0.9. Therefore, in a 3-hops topology (see Figure 4), the overall probability for the source to successfully relay the message to the destination and vice-versa is merely 0.25, which results in poor message completion rates. This is not acceptable for tactical MANETs.

A reliable transport protocol was designed by DSO to achieve good message completion rates in a dynamic multi-hop environment. With a change in mindset, instead of only allowing the source node to retransmit messages, the proposed transport protocol will also allow all intermediate nodes to do the same intelligently, analogous to the robust store-and-forward technique commonly used in dynamic environments. By using intelligent caching and retransmissions at intermediate nodes to ensure hop-by-hop reliability, end-to-end reliability with good message complete rates can be guaranteed in a dynamic multi-hop environment. Furthermore, as lesser packet retransmissions are required to complete the two-way message-acknowledgment between the source and destination, precious bandwidth resource is conserved. This property makes it suitable for tactical networking using narrow-band radios.

Over the years, DSO has gained invaluable experience and also built-up an in-house capability to design and develop the RSN's suite of tactical MANET protocols. The entire protocol development cycle follows a methodical process which starts at the design phase, followed by the implementation phase and finally, the testing phase. The testing phase leverages on advanced network simulators like OPNET and actual hardware test-beds, so as to thoroughly test and validate the protocols before proceeding to harbour and sea trials. Moving ahead, DSO will continue to work closely with the RSN to better understand its evolving operational demands and strive to meet future networking needs.

Figure 3 LS and DV hybrid routing

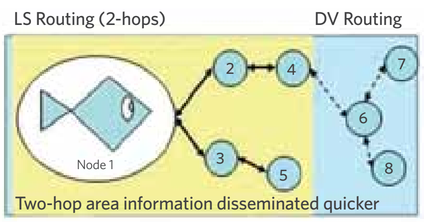
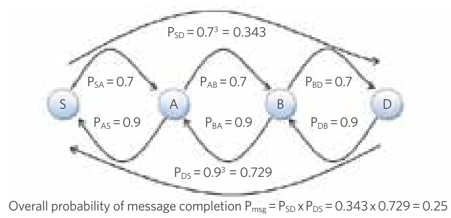
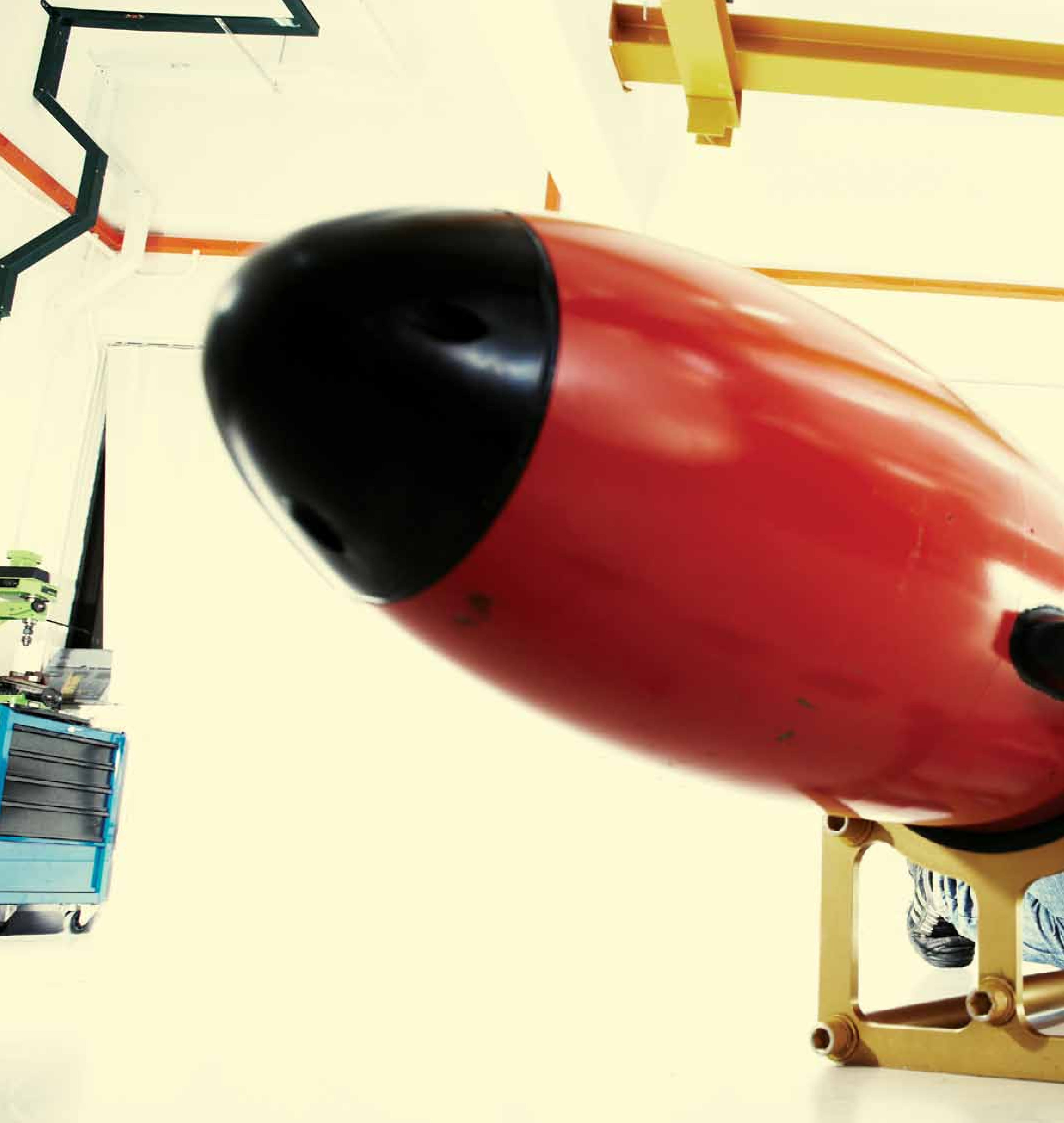


Figure 4 Probability of message completion in a 3-hops topology





AUTONOMOUS UNDERWATER VEHICLE TECHNOLOGY

The rapid advances in Autonomous Underwater Vehicle (AUV) technologies have enabled the use of such platforms to perform demanding tasks for the offshore industry, as well as for the scientific and military communities.

AUTONOMOUS UNDERWATER VEHICLE TECHNOLOGY

AUVs can be employed as a cost effective and safe alternative to the current manned Mine Counter Measure Vessels (MCMV) and future Unmanned Surface Vehicle (USV). These platforms use a towed sonar system to perform underwater surveying along busy shipping lanes. One of the advantages of an AUV over MCMVs or USVs is its better mobility, leading to greater survey flexibility and quality. For example, the AUV's ability to cruise close to the seafloor and survey its profile from a distance of mere metres, can provide operators with more detailed information to assess detected objects. This advantage positions the AUV as an attractive alternative solution to meet underwater surveillance requirements. DSO's Underwater Programme (UWP) was initiated in the early 2000s to design, develop, integrate, test and evaluate autonomous underwater systems. An overview of a DSO-developed AUV, the MEREDITH 250 (M250) is depicted in Figure 1.

MEREDITH 250 AUV System

The M250 comprises a suite of modules. One of the two main modules required for performing waypoint navigation is the HOST module. This module controls the overall state of the M250. Based on the mission requirements, the HOST module sequences and synchronises the execution of the M250 tasks that correspond to the mission execution. The second main module is the Guidance, Navigation and Control (GNC) module. It accepts reference trajectory inputs from the HOST module, and navigational data provided by the in-house customised navigation system. The M250 mobility controller residing in the GNC module uses the navigational data to maintain the platform's stability. The GNC module outputs commands to the AUV actuators to achieve precise trajectory tracking in the presence of varying sea currents. The M250 has been integrated with various sensors/payloads and has been successfully demonstrated at sea with a Side Scan Sonar (SSS) and Forward-looking Sonar (FLS) as its mission payload.

Side Scan Sonar System

The SSS system was incorporated in the M250 to enable it to perform sea-bottom surveys. The acoustics returns of the SSS are processed into an image similar to an aerial photograph. Both processing and recording of images are performed in real-time. Figure 2 depicts an image of a ship wreck captured by the SSS system. An AUV with a SSS payload would be useful in area search operations. This is because the AUV can be programmed to automatically survey a given area and provide the image and location of detected objects for further investigation.

Forward Looking Sonar System

In order to navigate safely, the M250 is equipped with a high resolution, multi-beam FLS to acquire a real-time update of the perceived environment. This enables the M250 to perform feature based navigation and avoid obstacles that arise in its programmed path. Obstacles Avoidance (OA) is important when operating in shallow coastal waters where potential hazards such as wrecks and natural outcrops are prevalent.

Challenges in Navigation for Obstacles Avoidance

To achieve a reliable OA capability, the ability to identify unknown obstacles while discarding false returns and noise is important and extremely challenging. The crux of the problem is to correctly detect potential obstacles from the FLS image. As the beamformed image from the FLS is generally noisy, filtering is required. The OA detection algorithm employs both spatial and temporal filtering to detect potential obstacles. Detected obstacles are then synchronised or time-tagged with the vehicle navigation inputs.

Figure 1 An overview of the MEREDITH 250 AUV

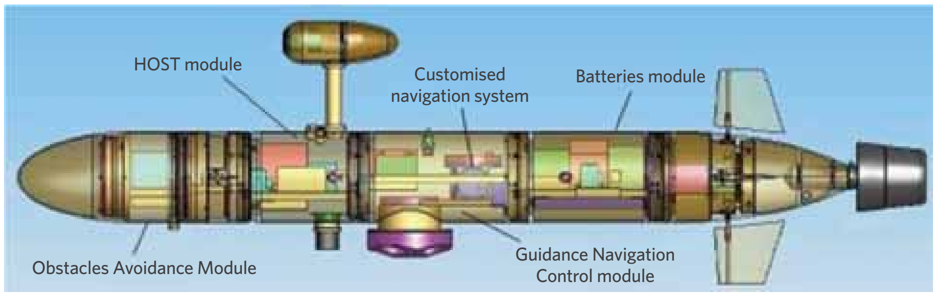
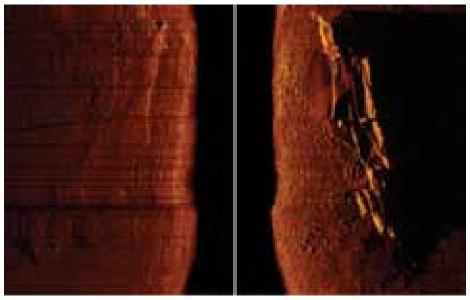
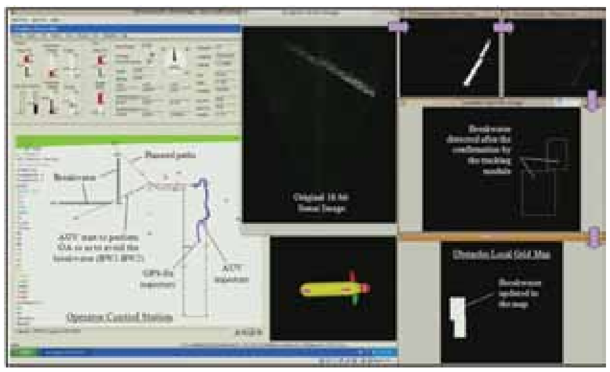


Figure 2 A processed Side Scan Sonar image of a shipwreck (right)



The spatial filtering algorithm consists of an image processing algorithm that extracts obstacles from each sonar frame in sync with its computed two-dimensional positions based on: (i) *median filtering* to reduce noise and remove outliers; (ii) *morphology* to locate objects and boundaries in the filtered image; and (iii) adaptive thresholding to segmentise the hotspots and the background. Spatial filtering obtains the highlighted hotspots of each frame based on the detection constraints set. However, random noise or unwanted hotspots such as seabed rocks will still be present. Every frame has a different noise level due to the dynamic motion of the AUV mounted with the FLS. Moreover, sea waves or underwater currents are constantly fluctuating and alter the image return strength of the FLS. Therefore, temporal filtering is essential to further filter each output frame from the spatial filter so that noise and outliers are eliminated over the entire frame run. The temporal filtering algorithm comprises a Kalman tracking filter to effectively remove unwanted hotspot data over multiple frames, and tracks the obstacles by a dynamic state with elements of two-dimensional Earth positions and velocities. The implemented tracker is a recursive multiple target tracking system consisting primarily of: (i) *track association* to pair the most possible target measurement of the current sampling period to the existing target track; (ii) *kalman filtering* for updating of the current track position; and (iii) *track management system* to manage the tentative, confirmed and deleted tracks. Spatial and temporal filtering can therefore effectively extract and confirm the presence of obstacles with position and velocity information within the field of view of the sonar. The false alarm rate arising from such an OA algorithm will be greatly reduced as compared to a detection system that does not consider the dynamics of the AUV.

Figure 3 Operator control station interface showing a playback of the obstacle detection and avoidance process during a sea trial



Obstacles Representation

The obstacles that are "confirmed" by the tracker are updated into a Local Grid Map (LGM). Generally, the LGM attempts to "remember" obstacles detected in earlier frames but may not be detected in the current frame for a considerable amount of time. The rationale for incorporating this "short-term memory" is because the FLS only has a fixed 45° horizontal field of view (FOV). This narrow FOV can considerably affect path planning stability. For instance, when performing OA, obstacles may "disappear" and "re-appear" in the sonar FOV. This results in a jerky avoidance path as any detected obstacles have to be avoided. In the worst case scenario, obstacle avoidance may not be successful. To prevent this, and achieve more successful obstacle avoidance, a solution was implemented to allow the AUV to have some form of short-term memory when avoiding obstacles. In other words, the AUV will "remember" the last seen obstacle by updating the LGM with the obstacle's location and velocity (whether static or moving) while it is performing the avoidance action. This is similar to the decision-making process that human beings perform when avoiding obstacles. A car driver avoiding or over-taking a static or moving car is a good example to illustrate this methodology. As the driver overtakes a car, he or she maintains a memory of the position of the car as it passes out of the driver's FOV. The duration of the memory is implemented using the tracker output, which "remembers" the last seen obstacle location and velocity for a predefined duration. The confirmed obstacles in the LGM are subsequently sent to the navigation controller so that it can plan a safe trajectory for the AUV. Such a capability provides the AUV with the ability to perceive, interpret and act upon unforeseen changes in the environment. Consequently, this facilitates the AUV in adjusting to changes in mission goals/status and re-planning based on risks and "traits" weightings. Simulation studies and sea trials were conducted to verify the implementation as depicted in Figure 3.

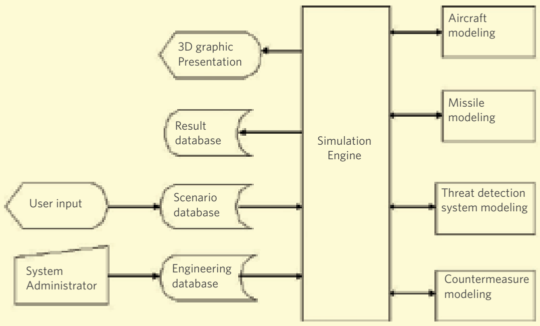
ELECTRONIC WARFARE

Electronic Warfare (EW) is an important capability which DSO and the SAF and have jointly built up over the years. High-value assets, such as aircraft, require highly effective countermeasure solutions for protection against missile threats. Many of these threats are equipped with Infrared (IR) sensors to detect and track the heat signature emitted by their target of interest.

ELECTRONIC WARFARE

Figure 1 EW scenarios in ground-to-air combat

Figure 2 Block diagram of an EW simulation software tool



The IR seeker typically has a very narrow field of view (FOV) in the order of a few degrees. It is designed with processing capabilities for autonomous target acquisition and tracking. Flares (infrared decoys) are one form of countermeasure widely used against the heat-seeking missiles. These are solid pyrotechnics that are dispensed in response to possible missile attacks.

DSO's Capabilities in Developing Operational EW Solutions

The capability that directly supports the development and delivery of operational EW solutions begins with research on the threat. To support the research, software simulations are carried out to study, develop and verify effective countermeasure against the threat. In particular, DSO has developed and delivered one such EW simulation software to support the Republic of Singapore Air Force (RSAF) in the evaluation of EW techniques against potential adversaries.

EW Simulation Software Tool

Software simulation is a practical and cost-effective method of examining the protection of military platforms against missile attacks. It provides the capability of examining the effect of a missile closing in dynamically on a platform. The assessment of dynamic properties is vital in the effective analysis of flare countermeasures, as the response of the threat at various points in its flight is highly dependent on its relative geometry to the moving target platform, and the separating flares.

The software simulation that DSO developed comprises individual models that are integrated to generate the desired outcome. A block diagram of the individual models is shown in Figure 2.

The main component models of an EW software simulation tool are described below:

1. Missile Model

This model determines the performance of a missile body in flight. It represents a typical kinematic model of missile dynamics and aims to replicate the missile flight dynamics by considering rocket motor thrust, guidance and auto-pilot. The guidance comprises the seeker's gimbals model and the proportional navigation algorithm to generate commands for the auto-pilot. The auto-pilot will translate acceleration commands into fin, wing and canard deflections within the considerations of the airframe.

This module also comprises known tracking algorithms of a missile. The missile seeker will perceive a different scene at each instance. Based on a collection of decision rules, this model replicates the response of the seeker to its perceived scene, generates the seeker's desired line-of-sight (LOS) and determines the final achieved LOS. Thus, it represents the behaviour of the missile seeker under different conditions of irradiance of the target and the flares perceived within the seeker's FOV.

2. Countermeasure Model

This is a model to specify the spectral signature of different flares and the dispensed trajectory of the flare. The flare's trajectory is determined based on its initial condition which is the status of the aircraft before the flare was dispensed. The velocity of the ejected flare and its dispensed aspect determine the rate of separation from the aircraft. The model also has a deceleration module that analyses the effect of air flow drag and gravity. The final signature value of the flare is generated to represent the IR signature profile (intensity vs time), taking into account of the effect of flare altitude, and the velocity of air across the flare at each instance in the simulation.

3. Aircraft Model

The aircraft model generates the position of the target for the missile model. It uses a kinematic model and its flight path can be specified through waypoints. The manoeuvre of the aircraft can be specified to evaluate the effectiveness of different flight tactics within the flare dispensing period. This model also calculates the IR signature of the aircraft at different aspects viewed by the seeker. The main factors include the calculation of the IR signature for the waveband of interest, the source intensity of the aircraft, its operating power setting or Exhaust Gas Temperature (EGT), and the view aspect angle reference from a missile's position.

4. Atmospheric Propagation Model

When computing the IR signature within the countermeasure model and aircraft model, the atmospheric effect on the transmittance of IR signature has to be accounted for. An empirical formula can be derived based on MODTRAN data to estimate the attenuation in different situations. The factors included in the computation are wavebands of interest, look angles of sensor to object, slant ranges between the sensor and object, and the altitude of objects.

5. Three-Dimensional (3D) Graphic Presentation

The generated results can be shown in 3D mode to enhance the efficiency when analysing outcomes. The view perceived by the threat displays the interaction of aircraft and flares, and can also reveal the moment when the missile shifts its LOS. The values of the simulation can be shown in graphical plots for detailed analysis of each instance in the simulation.

Operational Support and Delivery

DSO has delivered operational EW solutions and supported the RSAF on several occasions to validate the effectiveness of solutions in real operational environments through various Operational Training and Evaluation (OT&E) trials prior to their operational missions. These missions include the United Nations peace support for multinational reconstruction efforts in Iraq.

Supporting Operations

Beyond the battlefield, DSO's buildup of indigenous expertise has enabled the development of technologies that support the Singapore Armed Forces' (SAF) peacetime operations and systems acquisition processes. DSO's expertise and technologies have also played critical roles in supporting other agencies to solve national level issues.

CHEMICAL AND BIOLOGICAL DEFENCE RESEARCH

Ever since chemical warfare demonstrated its horrific potential to cause massive loss of human life during the First World War, the threat posed by this scourge of human ingenuity has ebbed and flowed but never disappeared completely. By the mid 1990s, chemical weapons had evolved from its use on the battlefield, into one that could be employed by terrorists across national boundaries to cause both physical and economic damage. Its use was amply demonstrated during the Tokyo subway Sarin gas attack in 1995 by the Aum Shinrikyo cult.

Closer to home, our military personnel can potentially be exposed to a variety of biological threats. These range from tropical infections such as malaria and melioidosis; common infections such as influenza and diarrhoea; highly transmissible diseases such as pandemic influenza; emerging infections such as Severe Acute Respiratory Syndrome and Nipah; or potential bioweapons such as anthrax and botulinum toxin.

Over the past two decades, DSO has built up an indigenous expertise in chemical and biological defence, and possesses a suite of capabilities that enhances our nation's defence against such threats. The following pages highlight DSO's status as an OPCW (Organisation for the Prohibition of Chemical Weapons) Designated Laboratory; our work in the development of a universal decontaminant; and our efforts to support the SAF and other national agencies in the detection and identification of infectious disease outbreaks.

Also highlighted in other parts of this book is DSO's work in the development of therapeutic antibodies (page 104); novel countermeasures for viral and bacterial infections (page 110); and Scentmate – a portable nerve agent diagnostic kit (page 172).

DSO: AN OPCW DESIGNATED LABORATORY

Ratified by Singapore in 1997, the Chemical Weapons Convention (CWC) aims to eliminate an entire category of weapons of mass destruction by prohibiting the development, stockpiling, retention, transfer or use of chemical weapons.

DSO: AN OPCW DESIGNATED LABORATORY

To implement and achieve the aim of the CWC, the Organisation for the Prohibition of Chemical Weapons (OPCW) was formed that same year.

In March 2003, DSO was designated by the OPCW as one of the select laboratories in support of the OPCW Verification Regime. Performing competently through regular OPCW Proficiency Tests, DSO is the only laboratory in the Southeast Asia and Oceania region, and one of 21 laboratories worldwide, that has been given designated status. This status places DSO in the same league of elite laboratories from countries such as the United States, United Kingdom, France and Finland that support the verification work of the OPCW. In joining this league of elite laboratories, DSO continues to further Singapore's commitment to the non-proliferation of chemical weapons by maintaining an operationally ready, OPCW-designated verification laboratory that is able to provide unequivocal confirmation of the presence or absence of chemical agents and its related chemicals.

Beyond the OPCW Proficiency Tests, DSO has also participated actively in the First Proficiency Test for the detection of Ricin Toxin, as well as confidence-building exercises to develop international proficiency tests for the detection of chemical agents and the verification of biomedical samples.

DEVELOPMENT OF A UNIVERSAL DECONTAMINANT

The first Chemical Warfare Agent (CWA) decontaminants available in the market were formulated to remove CWAs from military vehicles coated with polymeric paints. These decontaminants have strong extracting properties which can damage numerous materials that they come into contact with.

DEVELOPMENT OF A UNIVERSAL DECONTAMINANT

In the early 2000s, less aggressive decontaminants started appearing in the market. However, tests carried out by DSO have found them to be effective towards only certain classes of CWAs. Moreover, decontaminants that work on chemical agents are not effective against Biological Warfare Agents (BWAs). These factors were the impetus for DSO's development of a universal (i.e. effective against all classes of CWA and BWA) and non-aggressive decontaminant that would significantly simplify first responder operations. Furthermore, an in-house developed decontaminant would enable for the manipulation of the formulation so that future emerging threats can be countered.

In 2003, the first generation of DSO's decontaminant, Demul-X, was formulated. Demul-X was a water-in-oil emulsion containing oxidising agents as the active ingredients. In 2011, a second generation of the DSO decontaminant, ME21, was developed and extensively tested. ME21 is based on another group of oxidisers dispersed in an oil-in-water microemulsion. A microemulsion is a thermodynamically stable, isotropic mixture of water, organic solvent and surfactant. The organic solvent is dispersed within the aqueous continuous phase.

CWAs, being more organic in nature, are dissolved within the solvent phase, whereas the active oxidisers are dispersed in the aqueous layer. Reactions occur at the organic-aqueous interface, and the oxidisers function at this interface to neutralise the CWA while killing any BWA present. The organic droplet in ME21 is also smaller (<0.1μm) compared to that of the macroemulsion of Demul-X (~10μm). This leads to an enhanced reaction rate. As ME21 is thermodynamically stable, the microemulsion forms almost instantaneously upon mixing the liquid components. This is unlike the macroemulsion of Demul-X, which is kinetically stable, and thus requires a specific stirring procedure.

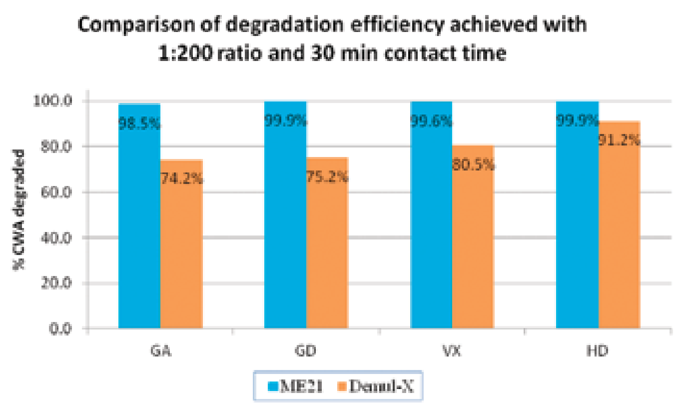
The main challenge faced in the development of Demul-X and ME21 was the need to balance various contradicting factors to achieve an effective decontaminant. One such challenge was the different requirements resulting from different reaction mechanisms of nerve and sulphur mustard (HD). Similarly, the removal of CWAs and BWAs require conflicting conditions. CWAs are usually organic and thus react better in an organic medium. BWAs on the other hand, require the presence of water for it to be effectively killed. A compromise on the aqueous-organic ratio was therefore required to achieve the effective decontamination of both CWAs and BWAs.

Another example of a conflicting requirement is the extraction capability versus the non-aggressiveness and ease of removal of the decontaminant. CWAs tend to penetrate paints and materials. A solvent component was therefore formulated into the decontaminant to enhance the extraction of penetrated CWAs. However, a solvent with higher extracting capability is usually more aggressive, and more difficult to remove by simply washing with water. Thus, ME21 makes use of an emulsion-based formulation, with carefully selected solvent-surfactant components, to reduce the aggressiveness of the decontaminant, and improve its ease of removal with water at the end of the decontamination task.

A comparison of the degradation capability between ME21 and Demul-X shows that ME21 is able to degrade at least 99% of Tabun (GA), Soman (GD), HD and VX within 30 minutes (see Figure 1). ME21 also gave an effective 9-log kill for *Bacillus anthracis*.

Currently, DSO is preparing for a pilot scale demonstration, as well as exploring other applications for ME21.

Figure 1 Comparison of degradation capability between ME21 with Demul-X



CLINICAL DIAGNOSTIC SERVICES LABORATORY

During an infectious disease outbreak, timely detection and identification of the causative pathogen is crucial for implementation of appropriate treatment, as well as preventive measures. Such measures include the need for isolation, quarantine and vaccination to curb the outbreak.

CLINICAL DIAGNOSTIC SERVICES LABORATORY

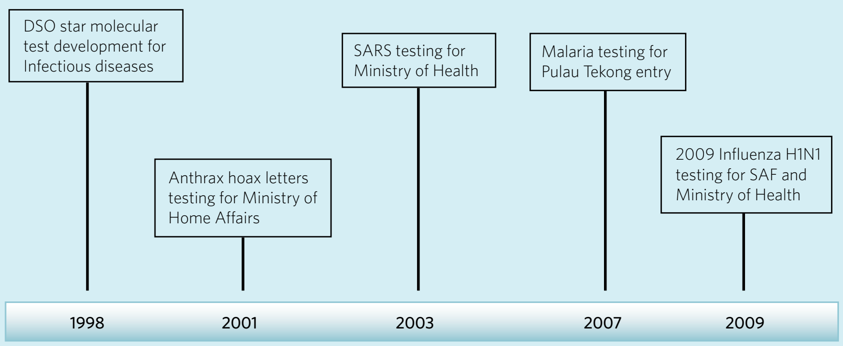
DSO has developed and improved the SAF's capability to detect and identify infectious disease pathogens using molecular biology techniques such as real-time polymerase chain reaction (PCR). The gold standards of culture and biochemical identification used in hospitals today were too slow and laborious (2-5 days) to be used by the SAF to execute preventive measures quickly. In the year 2000, the field of PCR diagnostics was in its infancy, but DSO foresaw that it had the potential to change the way infectious disease investigations were being conducted, rendering it more accurate while shortening the time frame drastically from two to five days, to three to five hours. The drastic reduction in time frame needed to investigate infectious diseases is important for the SAF. This is because close contact of numerous military personnel during training and deployment means that infectious diseases can potentially spread very much more rapidly compared to the spreading of such diseases within the general public.

Since 2000, DSO's researchers have responded to various SAF outbreak investigations and national level investigations such as the testing of anthrax hoax letters for the Singapore Police Force in 2001; the Severe Acute Respiratory Syndrome outbreak testing work for the Ministry of Health in 2003; the H5N1 avian influenza preparedness work for the Agri-Veterinary Authority of Singapore; and most recently, the 2009 Influenza A H1N1 outbreak investigation for the SAF and the Ministry of Health.

DSO's researchers also obtained ISO 15189 accreditation for the conduct of molecular diagnostics, and they continue to take part in several external proficiency test programs to ensure their proficiency level is maintained. In addition, the laboratory continues to develop molecular diagnostics for various new and exotic disease pathogens, as well as assists the SAF in infectious disease outbreak investigations. Continuous development of diagnostics for new pathogens is necessary as air travel could very quickly bring a new infectious disease across the world to Singapore. Examples of new pathogens and outbreaks from the last few years include the 2009 Influenza A H1N1 pandemic, the 2010 cholera outbreak in Haiti and the 2011 *Escherichia coli* O104:H4 outbreak in Europe.

Lastly, DSO also plays an important role in supporting the SAF through the detection and screening of malaria in Pulau Tekong. This is done by conducting malaria screening using real-time PCR, which is more sensitive compared to conventional microscopy. Malaria diagnosis via conventional microscopy is laborious and requires a highly skilled operator. In addition, asymptomatic cases of malaria, as well as those harbouring low levels of parasites may be missed if screened using microscopy. PCR diagnostics is able to effectively detect such individuals, thus enabling authorities to prevent malaria-infected personnel from entering Pulau Tekong.

Figure 1 DSO's capability buildup and support to the SAF and other national agencies since 1998



DEFENDING AGAINST UNSEEN THREATS

Dr Loke Weng Keong Programme Director DMERI@DSO Years in DSO: 15	**Andrew Chia** Member of Technical Staff DMERI@DSO Years in DSO: 1	**Dr Ma Yifei** Programme Manager DMERI@DSO Years in DSO: 10

Chemical warfare has been around since the turn of the century, and as these unseen weapons get deadlier, our defence against them has to be ever stronger. Dr Loke Weng Keong, Dr Ma Yifei and Andrew Chia contribute their expertise in the analysis and development of such defences, so that they can make a critical difference to our nation's safety and security.

So tell us, what was the bait that got you started in this field?

Andrew Chia (AC): When I joined DSO, I was presented with an opportunity to learn about the field of Personal Protective Equipment, and how to evaluate such equipment for their protective efficacy. It was amazing to know that there are so many different kinds of protective equipment out in the market! From gas masks and suits, to chemical overboots, the range is quite astounding. The fundamental principles behind the development of such equipment are really intriguing for me, and I guess this was the bait that got me hooked!

Yifei (YF): Back when I was doing my post-graduate studies at the National University of Singapore (NUS), my supervisor was working on a collaborative project with DSO, which was quite similar to what I was doing for my doctorate. Later, when I realised that DSO needed people to work on their project, I seized the opportunity and have never looked back since.

Weng Keong (WK): When I joined DSO, my first boss gave me the freedom to work on my own, within the defined boundaries of the assigned projects. As pioneers building everything from scratch while trying hard to meet the operations requirements, there was a strong environment of entrepreneurship as well as the need to be adaptable. You needed to have a pioneering spirit. The environment and spirit attracted and excited me to keep going despite the challenges I faced from time to time.

Chemical defence can be considered quite a hazardous area to research into. What were some of the challenges at work that you had to overcome?

AC, YF and WK: Luckily for us, no physical harm to overcome!

AC: I've only been with DSO for slightly over a year, so there's a lot of learning to do. I also had to pick up the necessary skill sets within the shortest time possible so that I can meet project deliverables. Luckily, I work with great colleagues who have a wealth of experience in their respective fields of research – people like Weng Keong and Yifei – who are always willing to offer their guidance. There's much to learn from them and no time to waste!

YF: For me, the greatest challenge is in understanding operational requirements and finding technological solutions that meet or even exceed these requirements. These days, research is getting more interdisciplinary and expertise from one source is often not enough. We need to seek and integrate knowledge and expertise from different areas to be able to offer an effective solution. This is easier said than done because working with people of different scientific or engineering backgrounds means that they have different ways of solving certain problems and have different perspectives. Sometimes they even speak their own scientific or engineering lingo!

WK: One example of a challenge would be the transiting of the Scentmate, a portable nerve agent diagnostic kit, from the innovation stage to the application stage. This umbrella of a challenge covers other challenges within, ranging from technical innovation and co-operation with industry partners, to transiting the technology into a practical field testing tool and maintaining the user's interest over the years!

Overcoming those challenges must have been truly satisfying. Moving forward, what's next on the agenda for you?

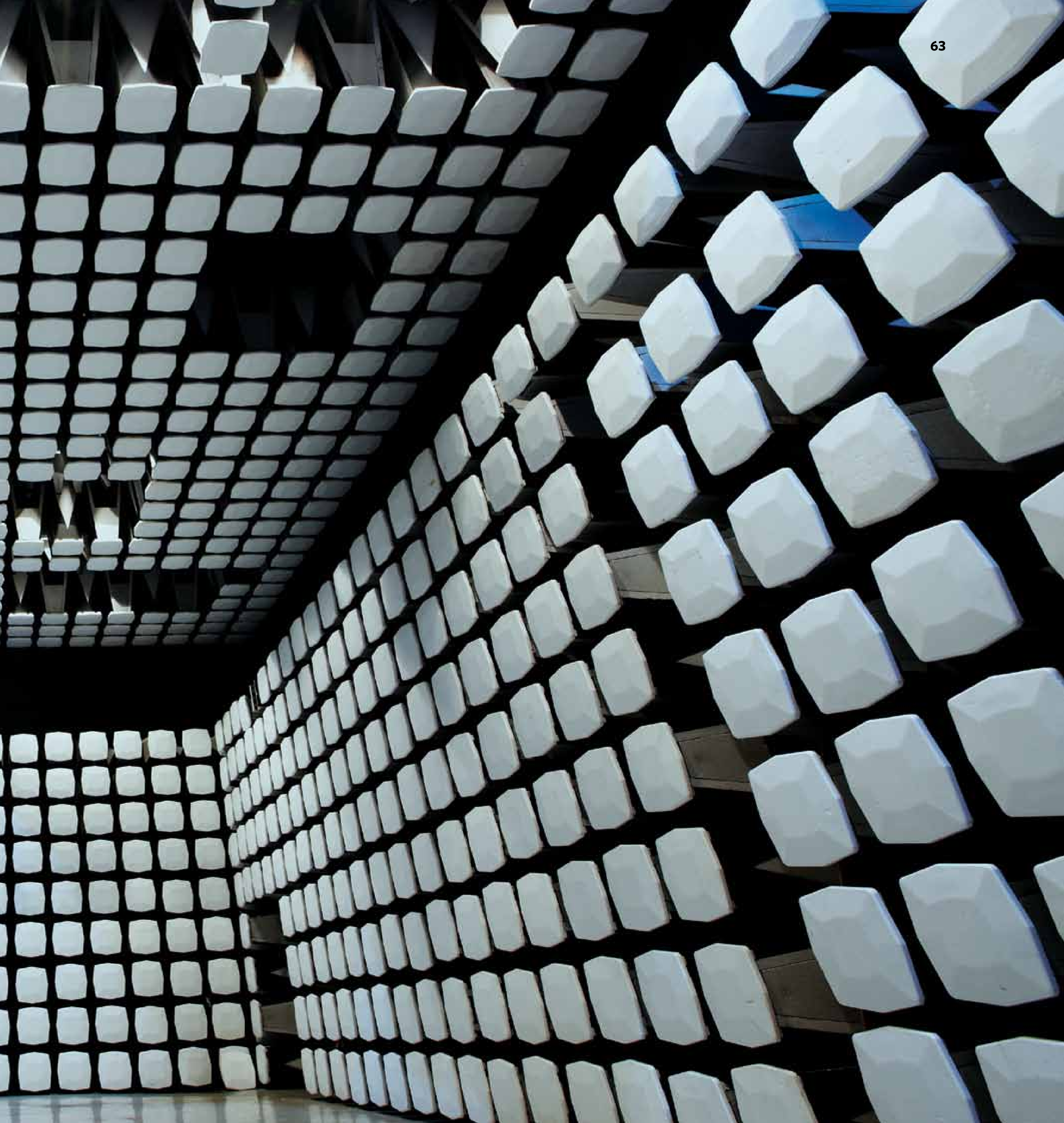
AC: I hope that in future, we can look into how we can modify products which were designed and manufactured overseas to suit the Singapore climate. However, this vision cannot be achieved without knowing what's happening out in the field. Hence, with a better understanding of our soldiers' needs and the kind of operations they're involved in, we will be able to enhance their operations with DSO's technology!

YF: Over the years, we've been the point of contact for the SAF and other agencies for chemical and biological related matters. Currently, we're moving in the right direction through various training programmes and the development of various in-house analysis tools that are customised for the local environment. Through these efforts, I hope that we can continue to build on our capabilities in threat analysis to better defend against chemical and biological threats, and be recognised as experts in the field.

WK: To be able to establish DSO's Chemical, Toxins, Radiological and Nuclear (CTRN) defence capability so that DSO becomes a respected national authority in CTRN defence matters, both locally and internationally. I also hope to make many more impactful contributions to our country's defence capabilities, either through my research work, or the effort of the teams that I have the privilege to work with. To me, CTRN also stands for Communication, Trust, Respect and Nurture, which are the values through which my vision can be achieved.

ELECTROMAGNETIC INTERFERENCE AND COMPATIBILITY

DSO started looking into Electromagnetic Compatibility 30 years ago with the setup of an EMC Test Centre to certify military electronics to meet Mil-Std 461C - the military standard for the control of Electromagnetic Interference for subsystems and equipment.



ELECTROMAGNETIC INTERFERENCE AND COMPATIBILITY

The History

On 4 May 1982, the British HMS Sheffield was sunk by an Exocet missile fired from an Argentinian Super Etendards aircraft. The HMS Sheffield was a Type 42 destroyer equipped with sensors and missiles to defend against missile attacks. However, it did not detect the incoming aircraft nor the missiles until it was too late. An account of the event given in the Royal Navy Memories states that "at that precise moment, her satellite communications terminal was in use and that prevented the onboard Electronic Support Measures (ESM) equipment from operating." In layman terms, this means that the transmission from her satellite communications terminal interfered with the operation of the ESM equipment, thus affecting its ability to detect the incoming aircraft and missiles at a longer range. Such interference is known as Electromagnetic Interference (EMI), and the design aspect to reduce EMI is called Electromagnetic Compatibility (EMC).

Since the setup of the EMC Test Centre, DSO has built up its expertise in EMI testing, troubleshooting and prediction, as well as EMC design. Other than providing consultancy support to the SAF, DSO has supported numerous projects that range from in-house system/platform design and integration, to combat systems and platform acquisition projects managed by the Defence Science and Technology Agency.

EMC Design

The Electromagnetic Environment (EME) on a naval platform is severely congested due to the large number of high power transmitters onboard. This congestion also poses very serious EMI issues due to numerous broadband receivers onboard. An example was the design and installation of a communication system where the antennas faced direct radiation from a high power surveillance radar, and its transmission interfered with other electronic systems located nearby. To ensure EMC, we first worked with the antenna designer to shape the antenna radiation pattern to minimise reception from the surveillance radar. Limiters and high power handling filters were designed into the Radio Frequency (RF) front end to attenuate the RF signal entering through the antenna. Shielding of the electronics was incorporated to prevent strong RF signals from coupling into the circuitries. To minimise RF interference to other electronic systems, careful positioning of the antennas and the design of the shielding structure greatly attenuated the transmitted signal entering the receivers of these electronic systems.

Since the setup of the EMC Test Centre, DSO has built up its expertise in EMI testing, troubleshooting and prediction, as well as EMC design.

Research Collaboration

To support the research and development effort in EMI effects and EMC design for both military and commercial equipment, DSO collaborated with NTU to establish the Electromagnetic Effects Research Laboratory (EMERL). EMERL operates a major EMI/EMC Test Facility, which comprises a Semi-anechoic Chamber (SAC) and a Reverberation Chamber (RC).

The SAC is a shielded room with its four walls and ceiling lined with absorbing materials. This allows for radiated testing inside the chamber with minimum reflections from the walls and ceiling. The shielded enclosure provides at least 100dB of shielding effectiveness from Direct Current (DC) to 40GHz, and is capable of supporting a wide range of research activities that range from low frequency magnetic field interaction of down to 30Hz, to radar and communication equipment testing of up to the Ka band. Due to a shielding effectiveness that is greater than 100dB the ambient noise level inside the chamber is almost undetectable. Hence, it can support extremely sensitive receiver testing or the detection of very weak emissions. At the same time, High Intensity Radio Frequency (HIRF) radiation can be carried out within the SAC to support susceptibility testing without affecting nearby electronics. The SAC has an internal dimension of 18m x 12.5m x 7.5m (height), and together with a 4m diameter turntable capable of taking a 20 tonne dynamic load (30 tonne static load), the SAC can support the testing of large objects such as commercial and military vehicles for advanced vehicular electronic research work.

The RC on the other hand, is a shielded chamber which is not lined with absorbing materials. The reflections from the metallic walls create resonances within the enclosure and produce high electric field strength. However, as fixed geometries can only support a limited number of resonances, two large metallic stirrers were installed to modify the boundary conditions in order to support resonances over a wider range of frequencies. Testing inside the RC is very different from that of in the SAC. In the SAC, an antenna is used to either radiate a fixed beam towards the test object, or to receive emissions from it within the main lobe of the antenna. Hence, SAC testing provides information on EMC weak spots at the expense of a long test duration. RC testing on the other hand, generates random but uniform fields within its working volume.

The working volume in the RC is defined as the space where the electric field within it is statistically uniform in amplitude, as well as random in angle of incident and polarisation.

Any test object placed within this working volume will then be subjected to a worst case illumination scenario. Similarly, emissions from the test object will be combined and received by the receiver through an antenna placed in the RC. The RC also has more than 100dB of shielding from DC to 40GHz, and is thus capable of supporting high radiated power and weak emission testing. The working volume of the RC is 7.6m x 4.75m x 3.9m (height), and is large enough to accommodate vehicular test objects.

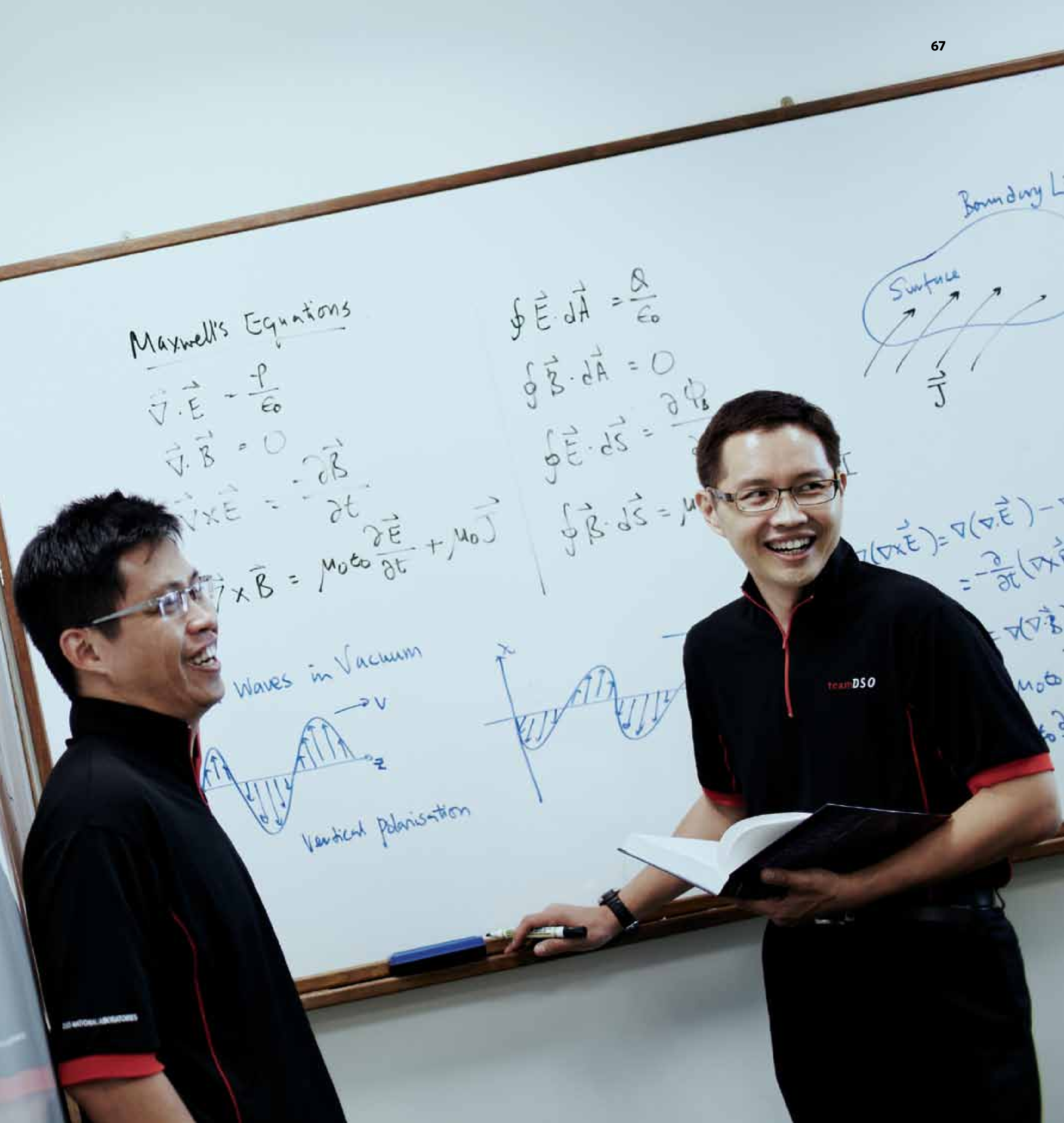
Besides being able to produce higher field strengths with lower input power as compared to the SAC, the other advantage of the RC is that the test duration can be greatly reduced as the test object and the test antenna are stationary. The test duration reduction is especially significant for test objects that require scanning over large azimuth and elevation angles. However, the RC suffers from one main disadvantage, which is the Lowest Useable Frequency (LUF). To produce uniform fields within the working volume, the RC must support many resonance modes at the test frequency. The LUF is typically about four times above the lowest resonance frequency of the chamber. The RC in EMERL has an internal dimension of 12.5m x 8.5m x 6m (height) and its LUF is 80MHz.

Most military and commercial radiated susceptibility testing require the test objects to be tested down to 30MHz. To reduce the LUF down to 30MHz using the conventional mode stirring method, it is estimated that it will require an approximate increase of 27 times in volume.

DSO has collaborated with Supelec University in France, and developed the Multiple Antenna Stirring (MAS) technique that can lower the LUF down to 20MHz without increasing the chamber size. A patent for the MAS technique is currently being filed.

COMPUTATIONAL ELECTROMAGNETIC MODELLING

While Maxwell's equations describe macroscopic Electromagnetic (EM) fields perfectly, a closed-form solution is only achieved for canonical structures such as spheres and cylinders. However, military systems and platforms have structures that are complex and electrically large.


Maxwell's Equations
Waves in Vacuum
Vertical polarisation
Surface
teamDSO

COMPUTATIONAL ELECTROMAGNETIC MODELLING

Complex EM scattering, radiation and interference problems include large resonating cavities, full scaled complex structures at high frequencies, large periodic arrays, installed performance and system-system coupling. Full wave techniques such as finite element, moment, and time domain methods are derived to resolve the computational and mathematical aspects of modelling EM fields of large scale and complex systems in terms of accuracy and efficiency. Other methods such as asymptotic Physical Optics and Uniform/General Theories of Diffraction can be used in order to make computations faster. However, these methods are less accurate.

To solve a large and complex EM problem, the Domain Decomposition Method (DDM) technique was adopted. The DDM technique is a full wave CEM algorithm which allows a single large computation domain (e.g. a platform) to be broken into several smaller domains (e.g. sub-systems) to be solved independently while ensuring field continuities across the boundaries of the sub-domains. To achieve computation efficiency, the sub-domains are solved separately from each other. Results of the analysis are combined across the different sub-domains with mathematical coupling of the sub-domain solutions, to form a consistent full-wave solution for the single large domain. In this way, each sub-domain can be solved efficiently and optimally and later coupled together, thus making the solving of the large problem possible.

Large Scale Radiation Problem of Antenna Array Behind Dielectric Radome

The large scale radiation by a finite antenna array with radome is a challenging one for current commercial codes in terms of possibility, let alone efficiency. This is further complicated if the antenna element is of a non-trivial design.

Figure 1 shows a finite Vivaldi antenna array radiating within a dielectric radome. This single antenna-radome system can be broken up into sub-domains and solved by using the DDM technique. The simulated radiation results show the ingenuity and robustness of the DDM technique. Even though the problem was broken up into vertical sub-domains, the computed radiation fields, as shown in Figure 2, maintained their continuities across the boundaries as if it were simulated from a single large domain.

Such a capability serves antenna radiation characterisation of existing antenna systems onboard military platforms.

Figure 1 Antenna and radome problem setup for the Domain Decomposition Method

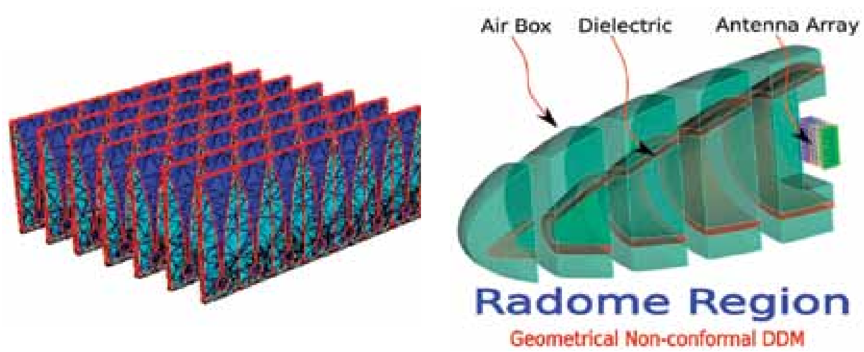


Figure 2 Computed radiation fields

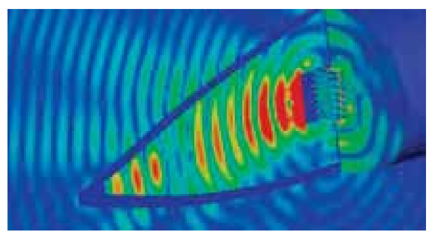


Figure 3 Domain splitting for long cavity structure

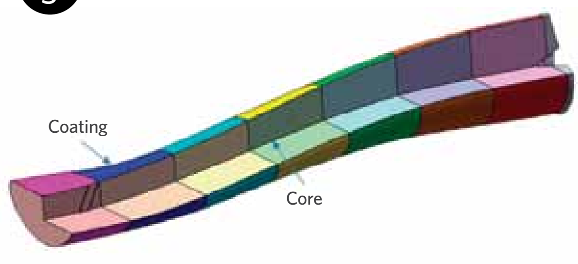


Figure 4 Total (scattered + incident) electric fields after computation using the DDM technique

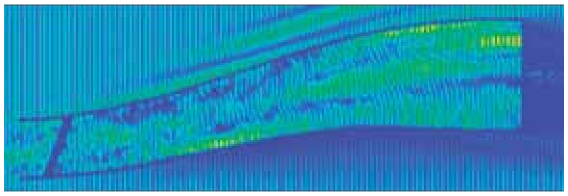
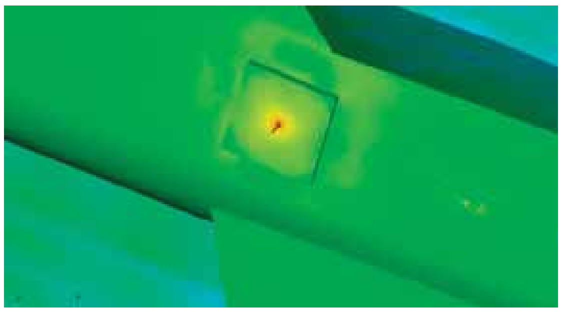
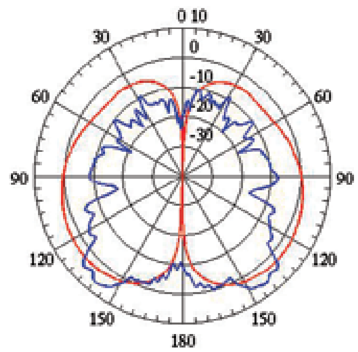


Figure 5 Monopole antenna mounted onto a large platform (above) and antenna radiation pattern (below)





Large Scale Scattering of a Deep Resonating Cavity

To date, the large scale scattering of a deep cavity at high frequencies remains one of the most challenging CEM problems faced by the international CEM community. Due to the resonance phenomenon innate to the problem, both matrix convergence and convergence speed become computationally challenging when the problem is attempted as a single domain. Asymptotic methods such as shooting rays or iterative physical optics techniques are typically used to generate approximate results.

However, the DDM technique solves this large scale problem in full wave. Figure 3 shows the successful use of the DDM technique to solve a cavity about 1,000 wavelengths deep.

Installed Antenna Performance on Large Platform

Installed antenna performance is a challenging multi-scaled problem because it involves electrically small antennas computed in the vicinity of electrically large and complex platform structures. While the single antenna may be solved using commercial off-the-shelf (COTS) CEM codes, the presence of structure changes the problem into a large scale one. Predicted performance of an installed antenna can be used by antenna and Electromagnetic Interference/ Electromagnetic Compatibility (EMI/EMC) engineers for antenna design, placement and coupling evaluation.

The antenna pattern of a monopole antenna mounted on the belly of a large platform generated using the DDM technique is depicted in Figure 5. Indeed, the simple radiation pattern of the antenna if it were in free space is greatly modified upon installation.


Physic
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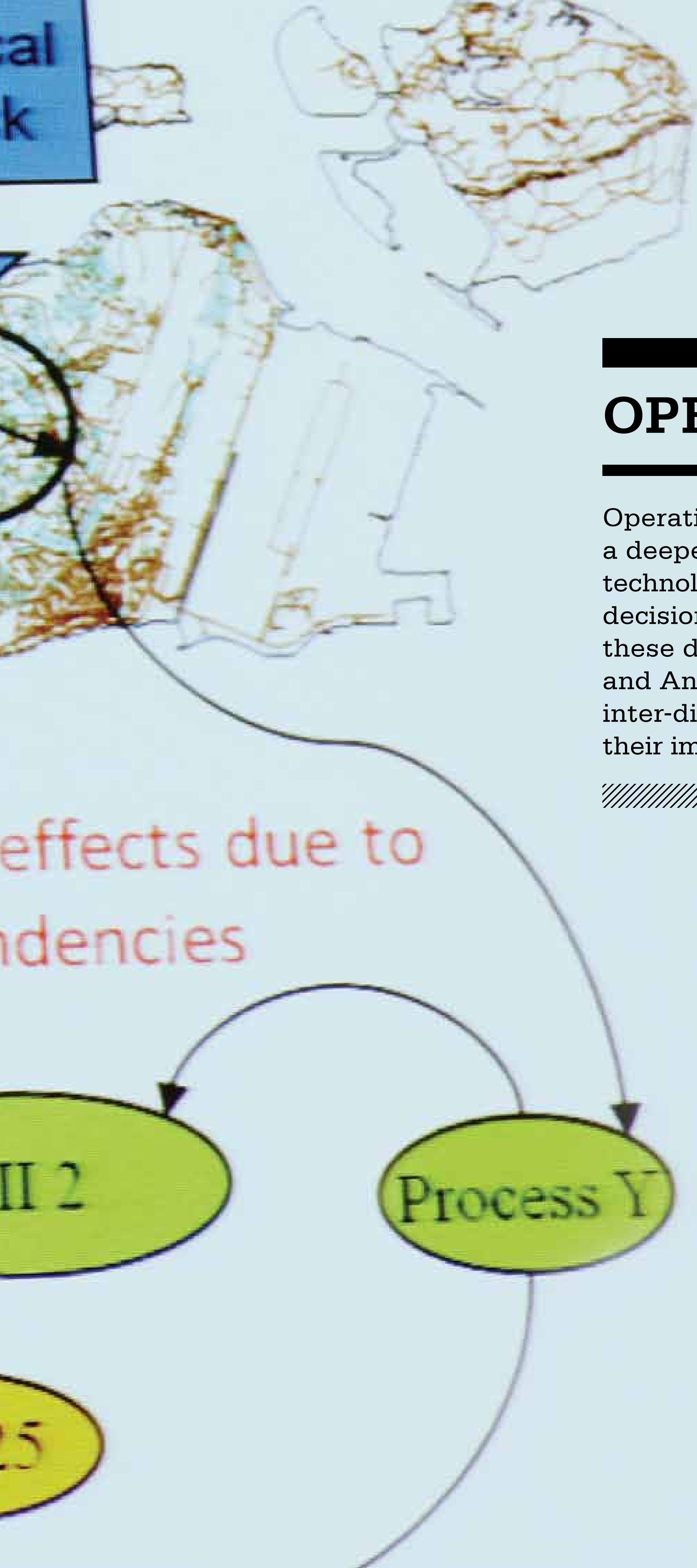
Cyber
Attack
EMP
Attack
CII 1
Cascading
interdepen
Site 12



OPERATIONS RESEARCH

Operations Research (OR) in DSO contributes to a deeper understanding of the operations and technologies related to defence systems. To support decisions in the acquisition and deployment of these defence systems, OR Modelling, Simulation and Analysis (MSA) techniques are used to study inter-disciplinary security-related problems and their implications.

OPERATIONS RESEARCH

MSA techniques can include analytical modelling, mathematical programming, computer simulation and data analysis. In particular, to address uncertainty, a combination of Design of Experiment (DOE) and Evolutionary Algorithm (EA) techniques are used to explore the unknown solution space. Given the limited experimental resources, this robust OR approach allows DSO to maximise the hypothetical scenarios which can be covered. Besides supporting the SAF's major acquisition decisions, our Operations Analysis (OA) studies also support Concept of Operations (CONOPS) evaluation, force-sizing, design trade-offs and tactics, and doctrine development. A successful OR study for the Republic of Singapore Air Force (RSAF) will be described below, followed by an OR study of a national security concern.

Application to Defence - NFRP OA Study

The Next Fighter Replacement Programme (NFRP) is an example of how OA studies support acquisition programmes. Under the NFRP, the RSAF intended to acquire a new multi-role fighter jet to replace the ageing A-4SU Super SkyHawks. DSO performed the technical and OA evaluations from 2001 to 2005. Together with counterparts from the Defence Science and Technology Agency (DSTA) and the RSAF, DSO supported the NFRP in its assessment of six candidate aircraft, which eventually led to the selection of F-15SG.

DSO's OA team worked with many technical Subject Matter Experts (SMEs) from other Divisions in DSO, DSTA and the RSAF to model the aircraft and its operational combat systems. The OA team also worked with operational SMEs, including RSAF fighter pilots and operational planners, on the tactical and operational inputs required for these combat simulations.

Our in-country developed air-to-air combat model enabled the detailed study of air combat capabilities of NFRP candidates with different aircraft configurations, mission roles and game plans in current and projected combat environments. These tactical fight outcomes were aggregated and used in a campaign level simulation model to determine and compare the relative contribution of each NFRP candidate to the overall RSAF mission.

The modelling and analysis capability built up in DSO to support the NFRP fighter acquisition decision has since been further enhanced to support the development and evaluation of other system concept studies for the Ministry of Defence and the SAF.

Application to National Security: Critical Infocomm Infrastructure - Surety Assessment (CII-SA)

DSO's OR team has also developed the methodology to conduct Critical Infrastructure Vulnerability Assessments (CIVA). Over the years, the team has studied the spread of a pandemic in the local population, the vulnerability of specific maritime trade-lanes, electrical facilities, internet infrastructure, power grid, as well as oil and gas supply chains. As an example, the OR team's work on the Infocomm Infrastructure is described below.

Being a "wired-up" modern city-state, Singapore's CII is essential to our daily lives. As part of the Singapore Infocomm Security Masterplan, the Infocomm Development Authority of Singapore (IDA) carried out the 2007 to 2009 CII-SA project.

DSO was appointed as the technical manager for this project. During project scoping, it was proposed that IDA also include information interdependency analysis as systems interdependency was important in connected networks. The DSO team was hence tasked to analyse the Critical Infocomm Infrastructure's (CII) interlinked dependencies and relative criticalities, and investigate the vulnerabilities of selected CIIs.

Figure 1 In-country air-to-air combat model

OPERATIONS RESEARCH

In the first part of the project, the IDA-DSO team had to liaise with more than ten Critical Infrastructure sector/sub-sector regulators and more than a hundred organisations with CIIs in the seven sectors.

Simultaneously, the team developed the methodology to undertake this project. The approach was a fusion of metrology, mathematical modelling, and multi-criteria decision analysis.

The team eventually identified a sizeable number of critical CIIs in Singapore's key sectors and ranked them by their relative criticality. The CIIs' static dependencies were also mapped. Quantitative impact assessments - or informed estimations for some of the more obscure CIIs - were done for all the identified CIIs.

In the second part of the project, DSO conducted detailed all-threats vulnerability assessments (VA) of a data centre and selected sites of a telecommunications company. DSO applied its consequence-based methodology to VA. Our physical security, cyber, Supervisory Control And Data Acquisition (SCADA), electromagnetic and weapon effect SMEs interviewed the CII operators, walked the grounds, conducted field measurements and computer simulations to uncover non-obvious vulnerabilities that could lead to the CIIs being disrupted, with the resulting undesired consequences.

Separately, another sub-team conceptualised and developed a CII interdependency model. This model can trace cascading disruptions due to information and communication dependencies. DSO analysts created the hierarchical, infocomm-based, service-oriented concept, supported by assets and telecommunications. This allows for an impact forecast given a service disruption, which could be due to one or multiple asset failures, or breakdowns in telecommunications.

The findings of interest, especially about key installations, were shared with the Ministry of Home Affairs and the Singapore Police Force. These findings allowed the CII owners to plug the vulnerabilities uncovered at the CIIs located at the data centre and telecommunication sites.

The analysis of CII interdependencies was put to good use during the IT system outages in mid 2010 and 2011. DSO was able to quickly assess that the outages were unlikely to spread, and that the adverse consequences were limited due to the recovery processes that operated as planned.

Figure 2 Seven Critical Infrastructure Sectors

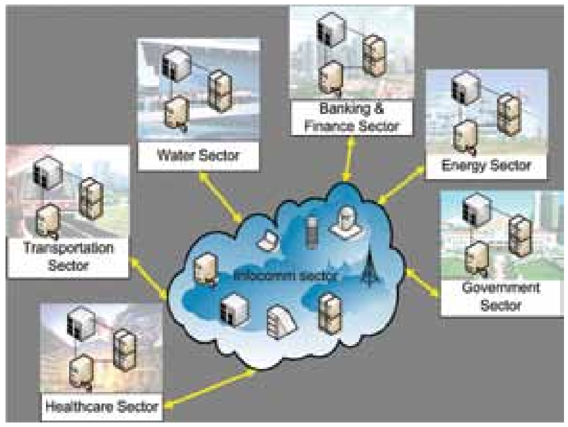
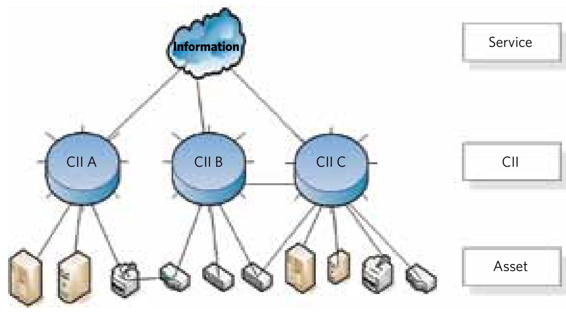
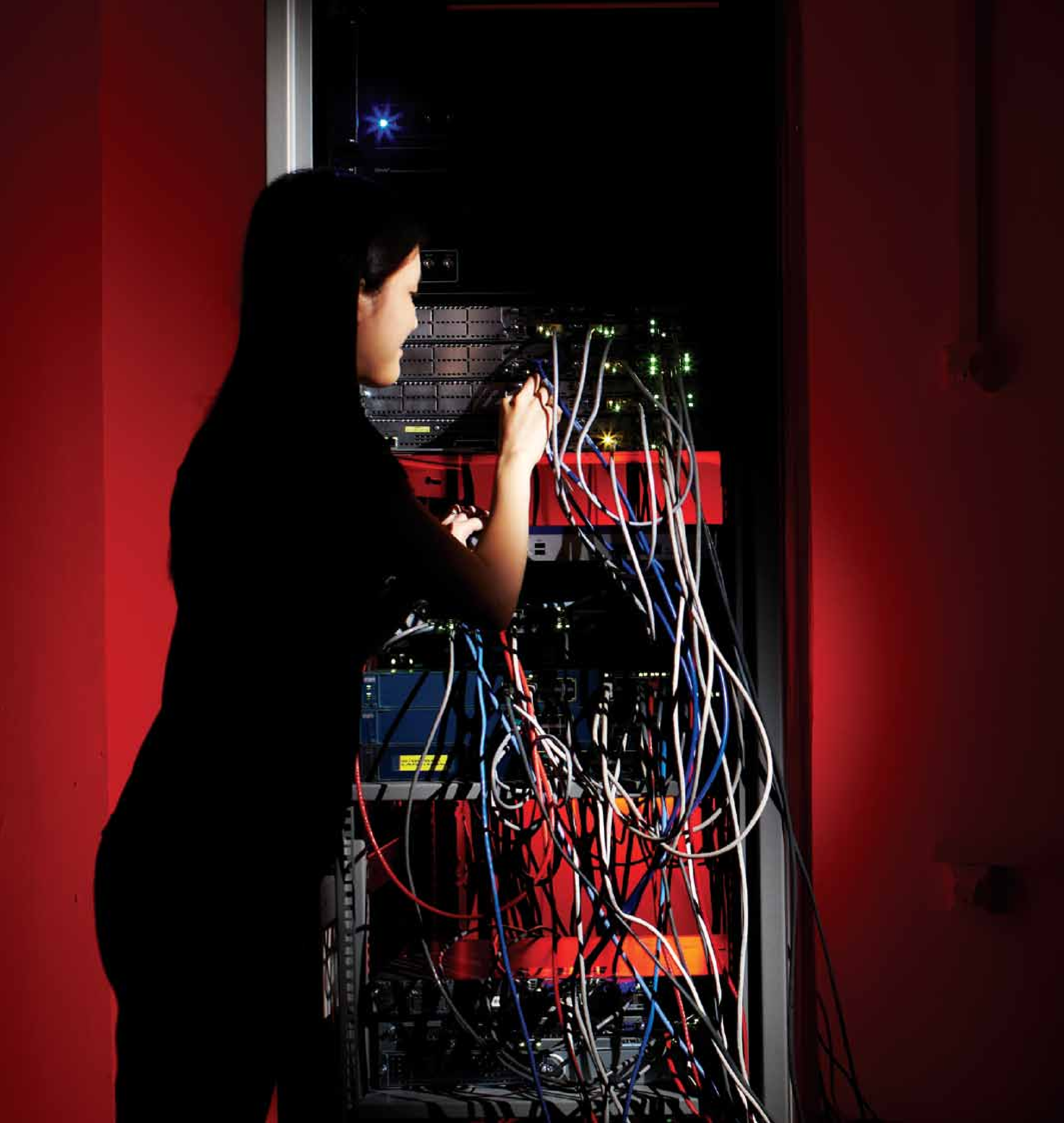


Figure 3 Hierarchical, Infocomm-Based, Service-Oriented Concept





INFORMATION SECURITY

DSO strives to defend Singapore against information security threats by spearheading advances in the field of information security.

INFORMATION SECURITY

The scope of research ranges from the design of information security systems, architecture, and cryptographic algorithms, to the techniques for reviewing design as well as validating system security implementations. DSO also leverages on the R&D efforts of local research institutions through close collaborative work.

Modern communications systems demand high throughput performance and high mobility. There is a strong desire to send multimedia and real-time information over communications channels from anywhere at any time. Information assets are also growing in size. At the same time, secure communications equipment need to be smaller and lighter for greater mobility. Such requirements impose further space and processing constraints on cryptographic algorithm design and implementation. As such, there is a need to have more efficient and stronger methods to secure communications today. To overcome these challenges, DSO has conducted research in modular encryptor security architecture, lightweight cryptography and high speed encryption.

Modular Encryptor Security Architecture

A high assurance encryptor should be designed with ease of validation and verification in mind. Complexity in design leads to complex implementation and it would be difficult to ascertain the trustworthiness and assurance of the encryptor. To tackle this challenge, DSO's design has three separated blocks: RED (plain information) processing, BLACK (ciphered information) processing and Cryptographic processing (transformation of plain information into ciphered information, and vice versa). Each processing unit performs its computation and data handling independently. In this way, security robustness and fail-safety are ensured through compartmentalisation and use of control points. This three-piece modular concept also facilitates reuse of modules and ease of future upgrades.

Lightweight Cryptography

Lightweight cryptography that requires *less hardware resources and lower power consumption* is suitable for constrained devices like Radio Frequency Identification (RFID) tags and smart cards.

For some applications where a smaller block size can be used, a lightweight cipher – Electronic Product Code Block Cipher (EPCBC) – was derived by reducing the block size and increasing the key size of a block cipher called PRESENT – a cipher known to be of ISO standard. Though its key size was extended, EPCBC was kept as lightweight as the PRESENT cipher through a simple refinement of PRESENT's bit-based diffusion structure. Even for a simple refinement, the security proofs against known attacks are not trivial. Complemented by a strengthened key schedule, the benefit is that this new variant can be proven secure against known statistical attacks - including the more recent related key differential attack - besides having better resistance against brute force key search attacks then PRESENT because of its longer key.

DSO also designed a new hash function called SPN-hash with Temasek Laboratories at the National University of Singapore (TL@NUS), The Nanyang Technological University's School of Physical and Mathematical Sciences, and the Institute for Infocomm Research (I^2R). In terms of hardware implementation, SPN-hash is a lightweight hash function requiring less gates equivalent compared to the NIST[1] Secure Hash Algorithm Round 3 (SHA-3) finalist. Despite this, it has a comparable throughput in software and better security proof against collision attacks. Improving on the latest techniques such as using parallel copies of serial Maximum-Distance-Separable (MDS) matrix over a smaller finite field to get a lightweight MDS over a larger finite field, and generalising the optimal diffusion layer to get a provably secure hash with a greater variety of output sizes, results in more lightweight and secure components.

[1] The National Institute of Standards and Technology (NIST) is the federal technology agency of the United States Department of Commerce that works with industry to develop and apply technology, measurements and standards.

High Speed Encryption

With advancements in technology, high speed applications such as trunk data communications require high encryption throughput performance. These applications can reach a speed of 10 gigabits per second or more. One common way to improve encryption speed is through pipeline encryption, where a register is inserted between rounds. Another way to improve encryption speed is through parallelised structures. DSO has delved into parallelisable structures, and cipher designs of parallelisable structures with provable security.

GF-NLFSR, Four-Cell+

The current trend in the cryptography community has been to use unbalanced Feistel designs such as SMS4 (China standard), and Skipjack (NSA standard). However, some of these Feistel structures cannot be parallelised. Thus, DSO designed a new parallelisable unbalanced Feistel structure called n-cell GF-NLFSR which can be shown to have good resistance against variants of mathematical cryptanalytic methods. In the Four-cell cipher design, the nonlinear function in each round was a Substitution-Diffusion-Substitution (SDS) network. This design was later extended to Four-Cell+ for protection against structural attacks after a review with external cryptography researchers.

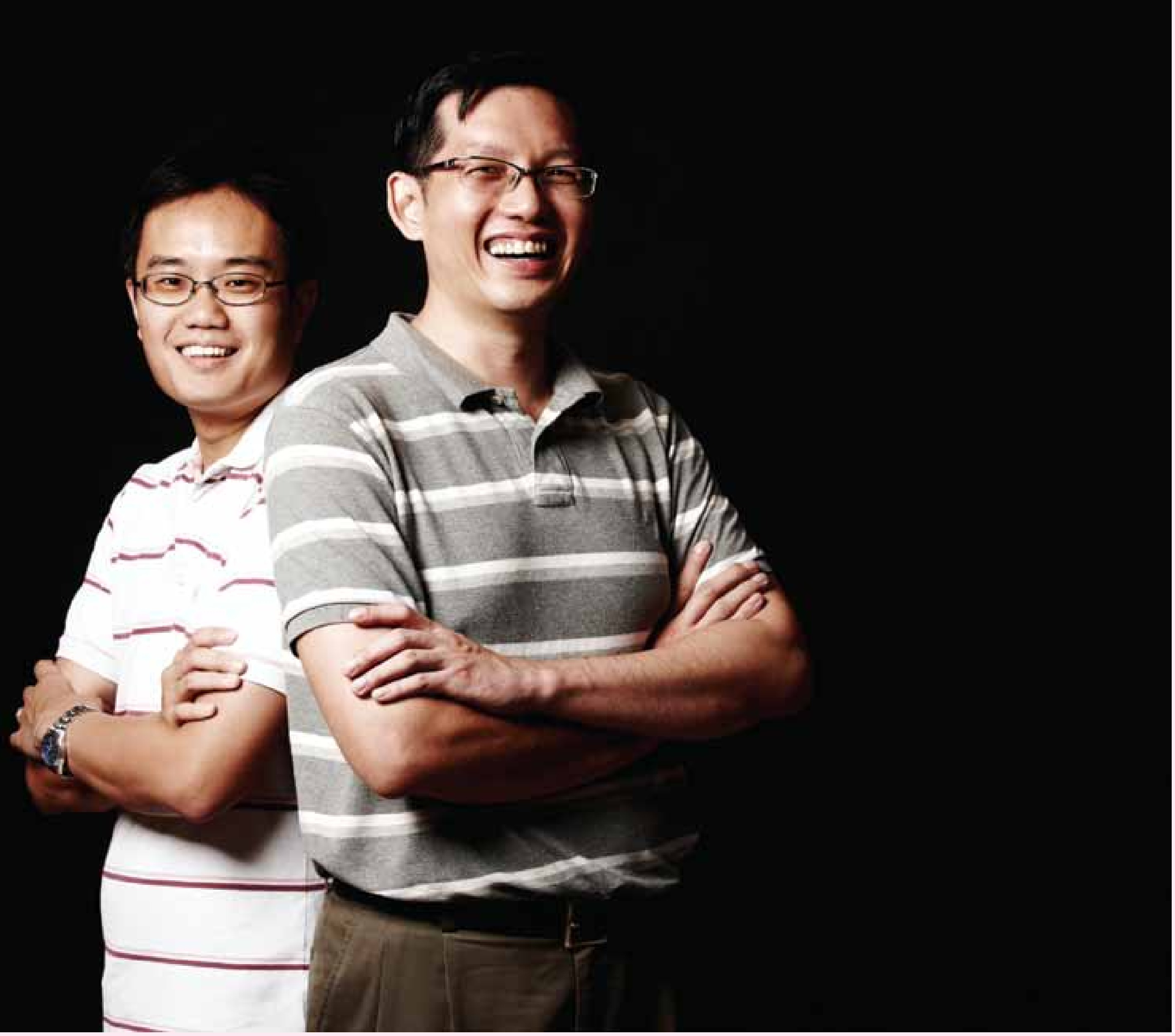
P-SMS4, p-Camellia

DSO's n-cell GF-NLFSR structure can be used to tweak Feistel ciphers such as Camellia (ISO standard from Japan) and SMS4 (China standard) to make them parallelisable, and thus improve their encryption speeds. However, the security proof obtained for that structure only holds for the SDS network, but not the mostly used Substitution-Permutation-Network (SPN) which can be faster and more efficient.

As such, DSO provided a new proof for the n-cell SPN structure so that it also has good resistance against common mathematical cryptanalytic methods. This was then applied to parallelise the Camellia and SMS4 ciphers to p-Camellia and p-SMS4, doubling and quadrupling the encryption speed respectively.

The wealth of knowledge and experience built up over the years has enabled DSO to provide timely advice on information security issues to both the Ministry of Defence and other national agencies in Singapore. In the years to come, DSO will continue contributing its expertise to support the SAF in securing its communications against security threats.

SECURING OUR COMMUNICATIONS



Henry Yip Senior Member of Technical Staff Networks Division Years in DSO: 2.5	**Dr Paul Khoo** Principal Member of Technical Staff Networks Division Years in DSO: 17

The field of information security is not a new one. In fact, the earliest known means of concealing a message carried by the Roman alphabet is the Caesar cipher, named after the Roman emperor Julius Caesar. Today, information security involves more than simple messages. The advent of the internet and portable communications devices have brought about a vast increase in the forms of data and messages that have to be secured. These developments place DSO researchers Dr Paul Khoo and Henry Yip at the forefront of a fast evolving research field, where they strive to find ever better methods and technologies for more secure communications.

Tell us what is it the both of you do in the area of information security.

Paul Khoo (PK): My focus is in the area of cryptography where I undertake research and development of cryptographic algorithms that keep information secure. Much of what I do is heavily based on mathematical theory.

Henry Yip (HY): I'm a security engineer and as such, I work with cryptographers like Paul to implement algorithms in hardware, develop encryption modules, and integrate them with communications systems.

What is it about your work that keeps you going?

PK: DSO has the right environment to carry out cutting edge research, including the opportunity to collaborate with researchers from local and overseas universities. These days, information security does not reside solely in the military domain. In fact, cipher algorithms and secure protocols can be found in the public domain, and university researchers are responsible for some really great work. Learning from them and applying these things in my own work is pretty exciting – I'm continually amazed at how mathematics can be applied in so many unimaginable ways to protect information. Of course, it helps to have great colleagues like Henry!

HY: Of course! From what Paul has mentioned, I think you can get the sense that Information Security is definitely not a stagnant field. New vulnerabilities are found and new countermeasures are being put in place all the time. This is what keeps me on my toes as there is always something new for me to discover each day.

What is the greatest challenge both of you have faced at work?

HY: I think the greatest challenge about security engineering is to manage the conflicting requirements of security, and what the system is supposed to do. When we were tasked to help secure a particular communications link, there was a lot of scepticism in the beginning – the engineers who built the original system had put in a lot of effort to make it work in the first place, and we were seen as adding "extra" things which may bring it down. We understood their concerns and worked closely with them to integrate our modules – after all, we want the system to work too! We built trust as time went by and today, we have a much better working relationship.

PK: For me, it has to be first time I had to do a Cryptographic Acceptance Test (CAT) to evaluate a vendor's security product! I had to understand system requirements, understand specifications, and familiarise myself with the standards used by the vendors. Being the type who is more inclined towards the mathematical applications of cryptography, I was at a complete loss! In fact, that was the only time I've felt lost at work! However, I mentioned working with great colleagues, and one of them came to my rescue by providing plenty of guidance!

And how about the greatest satisfaction?

PK: As a senior researcher, I help to teach cryptography to new researchers. I derive a great satisfaction from enabling them to understand how cryptographic concepts can be applied in our work, and then seeing them develop a passion for what they do. It's almost as if work becomes a hobby for them.

HY: There was a particular project I was involved in to develop an encryptor. Seeing through its development from a paper drawing to its implementation on actual hardware, and finally producing the first frame of encrypted data was a hugely satisfying journey! The team had worked hard for many months to come to this moment. However, in the very next moment, the second frame of encrypted data did not come out as expected! We then spent the next few days debugging and finally found the one bit that was misconfigured. What a relief!

VIDEO EXPLOITATION SYSTEM FOR UNMANNED AERIAL VEHICLES

In November 2009, DSO responded to the SAF's request to provide video exploitation tools to support the SEARCHER Unmanned Aerial Vehicle Task Group's (UTG) deployment in Afghanistan at the beginning of August 2010.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VIDEO EXPLOITATION SYSTEM FOR UNMANNED AERIAL VEHICLES

In a span of five months, DSO developed and integrated a rapidly deployable video exploitation system. The system was trialed and tested for two months in both local and overseas exercises, before being deployed to Afghanistan in August 2010.

System Overview

The laptop-based system is integrated into the UAV Ground Control Station (GCS) for real-time surveillance video collection and exploitation (see Figure 1).

Video Exploitation Technology

A suite of tools for the collection, storage and exploitation of UAV video was provided. These tools included the playback of archived data with time-shift functions, video brightness and contrast adjustment; exporting of videos in Windows Media Video formats for ease of dissemination; and saving of geo-coded video imagery. Advanced tools included video mosaicking and image super-resolution.

Video Mosaicking

Individual video frames in an UAV video sequence provide the user with only a limited view of the scene. Video mosaicking provides a panoramic view of the scene by stitching individual video frames together, to enhance situational awareness of a larger area. This includes providing an overall picture of a route and the tracking of a moving target during surveillance (see Figure 2).

Figure 1 The video exploitation system as deployed in the GCS

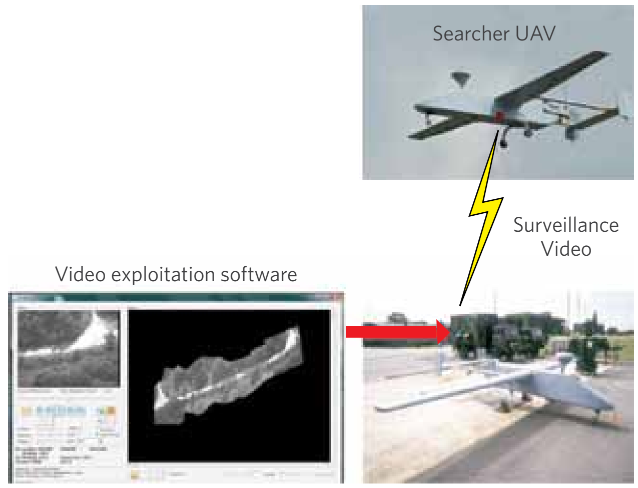
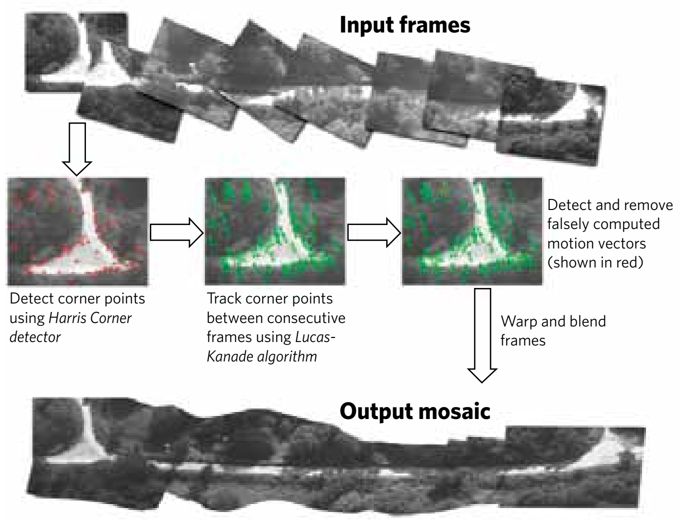


Figure 2 Video mosaicking algorithm



In the *image registration* stage, feature correspondences between consecutive image frames are first obtained. The *Harris Corner Detector* is used to detect corner points in an image frame, which are then tracked from frame to frame using the *Lucas-Kanade optical flow algorithm*. These initial feature correspondences are passed through Random Sample Consensus (RANSAC) to remove any wrongly tracked motion vectors. The final sets of feature correspondences are used to compute the motion transformation model between individual video frames by linear least squares estimation.

With the transformation parameters, individual frames can be warped to form the mosaic. A weighted averaging scheme is used to blend the warped frames together into a seamless mosaic.

Image Super-resolution

Super-resolution is an image processing technique that enhances low-resolution video sequences by modelling and removing the degradations inherent in the imaging process. A single high-resolution image is reconstructed from a sequence of low-resolution observed video frames. Figure 3 presents one sample result applying the developed super-resolution algorithm to an UAV video sequence. With improved imagery resolution, scene details and features are enhanced.

Conclusion

This system provided DSO with a valuable opportunity and experience in transiting such imagery exploitation technologies to actual operational capability for the SAF. It also serves as a baseline for DSO to develop future video exploitation systems for other airborne surveillance platforms.

Figure 3 Super-resolution example

Enhancing Capabilities

Through its research, DSO develops technologies that enhance the Singapore Armed Forces' (SAF) existing system capabilities to adapt to new warfighting concepts, and increases its soldiers' performance and survivability in the battlefield.

AERO-MECHANICAL CERTIFICATION FOR AIRCRAFT AND STORES

Aircraft/Store aero-mechanical certification refers to the process of determining the compatibility of stores for carriage and separation from an aircraft. A store is defined as a device carried on the aircraft, such as bombs, missiles and fuel tanks.

AERO-MECHANICAL CERTIFICATION FOR AIRCRAFT AND STORES

Figure 1 F-16 aircraft and store pitch vibration mode simulated using NASTRAN, a Finite Element code

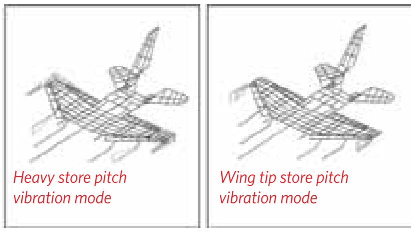


Figure 2 Simulation of bomb released from an F-16 aircraft

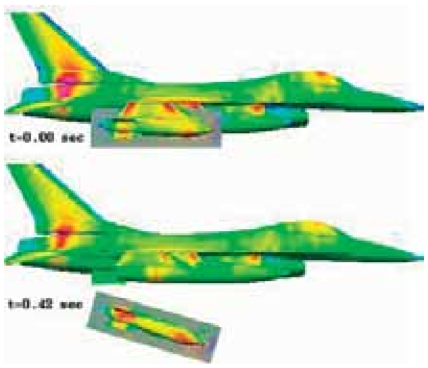
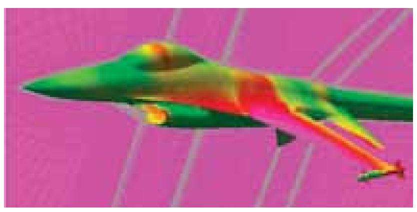


Figure 3 Wing deformations due to aircraft manoeuvre loads on wing

Figure 4 Computational Fluid Dynamics (CFD) simulation of the F-16 aircraft



DSO performs aero-mechanical certification analysis and testing, and is the engineering authority for the certification of carriage and operation of under-wing stores on the Republic of Singapore Air Force's (RSAF) F-16 aircraft. The capabilities and scope of DSO's analytical and testing work have matured over the years to encompass a wide range of disciplines such as flutter, store-separation, flight loads, aerodynamics, stability and control, as well as ground vibration testing.

Flutter

The F-16 aircraft is known to exhibit Limit Cycle Oscillation (LCO), a sustained, non-divergent aero-elastic oscillation with limited amplitude. The motion generates small levels of loads and does not cause structural damage, or impact the fatigue life of the aircraft. However, at sufficiently high levels, LCO may cause pilot discomfort and may affect the pilot's ability to perform his operational mission.

DSO's engineers are able to predict the flutter speed and mechanism (see Figure 1) for the onset of LCO using analytical tools. This information is valuable as it is used to obtain the aircraft's achievable operational flight envelope.

Store Separation

The release of stores poses a safety concern for both the aircraft and the pilot. The combination of inertia and aerodynamic characteristics of the store determines its separation trajectory profile from the carrier aircraft.

DSO's engineers are capable of computing the minimum miss distance between the store and the aircraft via aerodynamics and six degrees-of-freedom simulations (see Figure 2). The aim is to establish the allowable flight conditions for safe store release from the aircraft.

Flight Loads

The loads (or forces) on both aircraft and store due to aircraft manoeuvres may adversely affect the aircraft's structural integrity. DSO's engineers determine whether the aircraft and store suspension system can safely carry the stores with these induced loads. Figure 3 illustrates wing deformations due to the flight load on an F-16 aircraft.

Aerodynamics

Aerodynamics dictates the performance of the aircraft and stores. Different store combinations affect the overall drag of the aircraft, and hence, its takeoff, cruise, climb, manoeuvre, and dash performance.

DSO's engineers investigate the aerodynamic characteristics of aircraft/store configurations via Computational Fluid Dynamics (CFD) simulations (see Figure 4).

Figure 5 Flow separation of an aircraft at a high angle of attack

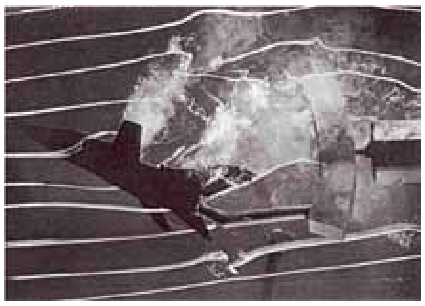


Figure 6 Ground vibration test set-up

Stability & Control

The various stores on the aircraft alter the centre of gravity and perturb the airflow surrounding the aircraft/store combinations. These changes impact the overall aircraft's stability and control. Figure 5 illustrates the complex aerodynamics of an aircraft at a high angle of attack.

DSO's engineers have developed extensive computer models/ simulation tools that are able to determine an aircraft's response when performing manoeuvres such as steady-state sideslips, pitch doublets, rolls and wind-up turns. As a result of these analyses, the aircraft's achievable flight envelope can be determined.

Ground Vibration Test

Ground vibration testing can be conducted for an aircraft, or stores. It is a measurement-based approach to quantify the structural behaviour - such as vibration mode shapes - of the aircraft and stores. Ground vibration test results also serve as a source of verification data for flutter analysis. Figure 6 illustrates an F-16 aircraft ground vibration test set-up conducted by DSO engineers.

In 2004, DSO enabled the RSAF to possess enhanced fighting capabilities through the certification of new take-off store configurations for their aircraft. In 2007, DSO was part of a team (along with the Defence Science and Technology Agency, the RSAF and Singapore Technologies Aerospace) that was awarded the Defence Technology Prize for this effort. This marks one of the many milestones in DSO's active involvement in helping the RSAF build up operational capabilities for their aircraft.

With the RSAF's recent acquisition of the advanced F-15SG aircraft, DSO is well positioned to provide continued aero-mechanical certification support to the RSAF.

THE PIONEERING SPIRIT

Johnson Tang Principal Member of Technical Staff Guided Systems Division Years in DSO: 16	**Dr Chew Siou Chye** Laboratory Head Guided Systems Division Years in DSO: 17

Meet Dr Chew Siou Chye and Johnson Tang, two DSO researchers who were pioneers in the successful build up of an indigenous aircraft and store aero-mechanical certification capability for the Republic of Singapore Air Force (RSAF) F-16 aircraft.

Building a credible indigenous capability for the SAF is not an easy task. As Siou Chye and Johnson share, it requires a healthy dose of dedication and commitment to overcome the many obstacles involved. However, their efforts have paid off. The pair has won numerous DSO awards and even the prestigious Defence Technology Prize – a fitting validation of their pioneering spirit.

How did the both of you get started in aero-mechanical certification?

Siou Chye (SC): I got arrowed. Seriously though, that was what I thought at the time but in hindsight, it was a case of being in the right place at the right time! When Johnson and I joined DSO, the RSAF was in the process of rolling out the F-16.

Johnson Tang (JT): I agree - right place at the right time. In fact, my mother had a part to play in this! Before I joined DSO, I had the opportunity to become a fighter pilot. However, the only person who stood in the way was my mother. She refused to sign the RSAF contract because she thought that being a pilot was too dangerous! So, I ended up in DSO as an engineer working on fighter jets instead of flying them.

What was it like in the early days when both of you were just starting to build up this indigenous capability?

SC: Actually, it wasn't just the both of us. We were part of a team that was tasked to build this capability. Also, aero-mechanical certification is actually not a new field so we did have some knowledge of it. However, there were many aspects of certifying a modern fighter aircraft that we did not fully understand then. Hence, we had to attend overseas training courses.

JT: And that was when Siou Chye encountered his first obstacle. Before attending one of these courses, he broke a finger on his master hand playing basketball! Suffice to say that he had difficulties clicking his mouse for the whole course!

Beyond a broken finger, what was the greatest challenge both of you faced?

JT: As Siou Chye mentioned, we had to attend training courses to develop our knowledge. Later on however, we came to realise that books and reports couldn't teach us everything. A lot of knowledge could only be learnt by getting our hands dirty. It's just like swimming – you won't be able to do it just by reading about it! And that was when flight trials came into the picture. These involved the project team that included our counterparts from the RSAF, and usually lasted for weeks at a stretch. It also involved many burnt weekends, late nights and waking up at god forsaken hours to drag ourselves to the air base.

SC: Only to have the trial postponed due to inclement weather!

JT: Initially, there was also much discussion and argument among the team. But thankfully, we always managed to reach an agreement! However, I think that it was the shared 'ordeals' that helped to cement our working relationship with the RSAF engineers and pilots involved.

SC: I think that in the process of working with the RSAF, we managed to earn their faith. Besides building an indigenous capability to support their operations, that is one of my greatest satisfactions. In fact, we consider our RSAF counterparts good friends now.

Moving forward, what do you hope to achieve with your work?

JT: I've actually moved on and am now working on Unmanned Aerial Vehicle (UAV) development. The knowledge I gained from working on manned aircraft is quite useful when it comes to pushing the design and technology development for UAVs.

SC: For me, the way forward can be put simply: realise more operational capabilities for the SAF! I am also aware of the adage "easier said than done", but I think with hard work and a can-do attitude, more capabilities can indeed be realised!

TRACK-BEFORE-DETECT

To safeguard the security of our territorial space, it is crucial to detect and track targets such as small aircraft or boats.

TRACK-BEFORE-DETECT

Such targets present two challenges for the sensors that are used for surveillance. Firstly, given their small sizes, these targets possess a low Radar Cross-Section (RCS) and hence, reflect very little electromagnetic signals to the radar. Secondly, due to their slow speed, the weak returned signal will be mixed with interference signals from stationary ground clutter, making the detection of the target extremely difficult.

In conventional detection, each scan of the received signal is processed one at a time, using a certain threshold level to determine target detection. As long as any signal crosses this threshold, target detection will be declared. Naturally, the threshold needs to be sufficiently high to avoid frequent false detections from overwhelming the operator. However, a high threshold poses a challenge for sensors as it cannot detect persistent weak target signals that remain below the threshold level.

The Track-Before-Detect (TBD) technique is an advanced tracking technique that overcomes this challenge. Unlike conventional methods, it involves the integration of received signals and data over multiple scans. This is to allow weak target signals embedded in noise to be cumulated for detection as such signals tend to have regular flight kinematics characteristics. In other words, the difficult decision-making on the presence/absence of a target is postponed until more data is received and evaluated. This eradicates the irretrievable loss of information by considering all the raw data input without applying the threshold upfront. However, operating on non-thresholded data leads to another set of challenging problems. These include high computational and memory requirements, and a large number of false plots/tracks that need to be handled, especially for sensors with large-sized signal maps.

Figure 1 Different detection methodologies

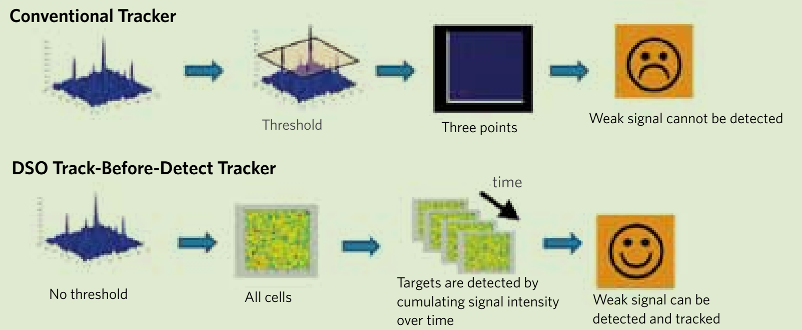
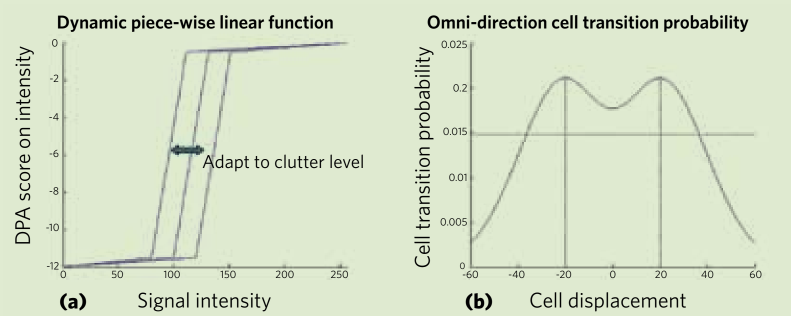
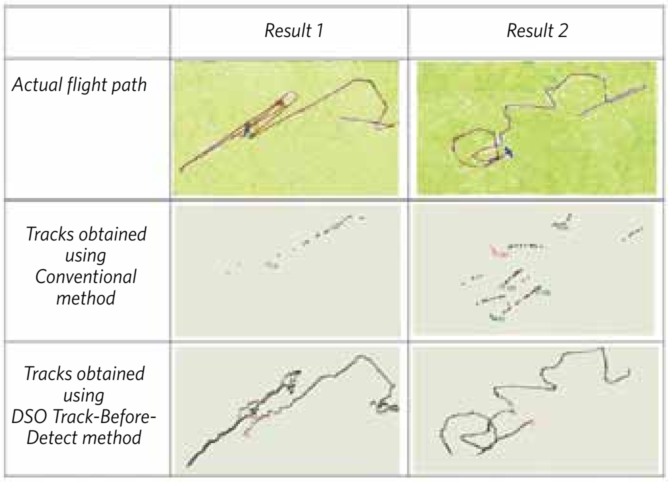


Figure 2 (a) The dynamic piece-wise linear function
(b) The omni-direction cell transition probability



TRACK-BEFORE-DETECT

Figure 3 TBD results from a ground-based air surveillance radar



DSO has successfully developed a TBD tracker based on an advanced Dynamic Programming Approach (DPA) to overcome these problems. The DPA algorithm cumulates a score for each detection cell over time on the most possible path, such that a low Signal-to-noise (SNR) target with high cumulated scores can then be distinguished from random noise. DSO has formulated a novel method of computing the DPA score, which is contributed by signal intensities and the geometry of signal cell displacement as shown in the equation below.

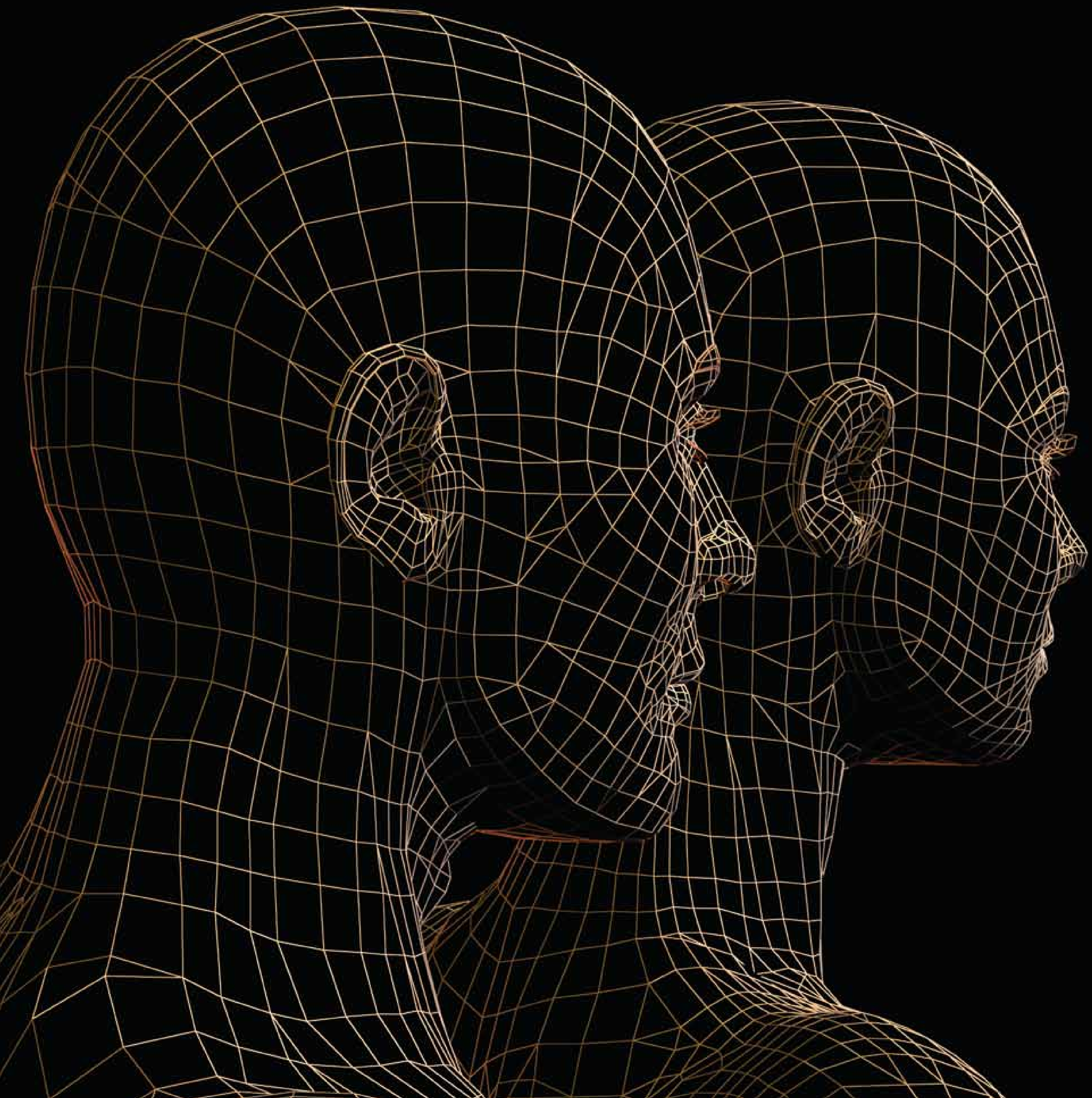
$$S_{(i,j)}(n) = (1-\alpha)\, CS_{(i,j)} + \alpha \max_{(i',j')}[\beta_{(i',j')} + S_{(i',j')}(n-1)]$$

where: $S_{(i,j)}(n)$ is the DPA cumulating score in cell (*i,j*) at scan *n*;
$CS_{(i',j')}(n)$ is the current score of cell (*i,j*) computed based on a dynamic piece-wise function;
α is the forgotten factor for history cumulating score;
$\beta_{(i',j')}$ is the transition factor from cell (*i',j'*) to cell (*i,j*);
(*i',j'*)s are the all cells in the previous scan which the current cell (*i,j*) linked to.

The cell intensity is converted into a score value based on a dynamic piece-wise linear function which can adapt the DPA score to clutter level. The score of the target movement is pre-computed from an omni-direction cell transition probability function. The two functions are shown in Figure 2. DSO's TBD tracker also extracts signal patterns from signal maps through pattern recognition techniques, and applies a point-based DPA on extracted patterns over time. This can further reduce the computational cost significantly without degrading the tracking performance. With these three features, DSO's TBD tracker can achieve real-time implementation even for sensors with large signal maps.

DSO has successfully applied our TBD solution to enhance the detection of challenging targets using trial data. Our results have shown that the performance of TBD is significantly better than conventional processing.

Figure 3 shows the detection of a small and slow flying target by a ground-based radar. From this set of results, it clearly shows that the conventional method of processing has limited performance in tracking such targets, providing only intermittent short tracks of the target. With DSO's TBD algorithm applied on the same set of raw signals, the tracks were obtained earlier, with an improvement in the mean track duration.



HUMAN FACTORS ENGINEERING

Human Factors Engineering (HFE) is an integral and vital component of any system where there is a 'man-in-the-loop'. Humans are often the weakest link in any complex system and there is a need to address human factors in system design.

HUMAN FACTORS ENGINEERING

HFE ensures the effective integration of humans with technology, leading to improved human-system performance and effectiveness. A well-designed human-centric system can also prevent mental and physical overload, and reduce the risk of human error (e.g. fratricide).

This article highlights two examples from the Human-Centric Crew Station of the Future (HCSF) to explain how information visualisation and auditory perception theories from the domain of Cognitive Ergonomics are applied to the design of military systems.

Information Stitching Dashboard (Information Visualisation Application)

The Information Stitching Dashboard or ISD (see Figure 2) is an example of how information visualisation theories are applied to the design of systems. ISD addresses issues related to the stitching of information on the driving displays to enhance the driver's situation awareness (SA) in closed-hatch operations. The aim is to enable the driver to rapidly monitor tactical digital information and maintain visual contact on the driving screens while driving.

One of the information visualisation theories applied in the design of the ISD is the concept of "data-ink ratio". This is a theory introduced by Edward Tufte, an expert in the field of data presentation. Tufte uses the term "data-ink ratio" to argue against using excessive decoration in visual displays of information. Data-ink is the non-erasable core of a graphic, the non-redundant ink arranged in response to variation in the numbers represented (Tufte, 1983). The data-ink ratio is the proportion of ink (or pixels, when displaying information on a screen) that is used to present actual data - without redundancy, compared to the total amount of ink (or pixels) used in the entire display, such as in a table or graph. The goal is to design a display that has the highest possible data-ink ratio (that is, as close to the total of 1.0 or 100%) as possible, without eliminating something that is necessary for effective communication.

The ISD uses modified versions of the maps used to maximise the data-ink ratio so as to enhance the presentation of critical information. The filled areas of the original map are removed, and the remaining contents are coloured white and set to be 50% transparent (see Figure 1). A transparent map allows the driver to still see the camera feed behind it. This is achieved by removing the unnecessary filled areas, leaving behind only the essential "data-ink".

Figure 1 Modified map on the ISD

Figure 2 Final outcome of the ISD design

Some ISD prototype design options were generated based on information visualisation guidelines and principles. These design options were evaluated with users to gather their feedback and to identify potential Human Factors and operational issues for the different ISD design options. Figure 2 shows the final outcome of the selected ISD design incorporating the findings from the evaluation sessions.

Multi-Modality Crew Console (Auditory Perception Application)

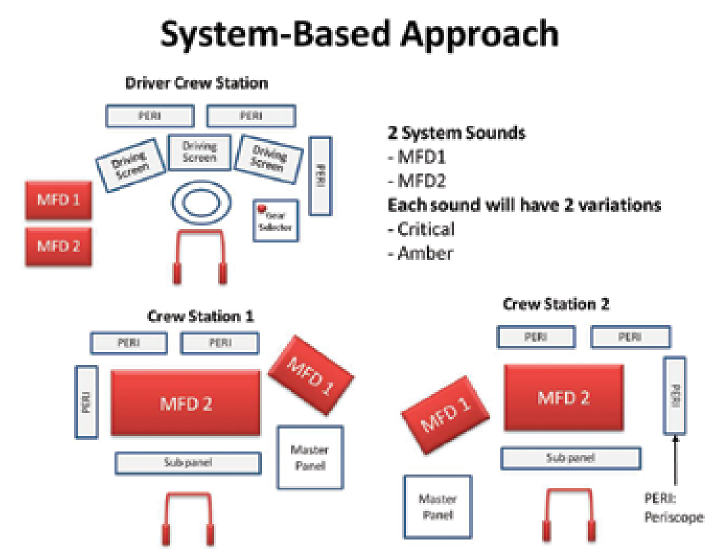
Another example of theoretical application from the Cognitive Ergonomics domain is the Multi-Modality Crew Console (MMCC). The MMCC uses auditory cues to improve the vehicular crew's performance and situation awareness when performing multiple tasks. Auditory cues were designed based on auditory perception (or Psychoacoustics) theories on pitch perception and sound localisation amongst others.

Visual perception is the most developed and most commonly used modality to interact with the environment. However, it is insufficient to rely solely on vision to fully perceive the environment. It has been postulated that audio cues can significantly supplement visual displays due to its omni-directional and light independent nature (Patterson, 1982). With intuitive and directional (such as three-dimensional localisation) auditory cues complementing visual displays, human performance can be maximised.

A set of auditory cues were developed to enhance crew performance and situation awareness. Based on the results from this study, the SGBA (see Figure 3) for system/screen identification process performed better than other approaches such as the Function-Based Approach and Event-Grouping Based Approach. In SGBA, sound alerts were designed for the different Multi-Function Displays (MFD). A total of two sound alerts (non-speech) were designed to represent MFD 1 and MFD 2. Each sound had two variations to represent critical and amber alerts. The critical alerts had double the frequency and intensity of the amber alerts to increase the perceived urgency.

The SGBA approach helps to direct the crew's attention to the affected system/systems more effectively, and also helps them to understand the criticality levels of the alerts more easily. This was tested in a series of scenario-based experiments that demonstrated its effectiveness to enhance the crew's situation awareness, reduce their workload and shorten their response time.

Figure 3 System Grouping Based Approach (SGBA)



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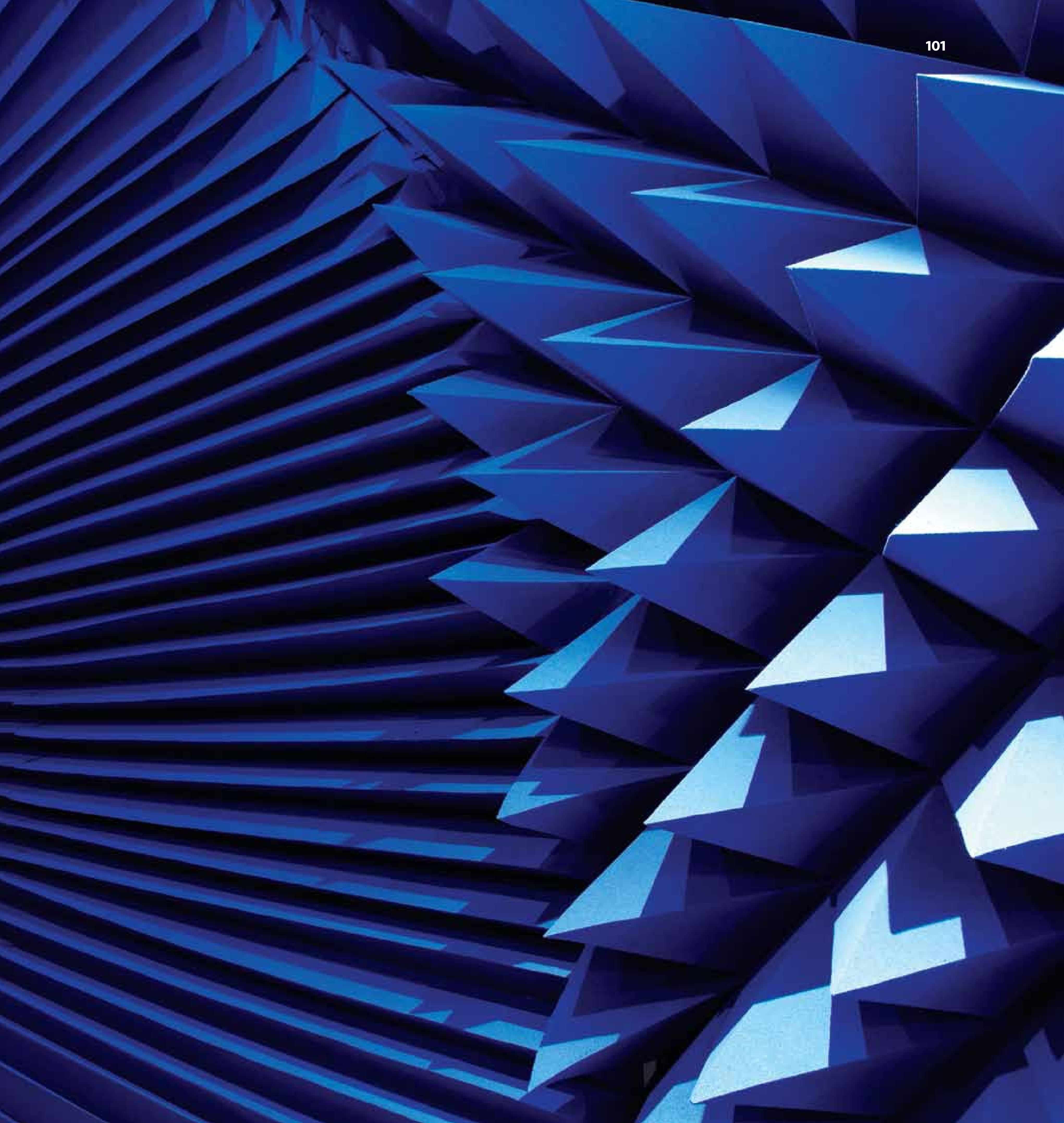
ANTI-JAMMING GPS ANTENNAS AND SIGNAL ENHANCEMENT TECHNOLOGIES

The Global Positioning System (GPS) - a radio position, precise navigation and timing system that provides worldwide all-weather coverage, was once a closely guarded asset of the U.S. military in the 1970s and mid 1980s. Their use was solely limited to military assets owned by the U.S. Since the service was made available to the commercial world 18 years ago, GPS technology has seen ever increasing use in both the military and commercial domains.



ANTI-JAMMING GPS ANTENNAS AND SIGNAL ENHANCEMENT TECHNOLOGIES

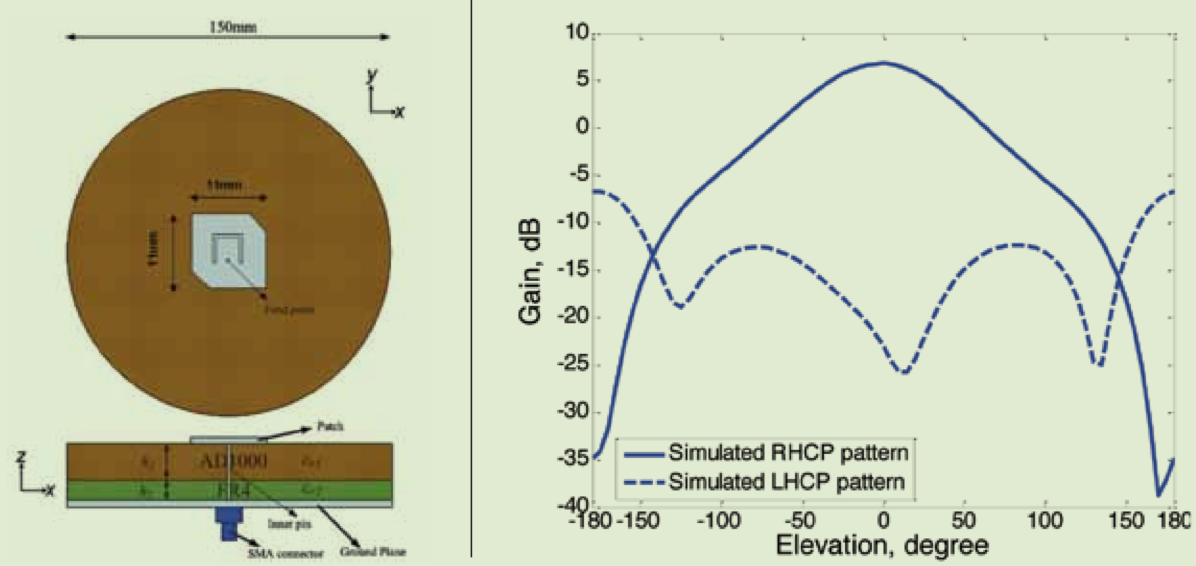
The rapid advancement in GPS receiver technologies has since penetrated and promulgated at a very fast pace in myriads of applications, especially in the domain of unmanned aerial systems surveillance for defence. These unmanned aerial systems equip military forces with an "eye in the sky" capability to see far and wide, with the kind of visual clarity and positional precision never experienced before.

Due to the very weak GPS Satellites signal strength (-160dBW or $10^{-10}\mu W$) at the user's GPS receiver (earth bounded), these receivers are very vulnerable to intentional and unintentional Radio Frequency (RF) interference. One of the most effective ways to counter jamming directly, so as to ensure signal robustness for GPS receivers used in the unmanned aerial system, is to equip it with a compact Adaptive Antenna Array that creates nulls in the direction of the jammers.

Compact Antenna Array for Anti-jam GPS System

It is well known that the low broadcast power of the GPS satellite (~ -160dBw) is the key reason why GPS systems may be prone to jamming. Furthermore, standalone GPS antennas typically have wide beamwidth to capture signals from as many satellites as possible, making it worse as the antenna wide beamwidth tends to allow in jamming signals. Digital Beamforming is a technique to reduce the susceptibility of a GPS system to jamming, but it requires an array of antennas instead of just a single element. If one desires to counter jamming from N sources, a requirement is N+1 antenna elements in the array. For deployment in a small Unmanned Aerial Vehicle (UAV), one of the key enabling technologies is a compact antenna array.

Figure 1 (a) A compact GPS antenna (b) The associated gain patterns at 1.575GHz



ANTI-JAMMING GPS ANTENNAS AND SIGNAL ENHANCEMENT TECHNOLOGIES

An antenna is typically sized about $\frac{1}{2}\lambda_o$ for it to operate efficiently, where λ_o is the wavelength of the operating frequency. For GPS, the nominal operating frequency is 1.575GHz, which means that a micro-strip patch antenna used for GPS is about 90mm x 90mm. As GPS broadcasts in a Circular Polarised (CP) mode, their antennas must be conventionally shaped, either rectangular or circular, to reduce signal fluctuation. For a small UAV, it would be difficult to deploy anything more than a couple of such antenna elements for anti-jam GPS applications. As such, DSO, in collaboration with Temasek Laboratories at NUS (TL@NUS), has been actively developing compact antenna arrays for GPS applications.

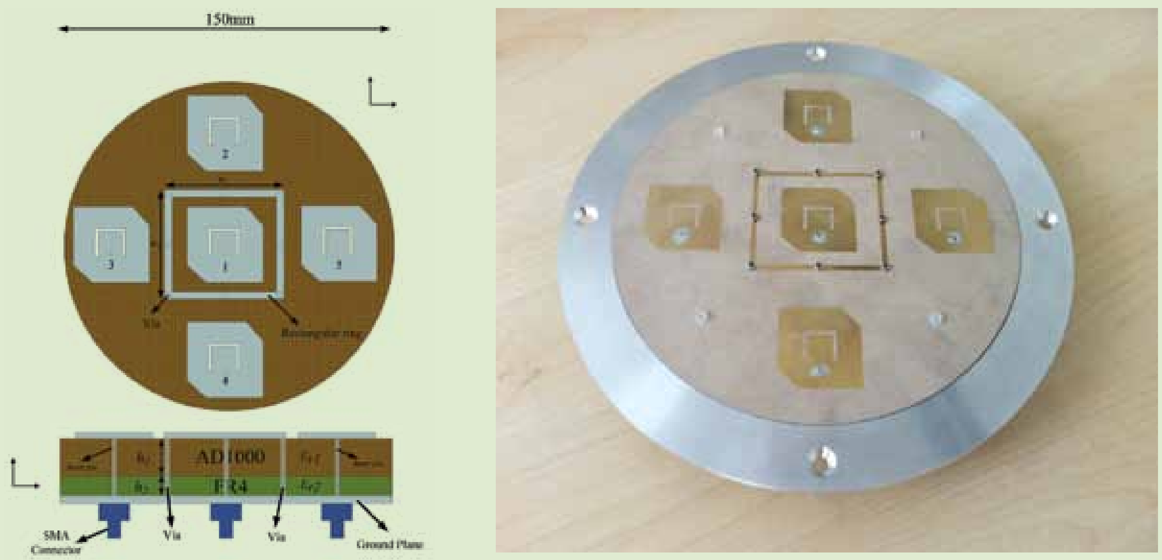
For small UAVs, it is advantageous to select low profile microstrip patch antennas. The size of these microstrip patch antennas are reduced by using high dielectric substrate. An example of such an antenna is shown in Figure 1a. The truncated corners of the square patch are needed to achieve Right Hand Circular Polarisation (RHCP), and the inverted-U slot is to further reduce the size of the antenna. The gain pattern (see Figure 1b), shows that the antenna exhibits good RHCP performance at 1.575GHz, which is necessary for GPS applications.

In this case, a ceramic material with high dielectric constant (Arlon AD1000) is used to reduce the size of the microstrip patch antenna. The antenna is reduced to 11mm x 11mm, compared to about 90mm x 90mm, if no dielectric material is used. This antenna is used as a basis for the compact antenna array.

In GPS lingo, anti-jam GPS antennas usually make use of a Controlled Radiation Pattern Antenna (CRPA) array. Such CRPA GPS arrays are typically circular in shape and have one reference element at the centre with auxiliary elements distributed along the circumference. A 5-element array jointly developed by DSO and TL@NUS is shown in Figure 2.

The primary challenge of designing the 5-element CRPA array is the mutual coupling between the closely spaced antenna elements. The rectangular ring with judiciously placed shorting vias is needed to reduce mutual coupling. Despite the effort, the gain pattern is still affected by the additional antenna elements, but careful design preserves the usefulness of the antennas for GPS applications.

Figure 2 A 5-element CRPA array prototype



THERAPEUTIC ANTIBODIES

Emerging infectious diseases such as Severe Acute Respiratory Syndrome (SARS) and dengue, as well as the pandemic potential of highly pathogenic H5N1 'bird flu', pose significant threats to a country's population and economic well being. As such, these diseases require urgent strategies to mitigate their impact.

THERAPEUTIC ANTIBODIES

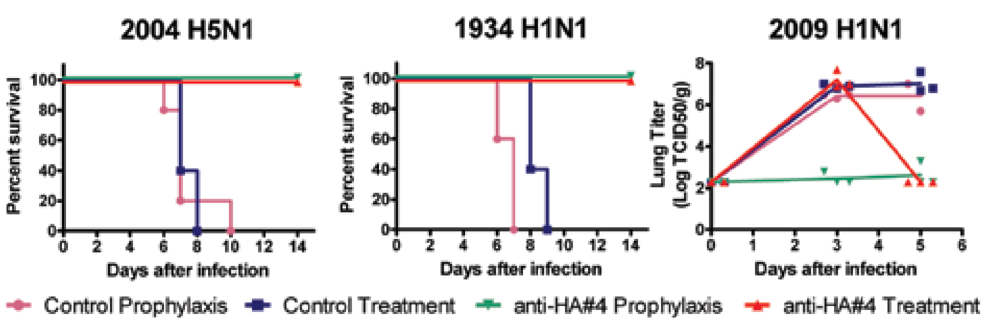
Passive antibody therapy – the direct introduction of therapeutic antibodies - predates the antibiotic age which largely resulted in the abandonment of this methodology for treatment of infectious diseases. However, advances in recombinant antibody technology to allow 'in lab' production of specific antibodies have revived this strategy as a countermeasure against viral diseases.

Due to the severity of the threat posed by 'bird flu', DSO initially focused on developing antibodies which could protect against this virus. The major target for this type of approach is called haemagglutinin (H) - the part of influenza that is responsible for entry into a cell, and necessary for the virus to multiply. In nature 16 different subtypes of H exist, but differences also exist within each subtype of H. Using these differences within H5, the team developed strategies to bias the selection of antibodies to regions common to all H5. Through these methods, 28 unique antibodies were identified which exhibited broad H5 reactivity, and five of them showed the ability to stop the uptake of H5N1 virus-like particles, and to protect against lethal virus challenge with attenuated H5N1 virus in mice (see Figure 1).

At the same time, other researchers had shown that antibodies similar to ours bind to a region of H which is common in many subtypes, allowing the 16 H subtypes to be ratified into two groups – the binding group (group 1), and the non-binding group (group 2). Our antibodies show a similar phenomenon, and demonstrated the ability to provide complete protection against challenge with other members of group 1 such as H1N1, including the recently pandemic H1N1 from 2009 (see Figure 1).

Since this initial discovery, research into this area has expanded worldwide. A therapeutic antibody has now been identified which can bind the group 2 haemagglutinins. In addition, through careful analysis of the immune response of an individual infected with the 2009 H1N1 pandemic influenza, an extremely rare therapeutic antibody which can protect all 16 H subtypes has been identified. Together, these antibodies provide a viable strategy to fight an emerging influenza pandemic whether it is caused by H5N1, H1N1, or a virus with some other haemagglutinin subtype.

Figure 1 Animal studies highlighting protective efficacy against lethal challenge with 2004 H5N1 or 1934 H1N1, and non-lethal challenge with 2009 H1N1'pandemic' virus. Antibodies were added either one day before (prophylaxis), or two days after (treatment) infection



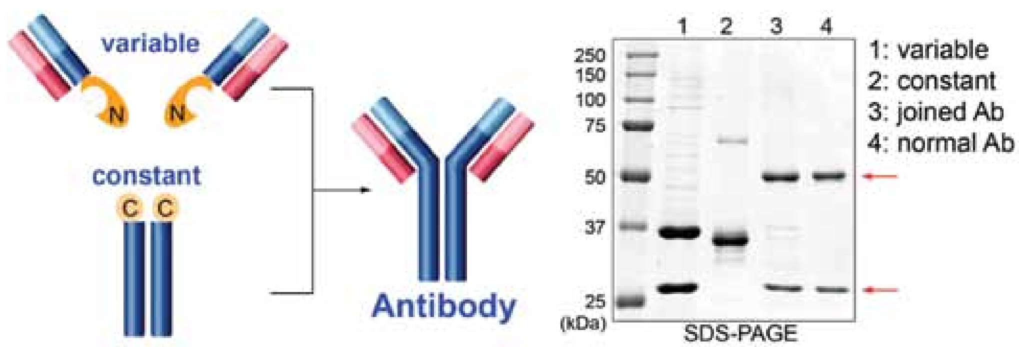
THERAPEUTIC ANTIBODIES

Tapping the human immune response to identify therapeutic antibodies has also been a focus in DSO as it may provide a mechanism for the rapid development of completely human antibodies from a future novel virus index case. Together with researchers from the laboratory of Associate Professor Paul MacAry at the Department of Microbiology in the National University of Singapore's Yong Loo Lin School of Medicine, DSO used the dengue virus infection, an important emerging infectious disease in its own right, as a surrogate. Using only 10 ml of blood from a patient who had recovered after being infected with the dengue virus, DSO isolated a potently protective antibody against all tested dengue serotype one viruses. This antibody binds dengue in a manner not seen over years of research using antibodies developed in mice. The antibody kills the virus by inhibiting the two mechanisms critical for virus infection in humans.

Isolation of the protective antibody is the first step in developing a treatment option against an emerging virus. In order to disseminate this treatment, it is critical that large amounts of the antibody can be made rapidly. Current methodologies for producing high quantities are slow, as the antibodies need to be produced in cell lines which have an inherent slow growth rate. Even developing the cell line itself takes a significant amount of time, thereby inhibiting rapid distribution of the antibody to the population.

The antibody moiety can be divided into two parts: the variable regions which provide specificity and changes with every antibody; and the constant region which does not change (see Figure 2). It is only the constant region that needs to be produced in these slow growing cells. The variable regions on the other hand can be produced much more rapidly using microbial fermentation. The team set out to find a way to separate the production of the two regions of the antibody in a manner that would allow them to be joined at a later time to make a functional antibody. In this way, the rate-limiting constant region of the antibody could be produced and stored in advance, while the variable region could be rapidly produced when needed. Using the properties of a class of protein domains known as split inteins, which can join two proteins together while themselves being removed, DSO has demonstrated proof-of-concept where both regions of the antibody could be produced separately, and then joined together to form a fully functional antibody at reasonable efficiency (see Figure 2). Efforts are continuing to develop this technology further.

Figure 2 Diagram of an antibody showing the variable and constant regions, and how they are organised in an antibody. The SDS-PAGE highlights joining of the antibody regions to give an antibody (red arrow) the same as that produced using normal methods



TARGETING THE INNATE IMMUNE SYSTEM

The emergence of new diseases could inflict tremendous stress on the social and economic stability of a country. Since Singapore is a vibrant tourism hub and business centre in the region, we are especially vulnerable to the threats of emerging and re-emerging infectious diseases in our region.

TARGETING THE INNATE IMMUNE SYSTEM

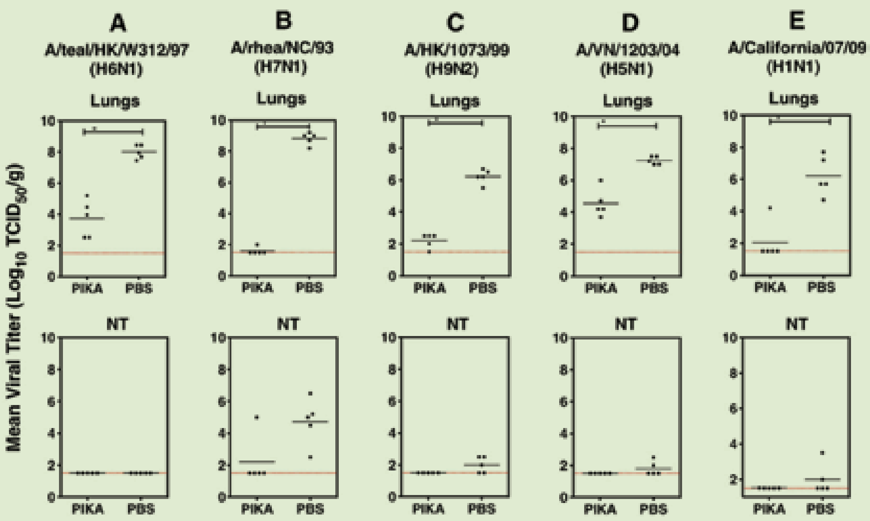
This has been exemplified by the appearance of novel pathogens in the past 15 years such as the Nipah virus, Severe Acute Respiratory Syndrome Coronavirus (SARS-CoV), avian influenza virus, the 2009 pandemic H1N1 virus and multidrug-resistant tuberculosis (MDR-TB).

With the high likelihood of the emergence of another novel bacterium/virus, and the impossibility to predict when and which infectious disease will hit our region next, many armed forces have stockpiled antiviral drugs and antibiotics as a mitigation strategy for maintaining operational readiness of their forces in the event of an outbreak. This means that a large variety of drugs needs to be stockpiled. Additionally, the appearance of drug-resistant pathogens before or during an outbreak would severely affect the efficacy of these treatment strategies. Furthermore, antivirals that inhibit highly specific targets might not be effective against novel causative pathogens lacking these targets. A novel approach of 'one-drug, multi-bugs' has the potential to enable the reduction of stockpiled drugs, countering novel pathogen outbreaks and reducing the likelihood of developing drug resistance.

Novel Countermeasures for Viral Iinfections

Instead of targeting the pathogens directly, DSO's 'one drug, multi-bug' approach uses novel compounds that mobilise generic anti-viral mechanisms of the host's innate immune system which can be activated within seconds/minutes. In a preliminary study, DSO discovered that PIKA, which is an analogue of double-stranded ribonucleic acid and a ligand for Toll-like receptor three (part of the innate immune system), inhibits influenza replication effectively in mice. The results from our collaboration with investigators from The National Institute of Allergy and Infectious Diseases, U.S.A., further strengthened this idea by demonstrating that intranasal administration of PIKA inhibits the replication of a broad spectrum of influenza viruses, including the 2009 pandemic H1N1 and avian H5N1 influenza viruses, in mice. Additionally, PIKA can be co-administered with Tamiflu to slow down the appearance of Tamiflu-resistant mutants. This approach of mobilising generic anti-viral mechanisms of the host to fight the infection, rather than to inhibit a specific pathogen directly, also makes it difficult for a virus to develop resistance. With the encouraging results from the animal studies, DSO is currently investigating the potential of using PIKA to treat other viral infections, and its potency in activating human cells as a proof-of-principle study to support the use of PIKA as a broad spectrum antiviral and adjuvant for humans.

Figure 1 Data demonstrating that administration of PIKA inhibited replication of a broad spectrum of influenza viruses in lungs of mice. (Extracted from Lau et al. Virology 406:80 2010)



TARGETING THE INNATE IMMUNE SYSTEM

Novel Countermeasures for Bacterial Infections

Based on the findings of previous research projects as well as literature reviews, DSO has inferred that one of the two categories of bacteria - the Gram negative bacteria - causes disease by evading immune detection until it has overwhelmed the human host's defences. This is done through a series of molecular events in the bacteria which results in a change in its cell wall structure, such that the initial immune response to an infection is not initiated.

Using the Gram negative *Burkholderia pseudomallei* bacterium (see Figure 2) - the etiological agent of Melioidosis (a disease endemic in Singapore and Southeast Asia) - as the model agent in our study, our team showed that the outer membrane of this bacterium contains lipopolysaccharide molecules. These were found to exhibit low-level immunological activities in vitro. Together with structural data, it indicates that *B. pseudomallei synthesises* unique lipid A species with long-chain FA C14:0(2-OH) and Ara4N-modified phosphate groups, hence allowing it to evade innate immune recognition by Toll-like receptor (TLR)-4.

Concurrently, DSO has also set up the Melioidosis disease model in mice in the Animal Biosafety Level Three Laboratory to probe host-pathogen immune responses as well as to identify the immune cell types and mechanisms involved in conferring protection against the inhalational bacterial challenge. Presently, DSO is also working closely with government hospitals to recruit patients with Melioidosis. This prospective study will enable us to investigate the pathogenesis of this infection in humans by characterising the host-pathogen interactions, and potentially translate *in vitro* and *in vivo* animal study findings into improving treatment regimens.

With our new understanding of immune evasion by the bacteria and the established murine model of melioidosis, DSO is currently working with industrial partners who have developed potential immune-modulators that could be used as novel therapeutics. Should the results be successful, this emerging concept could lead to a completely new mode of dealing with biological agents with the advantage of potentially achieving antimicrobial effects in a broad spectrum manner.

Figure 2 *Burkholderia pseudomallei* colonies on Ashdown agar


Maximum Load within chamber:
Do not exceed 500kg/m²
For tubs of water:
Do not exceed a depth of 50cm
n 1sq m of chamber space

HEAT STRESS MITIGATION FOR ENHANCED SOLDIER PERFORMANCE

The debilitating effects of heat stress on combat performance are well known. These include increased fatigue, a slower recovery time and the increased risk of being a heat stroke casualty. With the SAF training and operating in a tropical hot and humid climate, the Defence Medical and Environmental Research Institute (DMERI) has made heat stress research one of its key foci so as to ensure the safety, health and performance of the SAF trooper.

HEAT STRESS MITIGATION FOR ENHANCED SOLDIER PERFORMANCE

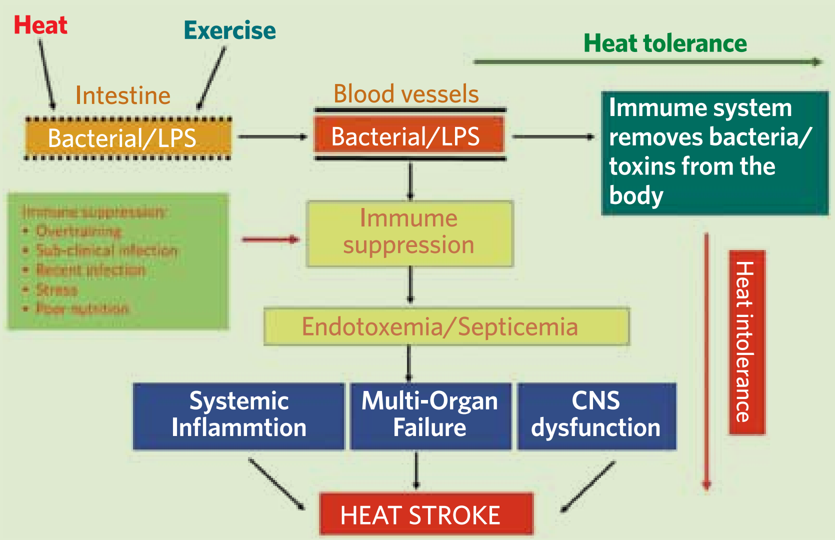
Understanding and Managing Heat Stress Better

DMERI has been working with the SAF over the past decade to understand the related issues on heat stress and investigate operational intervention and prevention strategies. This has built up a core capability in heat stress research that impacts how the SAF operates. While the detrimental effects of heat stress on the health and performance of soldiers dominated earlier research efforts, the recent thrusts encompass the full scope of operational factors affecting today's training and combat missions. These include investigations into how physical training, heat acclimatisation, cooling and fluid ingestion can be used as strategies to mitigate heat stress and even improve combat performance.

With the transformation of future fighting concepts, the SAF has introduced the use of the Integrated Body Armour Vest (iBAV) into their operational doctrine, so as to increase the level of protection and survivability of our soldiers. Studies were required to evaluate the impact of operating with body armour on the physiological responses and performance of a soldier exposed to the tropical heat. Heat Acclimatisation (HA) was one of the key strategies evaluated by DMERI to alleviate heat strain associated with the body armour. A 10-day HA programme was customised to integrate with the SAF's training, to bring about the necessary biological adaptations required to reduce physiological strain (e.g. heart rate and body temperature), and improve work capacity with the iBAV on. It was observed that even for trained individuals who habitually live and train in a tropical climate, undergoing this systematic 10-day HA programme can still mitigate the associated physiological stress. They were also able to enhance work tolerance by 21%. These findings have provided the SAF with the scientific evidence to better understand and appreciate the physiological costs associated with the use of the iBAV, resulting in the development of a new training directive implemented SAF-wide.

In addition to body armour operations, DMERI's expertise in this heat stress area was also extended to help ensure the safety of soldiers performing chemical, biological, radiological and explosive defence operations. As the protective suits donned by these personnel compromise effective heat dissipation, DMERI undertook an investigation to evaluate and optimise their Work Rest Cycles (WRC). The WRC evaluation trials showed that the current WRC, when used by heat-acclimatised Medical Response Force troopers in a typical deployment, is safe for both day and night operations. The study has given commanders a better assessment of the heat stress load faced by their troops during training and operational deployment, even when they are operating within the limits of the WRC. This enables commanders to make more informed decisions without compromising safety, should the need to change the operational profile or manning requirements arise.

Figure 1 The dual pathway model of heatstroke



HEAT STRESS MITIGATION FOR ENHANCED SOLDIER PERFORMANCE

Apart from training and behavioural interventions, DMERI has also done extensive research in the area of fluid ingestion as another mitigation strategy for heat strain. Ongoing work in this area is focused on continual verification of the merit of the existing guidelines for fluid intake, as well as investigating the performance and fluid balance in endurance races and activities in tropical environments. These continuing investigations have enabled the development of new scientifically sound and effective guidelines as part of the overall heat stress mitigation strategy for the SAF.

Beyond addressing the issues of heat stress from an applied research perspective, DMERI is currently undertaking a more basic research approach to understanding the science and mechanisms of heat stroke, in search of more novel and effective mitigating strategies. Investigations have been focused on the dual pathway model of heat stroke (see Figure 1), where below the point of cellular thermolysis, heat stroke is triggered by a combination of heat stress and endotoxemia. This is fundamentally different from the classical understanding of heat stroke brought about by high core temperature (i.e. heat stress). Based on this new understanding and further research, it is envisioned that preventive measures for heat stroke will not only focus on managing heat stress, but also on protecting the body from the effects of endotoxemia.

It was observed that even for trained individuals who habitually live and train in a tropical climate, undergoing this systematic 10-day HA programme can still mitigate the associated physiological stress. They were also able to enhance work tolerance by

21%

Emerging Technologies

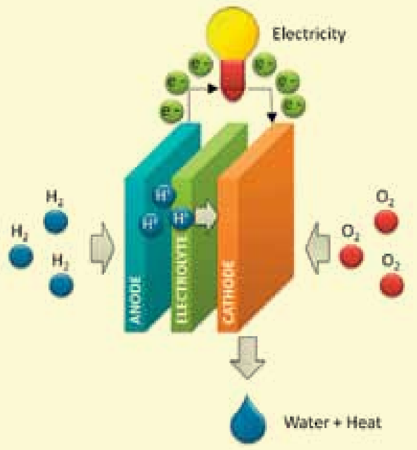
As Singapore's national defence R&D organisation, DSO looks beyond the horizon to exploit advances in modern technology, and innovate new systems and capabilities that will continue to give the Singapore Armed Forces (SAF) the critical edge.

HYBRID POWER UNMANNED AERIAL VEHICLE

The ability of UAVs to stay in the theatre of operation and maintain persistent presence over targets is pivotal in the modern battlefield. A longer flight endurance is required to achieve a persistent presence. This, in turn, is directly dependent on the type of power source used for propulsion of electrically powered UAVs.

HYBRID POWER UNMANNED AERIAL VEHICLE

Figure 1 Illustration of a single hydrogen PEM fuel cell



DSO's fuel cell system is able to provide a continuous power draw of 200W with a conversion efficiency of about

50%

throughout its design operating range.

The most commonly used power source would be advanced lithium-polymer (LiPo) batteries. Such battery technology offers an energy density of approximately 180 Watt hours per kilogram (Wh/kg) at best.

Recent research and development on UAV fuel cell technologies have shown that a Hydrogen Proton Exchange Membrane (PEM) fuel cell offers a much higher energy density - almost double - as compared to LiPo batteries.

In general, a PEM fuel cell (see Figure 1) refers to an electrochemical energy conversion device which converts hydrogen and oxygen into electrical energy. In the process, it produces only water and heat as by-products. Hydrogen is commonly used as a fuel in PEM fuel cells as it is a versatile energy carrier that offers the prospect of supplying the world with clean, sustainable electrical power.

With its energy density merit, hydrogen PEM fuel cells also represent a viable alternative power source that will help to enable better flight endurance, as well as the incorporation of more power demanding payloads to achieve expanded mission capabilities for mini-UAVs.

As such, DSO undertook an initiative to explore hybrid powered flight for mini-UAVs. With support from industrial partners, a Hybrid UAV Power System comprising a hydrogen PEM fuel cell system, a LiPo battery pack and a smart Power Manager was developed.

DSO's hydrogen PEM fuel cell system (see Figure 2) is a heavily customised version of a Commercial-Of-The-Shelf (COTS) unit that meets stringent mechanical packaging and operation constraints for UAV flight. One of the greatest challenges faced was the performance degradation of the fuel cell due to the major level of customisation needed for the system to fit into a space constrained airframe. However, DSO's fuel cell system is able to provide a continuous power draw of 200W with a conversion efficiency of about 50% throughout its design operating range. At over 450 Wh/kg, or 2.5 times the energy density of the available advanced batteries, this ultra compact fuel cell system is capable of meeting the nominal power demands of a mini-UAV during cruising, and can extend its flight endurance by two to three times, depending on flight conditions.

HYBRID POWER UNMANNED AERIAL VEHICLE

During periods of higher power demands such as take-off, climbing and manoeuvring in severe weather conditions, the LiPo battery is used to augment up to three times the nominal power of the fuel cell system. The battery also serves as an emergency failsafe power source for the UAV in the event of a fuel cell system shut down.

Managing the power from two energy sources into a single output that is able to meet varying power demands of the UAV is made possible with the smart Power Manager. Functionally, the Power Manager is capable of concurrently drawing power from the fuel cell and the battery in order to meet the power demands of the UAV. The Power Manager also incorporates a smart power management algorithm that handles seamless power switching between the energy sources, enables LiPo battery charging with excess power from the fuel cell system and provides essential power system health telemetry data to the flight control computer. Another challenge faced was to incorporate all these functionalities in the form factor of a small electronic card. However, with the help of industrial partners, the Power Manager measures only 10cm x 7.5cm x 2cm and weighs only 75g. It is also capable of delivering more than 800W of output power, has an efficiency of more than 95% and possesses extremely low Electromagnetic Interference/Electromagnetic Compatibility (EMI/EMC) characteristics.

DSO's Hybrid UAV Power System (see Figure 3) was successfully integrated and flight-tested in a technology demonstrator mini-UAV.

To date, DSO's Hybrid UAV Power System has been able to provide the technology demonstrator mini-UAV (see Figure 4) with a flight endurance of more than four hours.

This achievement represents an improvement of two to three times the flight endurance originally provided by one of the best LiPo batteries available in the market.

DSO is currently working closely with industrial partners such as Singapore Technologies Aerospace to overcome other key challenges such as life cycle cost, field operations and the durability of the fuel cell system.

Figure 2
Comparison between a COTS hydrogen fuel cell system (left) and a DSO-customised version (right) developed for a mini-UAV

Figure 3
Illustration of DSO's Hybrid UAV Power System

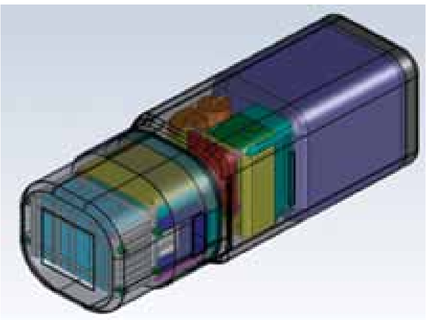


Figure 4
DSO technology demonstrator UAV with Hybrid UAV Power System

TORNADO-LIKE JETS TECHNOLOGY FOR UNMANNED AERIAL VEHICLE DRAG REDUCTION APPLICATIONS

Drag reduction has many payoffs in the performance of air systems. These payoffs can range from increased range and endurance, to reduction in fuel consumption and weight. As an example, a 1% reduction in total drag could save about 1% in fuel consumption.

TORNADO-LIKE JETS TECHNOLOGY FOR UNMANNED AERIAL VEHICLE DRAG REDUCTION APPLICATIONS

As such, drag reduction technologies have been of persistent and particular interest to the aeronautical community. To date, many drag reduction concepts have been explored in various flow conditions with successful demonstrations of apparent drag reduction effects in laminar-turbulent transitional flows (where parallel streamlines of a fluid start to crisscross each other), and boundary layer separation flows (where streamlines of a fluid separate from surfaces of vehicles). However, existing research remains notably deficient in fully-developed turbulent (chaotic and random) flow conditions where the slow-moving turbulent boundary layer flows are perfectly attached to the surfaces of the vehicles. The challenges lie in the physical nature of the near-wall turbulence production, and drag generation mechanism involving complex spatiotemporal dynamics in small turbulence length scale (order of approximately 0.1mm for aircraft) at random locations. The current state-of-the-art solution involves active boundary layer flow control via Micro-Electro-Mechanical Systems (MEMS) for sensing and actuation. However, the implementation and maintenance cost of such massive MEMS arrays is too high for practical applications.

As an alternative, DSO has looked into novel passive drag reduction approaches such as Tornado-Like Jets Technology (TLJT). In the late 1970s, it was discovered experimentally that when flow runs over a dimpled surface similar to a golf ball, it forms self-organised secondary vortex jets emanating from the dimples. These secondary vortex jets – or Tornado-Like Jets - have dynamically similar flow structures to those of naturally occurring tornadoes.

Technologies developed upon the physical properties of such jets have therefore been termed 'Tornado-Like Jets Technologies'. The detailed structures of the TLJ secondary flow in, and around, a dimple can be seen in Figure 1. The well-developed TLJ vortex jet sucks flow from the slow moving near-wall boundary layer flow around the dimple into its core, and carries this mass away from the dimple into the main flow. In doing so, small scale disturbances and turbulence are removed from the near-wall boundary layer flow, resulting in a decrease in the thickness of slow moving boundary layer flow, and a consequent reduction in the overall friction drag.

The design of the TLJT dimples to reduce drag in UAV components requires detailed experimental study of dimple parameters. Parameters include the diameter, height, spacing and density with respect to flow parameters such as the Reynolds numbers based on dimple size and general length scale of the UAV, as well as boundary layer parameters such as displacement thickness and momentum thickness. The wide range of TLJT parameters and flow conditions represent formidable obstacles for detailed experimental studies. DSO has overcome these obstacles by adopting an innovative dimple control concept in airfoil/wing models. Figure 2 shows the proposed dimple control concept along with a three-dimensional see-through view of the metallic model used in a TLJT airfoil/wing study. It can be seen from Figure 2 that the whole airfoil/wing is built upon an airfoil/wing base in which pressure tubes and vacuum pipelines are laid. A dimple-hole template with circular cut-outs is then mounted onto the base, followed by an upper layer of elastic membrane.

Figure 1 Illustration of TLJ vortex

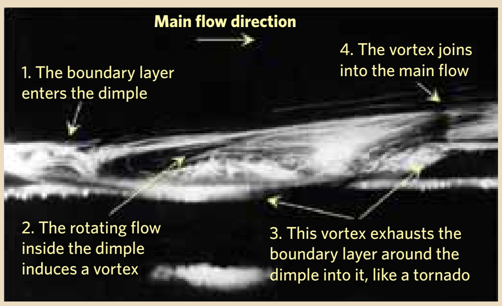
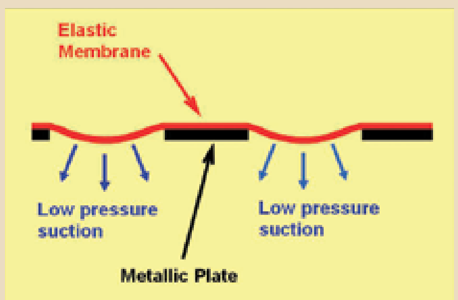
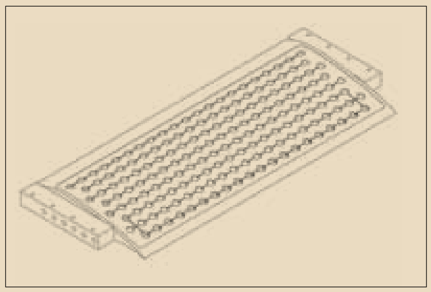


Figure 2 Dimple control concept used in TLJT airfoil study





The same construction is used for both the top and bottom surfaces of the airfoil. The pressure tubes and vacuum pipelines are laid along each row of dimples so that the dimple depth in each row can be controlled independently, or looped into a cluster of several rows.

With this setup, parametric studies can be conducted in a more systematic manner across the range of TLJT parameters for effective drag reduction, and to derive the final design of the TLJT airfoil/wing. Figure 3 shows the comparison of drag measurement results between smooth and TLJT airfoils.

With the successful drag reduction results achieved with the TLJT airfoil/wing, DSO incorporated the TLJT design in full scale UAV wing and fuselage components. As indicated in Figure 4, a low speed wind tunnel test of a large scale TLJT UAV wing demonstrated nearly 6% reduction in drag. In Figure 5, results from another low speed wind tunnel test using a full scale model of a UAV fuselage alone show a 6-8% drag reduction in conditions of high angles of attack (8 - 10 degrees).

Based on the low speed wind tunnel measurements of the large scale wing and fuselage models, it can be concluded that with properly designed TLJT dimples, drag reduction effects in a low speed flow regime are promising. However, more advanced research is needed to mature the technology for practical/engineering applications especially in flow regimes where flow characteristics are inherently three-dimensional, with mutual interference among different components.

Figure 3 Comparison of drag measurement results of smooth and TLJT airfoils

Figure 4 Comparison of drag measurement results of smooth and TLJT wings

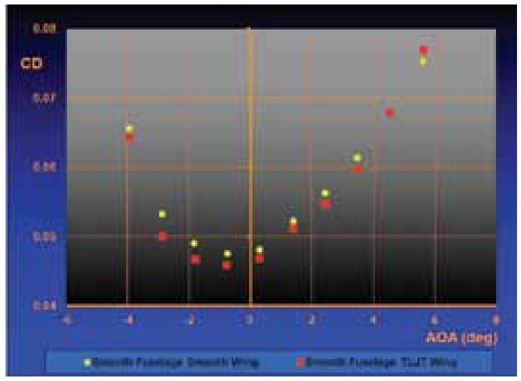
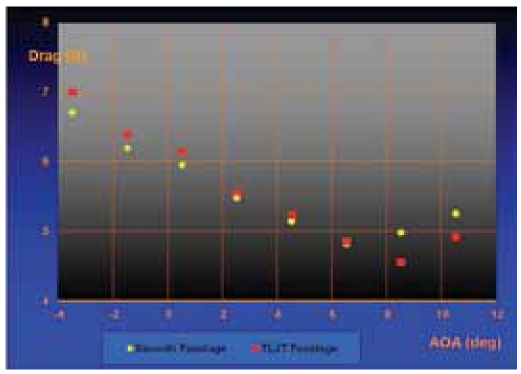


Figure 5 Comparison of drag measurement results of smooth and TLJT UAV fuselages




RGB Color Image
CIR Color
pike

HYPERSPECTRAL TECHNOLOGY FOR UNMANNED AERIAL VEHICLES

Hyperspectral sensors are able to capture information of a scene that is beyond the visible range. They can be mounted on an airborne platform, which scans the scene and then returns a three-dimensional data cube.

HYPERSPECTRAL TECHNOLOGY FOR UNMANNED AERIAL VEHICLES

Each data cube consists of spatial pixels, within which contain contiguous bands* of spectral information, usually in the form of radiance (see Figure 1).

Hyperspectral Sensor Technology

Current methods of Hyperspectral Imaging (HSI) fall broadly into two different classes: dispersive optics based methods and Fourier Transform Spectroscopy (FTS). Dispersive optics based methods typically use diffraction gratings or prisms to disperse light so that different optical wavelengths fall on different pixels of the detector array and their intensity can be measured.

With FTS methods however, the optics used create interferometric fringes on the detector array and the spectral data is extracted by performing a Fourier transform.

One of the more common FTS setups using a Michelson interferometer is shown in Figure 2.

The basic working principle is to split an incoming light beam into two separate beams. As a result of the difference in optical path lengths, the beams will interfere at the detector which measures the resultant intensity (see Figure 3).

By moving one of the mirrors, the optical path length can be varied. If the beam of light is monochromatic, a sinusoidal fringe pattern is observed. The peaks of the fringe pattern are a result of constructive interference when the optical path difference is a multiple of the wavelength of the monochromatic light, while the troughs are the result of destructive interference when the optical path difference is a multiple of half the wavelength of the monochromatic light.

The same interferometric effect can also be achieved through the use of birefringent crystals. A birefringent crystal is an anisotropic medium which exhibits double refraction and splits a light beam into two light rays called the ordinary and extraordinary rays. These two light rays are orthogonally polarised and experience different refractive indices when passing through the crystal.

At DSO, researchers made use of this fact to invent an optic called Polarisation-based Fourier Transform, also known as PolarFour, for implementation in an FTS-based HSI camera.

Figure 1 Hyperspectral data cube consisting of many contiguous bands of spectral information. Spectral information of the scene is extracted pixel by pixel. For each pixel, spectra information from each band is processed and combined to form a spectra curve of radiance against wavelength

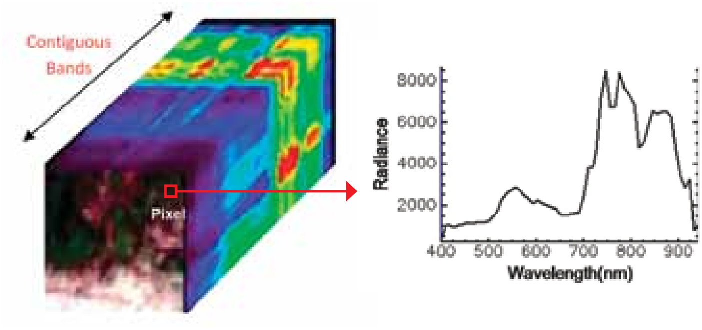
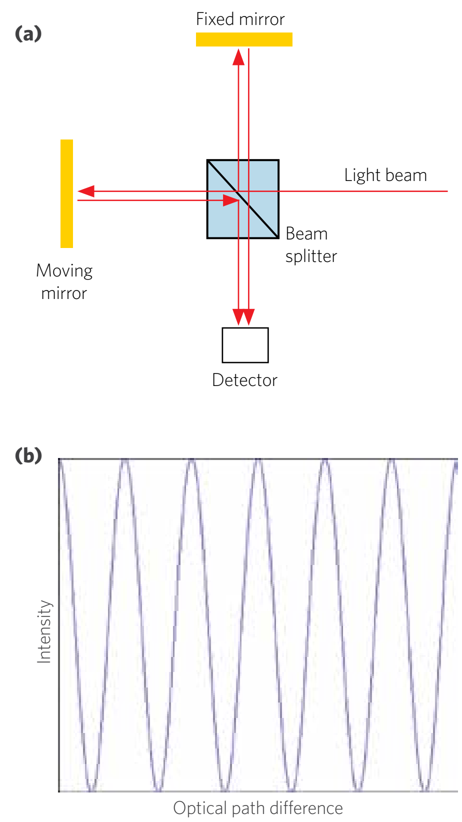


Figure 2 (a) Fourier Transform spectrometer setup using a Michelson interferometer
(b) A Sinusoidal fringe pattern observed due to a monochromatic input light source



* The EM spectrum is divided into discrete bands, where each band represents a range of wavelengths

The PolarFour HSI Camera

The PolarFour optic essentially consists of a cascade of specially cut and oriented birefringent crystals. One advantage of such a setup is that the interference of light occurs within the crystals thus making the fringes very stable when compared to other interferometric HSI cameras employing free space interferometers. This stability is vital in improving the accuracy of the spectral data obtained, and also in employing the camera in platforms that are always subjected to vibrations.

When the PolarFour optic is placed in front of a camera's lens, optical fringes are created in the captured image as shown in Figure 4.

These fringes are the result of the polarisation modulation effects of the birefringent crystals and the interference of light. Each point in the image corresponds to a certain optical path difference experienced by light passing through PolarFour.

To obtain spectral information, the PolarFour HSI camera first needs to be used to scan through the area of interest. Every pixel is then traced through the captured images, as illustrated by the coloured dots in Figure 5, to obtain their intensity values at the various optical path differences.

The intent is to build up the interferogram for each and every image point as it passes through the fringe pattern. Finally, a Fourier transform of the interferograms is used to obtain the spectrum of the image points (see Figure 5).

Compared to conventional HSI cameras, the PolarFour camera is light and compact, making it suitable for use on airborne platforms such as UAVs.

Figure 3 Illustration of a two-point source interference

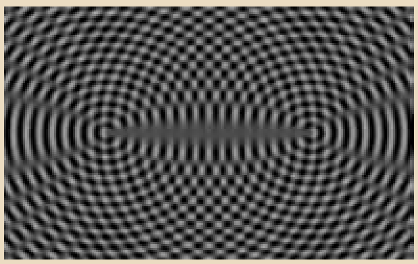
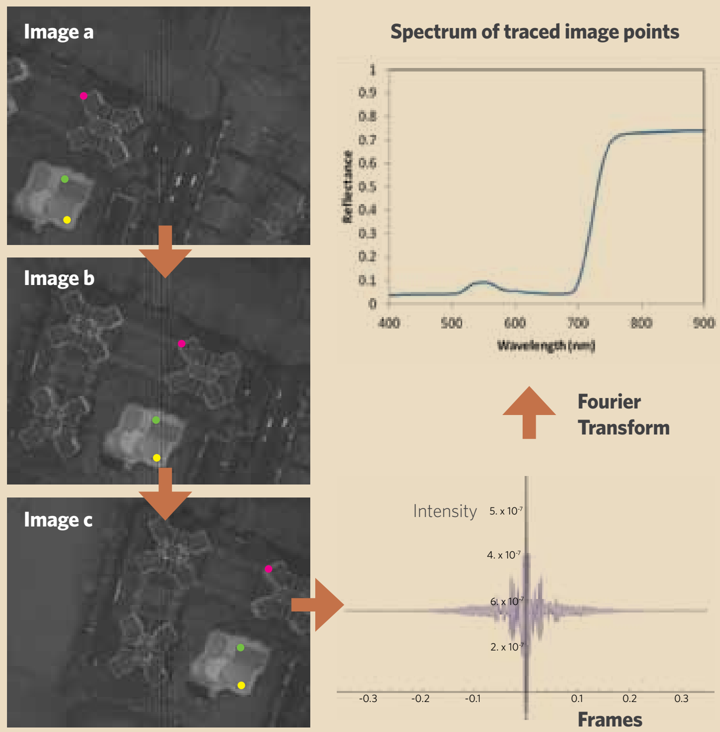


Figure 4 Sample image showing fringes as captured by a PolarFour HSI camera

Figure 5 Retrieval of spectral information



HYPERSPECTRAL TECHNOLOGY FOR UNMANNED AERIAL VEHICLES

Hyperspectral False Colour Image

Once the spectrum is recovered, each and every image point can be represented by a certain colour format. This is done by choosing any three wavelength bands of the recovered spectrum to be represented by the red (R), green (G) and blue (B) components of a regular LCD screen. Hyperspectral false colour images help us to visualise spectral information (see Figure 6).

Pre-processing of Hyperspectral Data

Due to effects from surrounding objects and the atmosphere, the Hyperspectral data obtained directly from Hyperspectral sensors is never 'clean'. As such, pre-processing has to be carried out in order to obtain meaningful data that can be exploited.

However, delving into the steps required for pre-processing requires an understanding of two frequently used terms in Hyperspectral technology: Radiance and Reflectance.

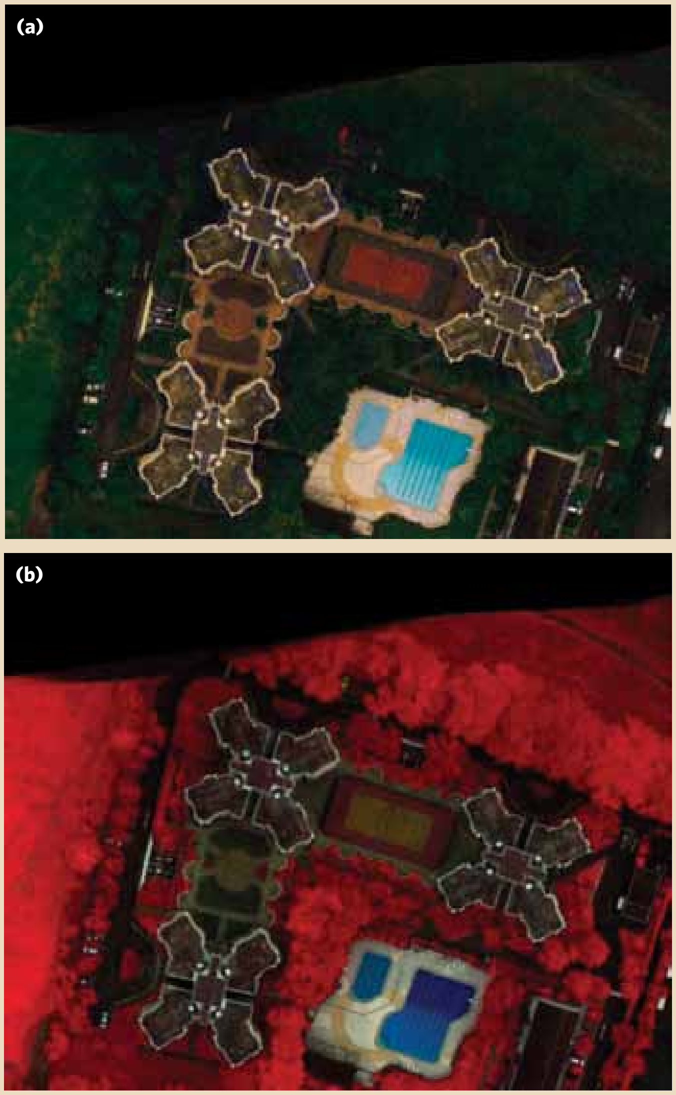
Radiance and Reflectance

Radiance, or material radiance, is a measurement that describes the amount of energy that falls on, or is emitted by a material surface. Material reflectance is the ratio of reflected energy to incident energy, as a function of wavelength. This quantity is unique to the material (see Figure 7), and with adequate spectral resolution, it can be used for material detection and identification. Ideally, the radiance obtained from each pixel of the data cube represents the spectral information of only the material that is present in that pixel - otherwise known as the target radiance.

However, in most situations, the radiance obtained from each pixel of the data cube is a mixture of the target radiance due to the material present in that pixel, coupled with radiance due to ground reflectance, atmospheric effects and the surrounding three-dimensional (3D) environment (see Figure 8).

Hence, it is important to untangle these varying effects to obtain the target radiance and hence derive the target reflectance, which remains unchanged in all scenes. In this way, the reflectance map of the scene can be used to identify and detect targets under all scenarios. DSO's Hyperspectral team has embarked on a project to correct the unwanted effects using atmospheric correction techniques.

Figure 6 (a) True Red, Green, Blue (RGB) image of a scene;
(b) Hyperspectral false colour image of the same scene



Pre-processing

The first step in atmospheric correction requires the retrieval of the atmospheric constituents, in particular, the water vapour content along with the aerosol type, and loading. With this knowledge, radiative models can then be used to correct the at-sensor radiance to reflectance.

Many examples of such retrievals can be found in existing literature and some use a method known as Dark Dense Vegetation. In this technique, the vegetation reflectance in the visible range is estimated using the reflectance in the Short Wave Infrared (SWIR) band. The basis of this method is that the aerosol impact is less obvious at longer wavelengths, and there is some known correlation between the vegetation reflectance in the SWIR and visible band. With this estimated reflectance, radiative transfer models are used to simulate the at-sensor radiance with various aerosol parameters, with the in-scene aerosol properties being the parameters which give a simulated radiance that best matches the at-sensor radiance received.

Another important factor to consider in reflectance retrieval, especially in urban environments, would be the 3D environment surrounding the target. This introduces effects such as increased light falling onto the target from secondary reflections off surrounding 3D structures, as well as occlusion of some parts of the light scattered by the atmosphere onto the target. Ignoring these effects can be detrimental, especially in shadowed areas. A collaboration between DSO and the French aerospace laboratory, ONERA, was established to study the ways in which such effects can be corrected. One way of correcting for surrounding 3D structures could involve, for example, assuming that the target pixel receives light from only half of the sky dome. Taking this into consideration in the retrieval would improve the accuracy of the final reflectance, giving rise to results shown in Figure 9.

After removing the shadow and atmospheric effects, the processed radiance curve can now be deployed to useful applications of Hyper-spectral Technology. Two of them are described in the next section.

Figure 7 Uniqueness of spectral information left behind by different materials

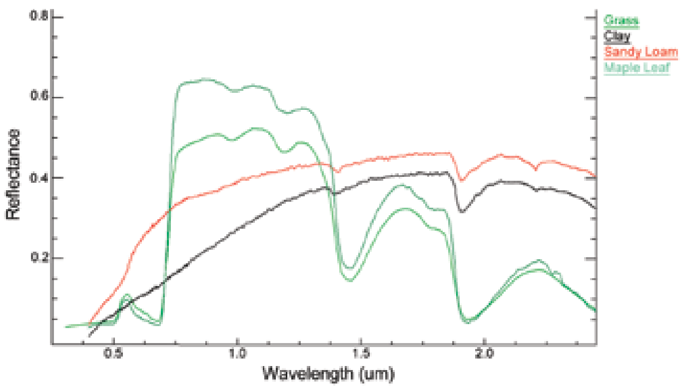


Figure 9 Shadow corrected image (a) before and (b) after

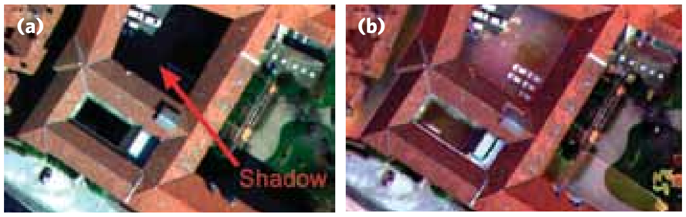
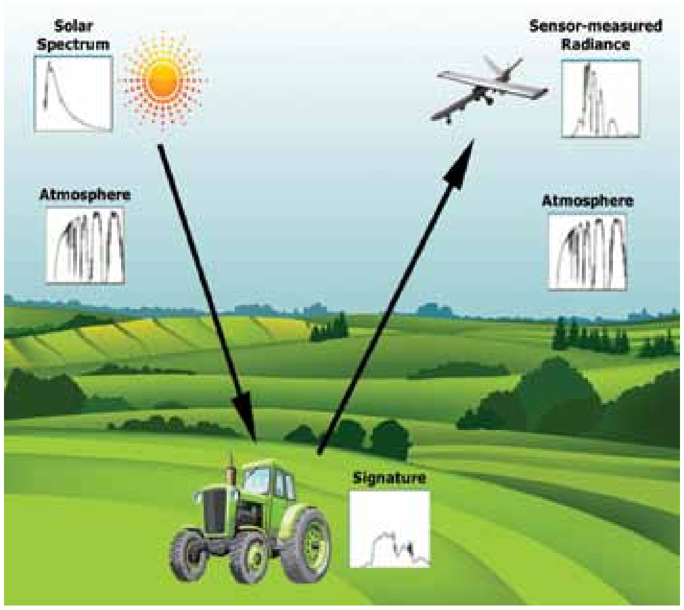


Figure 8 Illustration of the components that form the at-sensor radiance. Energy from the sun is absorbed or scattered by particles in the atmosphere; some of that energy reaches the material/object; a fraction of it then gets reflected; this reflected energy then goes through the atmosphere again (where some of it is absorbed or scattered) and is measured at the sensor. Secondary reflection of energy by surrounding materials in the scene may also be picked up by the sensor



HYPERSPECTRAL TECHNOLOGY FOR UNMANNED AERIAL VEHICLES

Applications of Hyperspectral Technology

Target Detection

An important ability in target detection is the automation of the process of picking out specific targets from a scene. Target detection can be carried out via material detection or anomaly detection (or both). A significant difference between the two methods is that material detection requires that the target's spectral (a spectral refers to the Radiance or Reflectance curve) be known while anomaly detection does not.

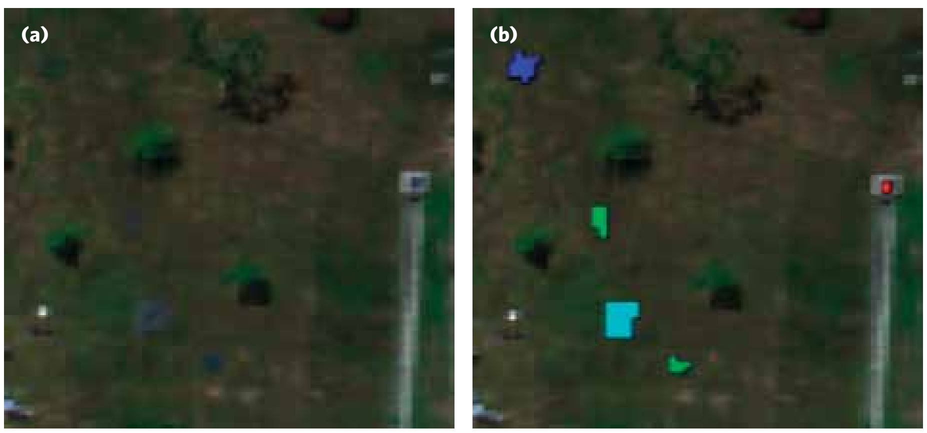
Material Detection

Every object has a unique spectral signature. We can make use of this property to perform material detection. Material detection is carried out via a method known as Spectral Matching.

Spectral Matching measures how similar the unknown spectral is to the target spectral. The smaller the spectral distance, the greater the similarity between the two spectrals. The job of the spectral matching algorithm is to flag out pixels that have similar spectral to the target spectral, assuming that the target spectral is known. Target spectral can be obtained from standard spectral libraries.

The Adaptive Coherence Estimator (ACE) match filter provides us with an alternative method to perform material detection. The spectral distance used here is measured by the correlation between the unknown spectral and the target spectral. The higher the correlation, the greater the similarity between the two spectrals. Material detection results using the ACE match filter are shown in Figure 10.

Figure 10 (a) Input image of a scene and (b) output image obtained after material detection was carried out. An experiment was carried out where some known targets (Materials A, B and C) were planted in the scene as shown in (a). The material detection algorithm managed to flag out the materials present (Material A: Blue; Material B: Green; Material C: Cyan)



Anomaly Detection

In situations where the target spectral is unknown, anomaly detection is used to pick out the target in a given scene. For a given scene, the spectral information of each pixel is stored as a vector.
A multivariate Gaussian distribution can be used to model the data. Outlier data points are taken to be the spectral anomalies (see Figure 11) and are highlighted by the algorithm. These points or pixels highlighted by the algorithm could potentially be target pixels.

Gas Detection

Another interesting application is the detection of gas plumes. Gas species have unique absorption features in the infrared region due to their chemical nature.

Radiance values obtained at the sensor are made up of the radiance due to the gas plume, background (through the gas plume), and scattering effects of the atmosphere (see Figure 12). Gas plumes not only absorb incident energy, but also emit their own energy. As a result, radiance curves obtained from pixels that belong to the spatial region where gas plumes are present exhibit strong features that distinguish them from the rest of the image.

The position of these features can be determined and matched to known databases of gas absorption features in order to identify the type of gas.

Hyperspectral imaging thus offers a possible option to monitor a large area for dangerous gas emissions from a remote location (see Figure 13).

Figure 11

Modelling of spectral distribution for anomaly detection. A multivariate Gaussian model was fitted to the data. For each data point, the Mahalanobis distance was calculated. The Mahalanobis distance is the normalised distance from the mean of the multivariate Gaussian distribution to the data point. A threshold, represented by the dotted line, was set and any data point in the region beyond this dotted line was considered to be an anomaly

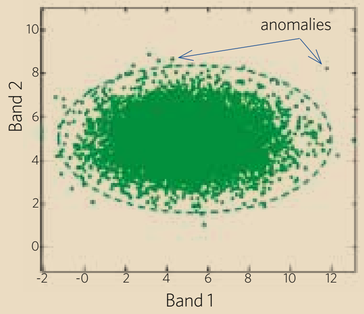


Figure 12

Radiance values obtained at the sensor are due to radiance from the gas plume, background and scattering. In addition to absorbing incident energy, the gas plume also emits its own energy, thus functioning as a radiative source

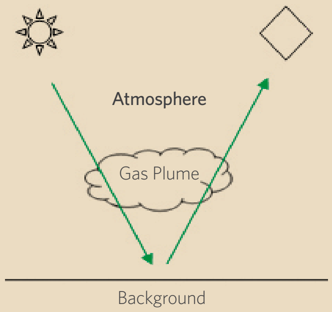
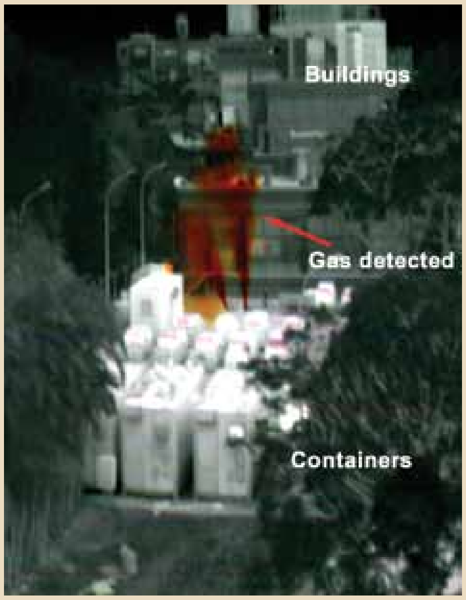
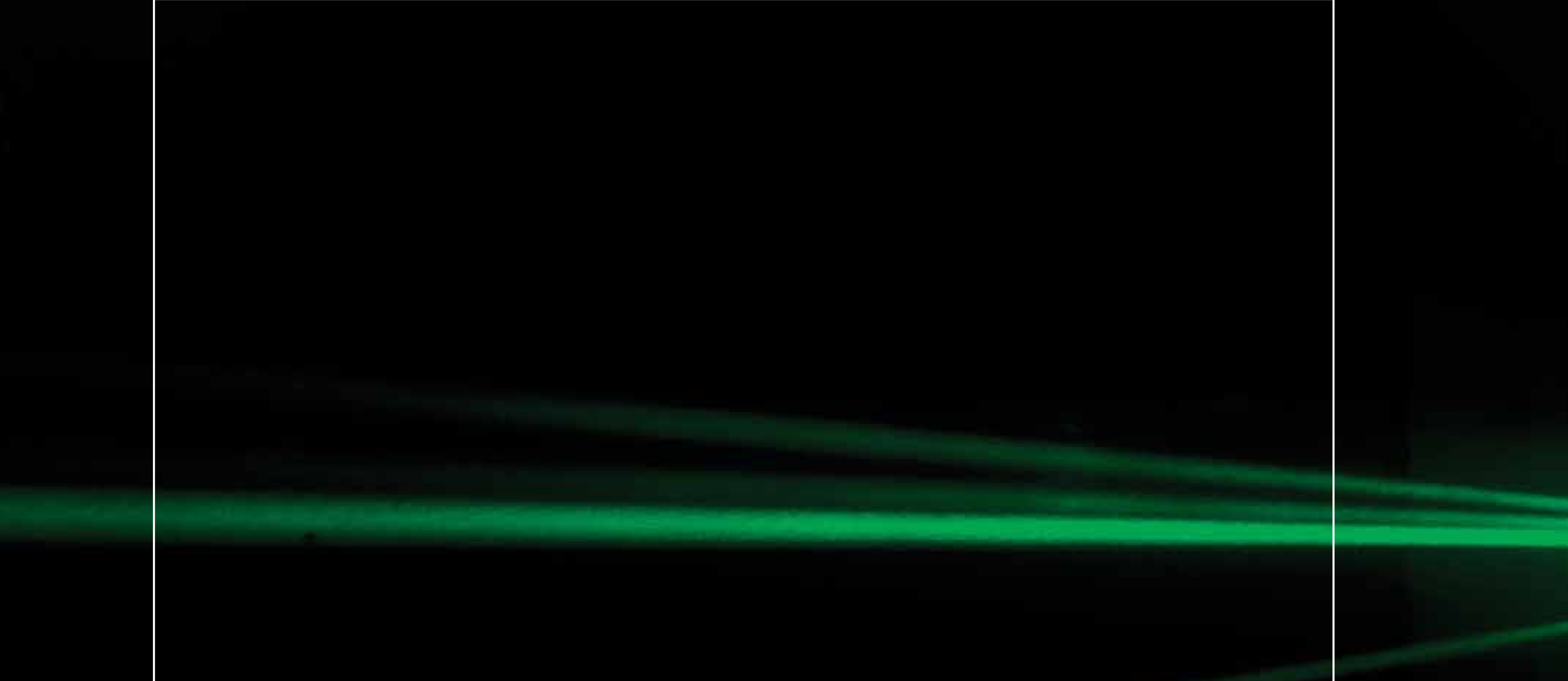


Figure 13

Hyperspectral false colour image. Illustration of gas detection





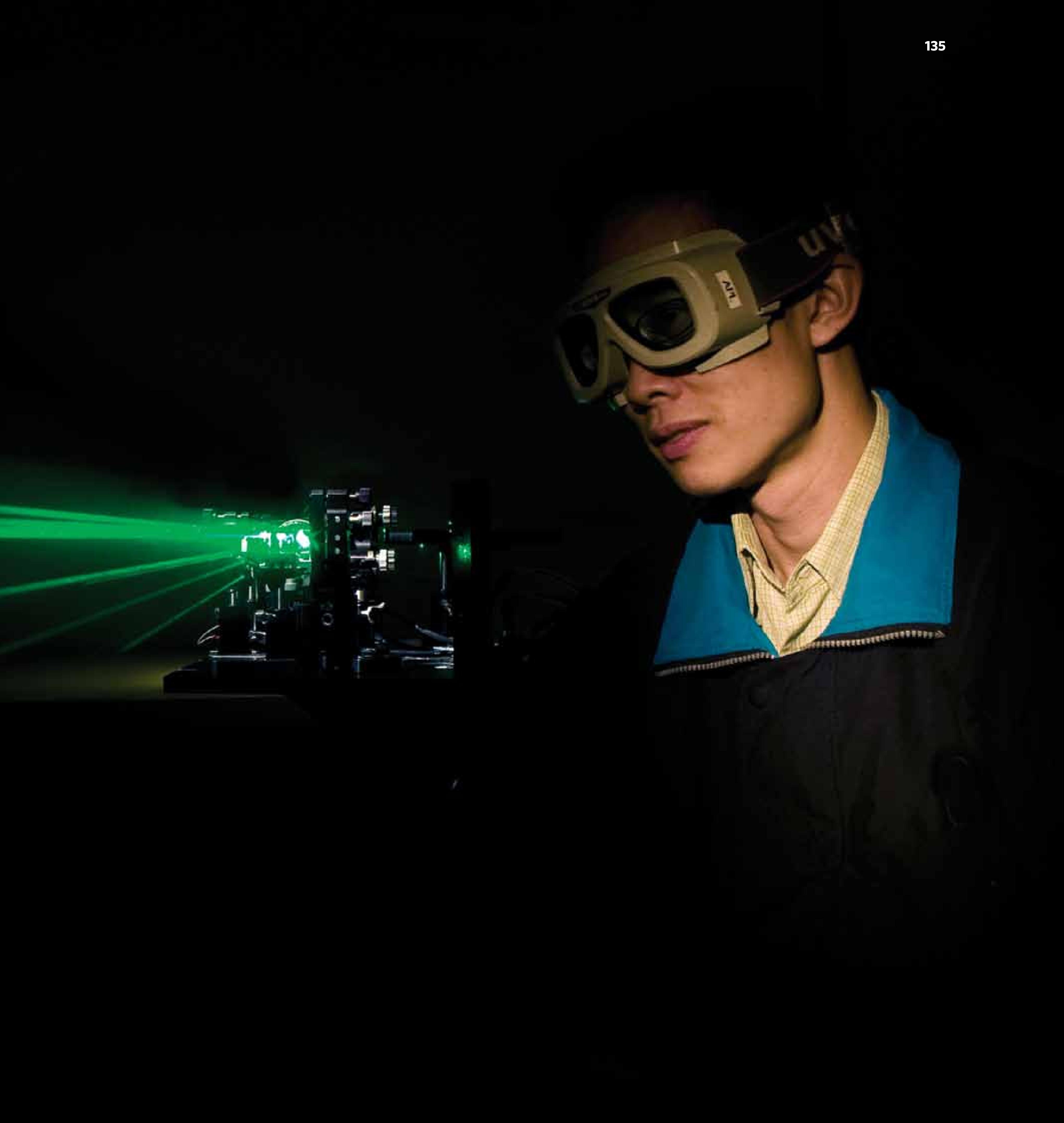
LASER RESEARCH

Lasers are attractive because of its high coherence, monochromaticity and ability to be delivered at the speed of light. There are many applications, and in defence, DSO is interested in exploring lasers for remote sensing.

Since its invention in 1960, the laser has diversified and advanced much in terms of its versatility in wavelength, pulse width, brightness level and type of active media. DSO is keen to explore and exploit this versatility by researching into novel, as well as more efficient and compact ways to generate femtosecond laser pulses (for higher peak powers), middle infrared radiation (to tap into the high transmission window of the atmosphere) and fibre lasers (for compactness, wavelength tenability and good beam quality), amongst others.

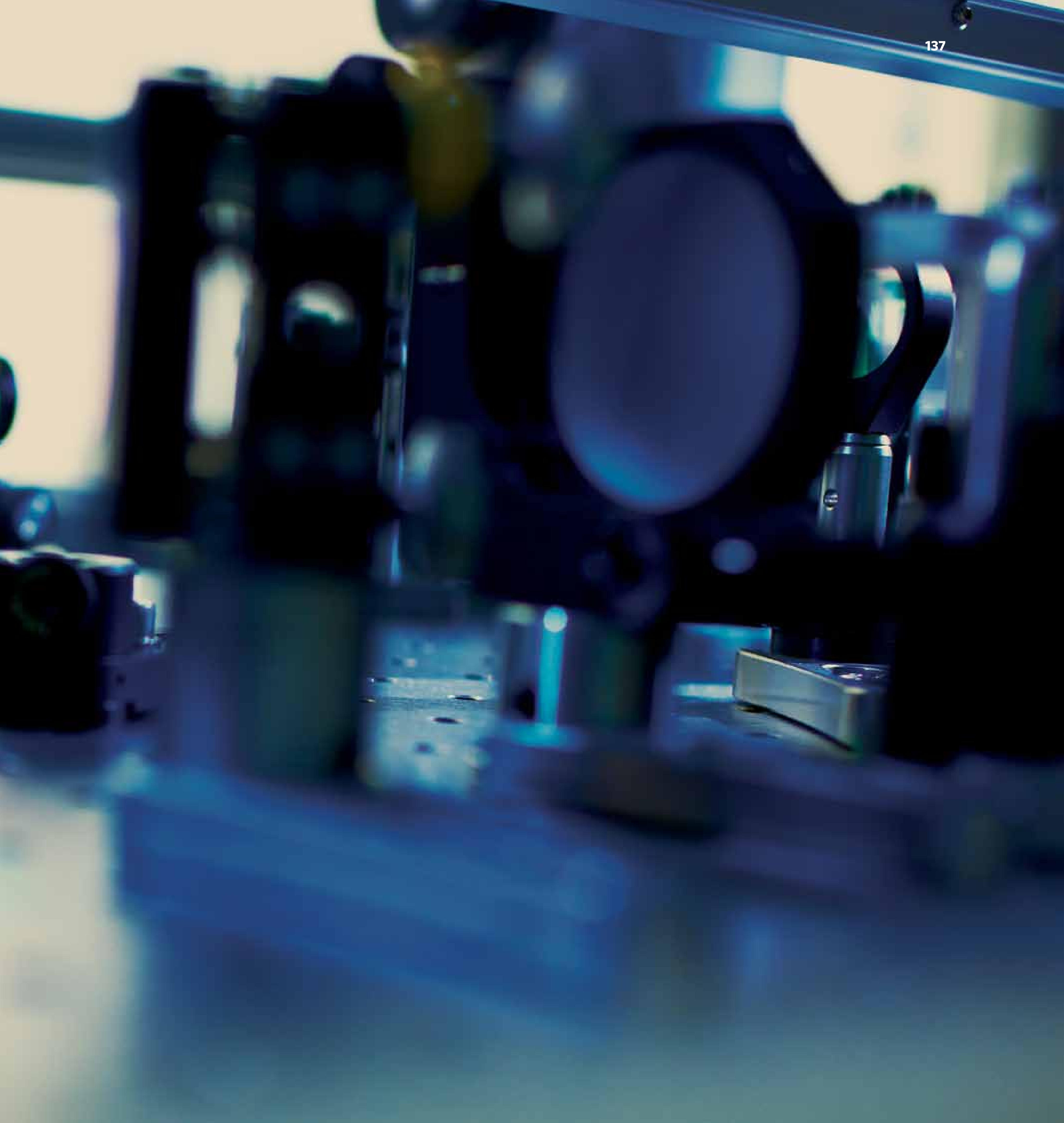
DSO is also interested in the interaction between different types of materials with lasers, for example, in the nonlinear optical response of new graphene materials.

Much of DSO's work has been recognised by peer-reviewed journals and international conferences, and we continue to actively seek collaborative partners to further advance our research.



FEMTOSECOND LASERS

Femtosecond (fs) lasers have pulse widths in the femtosecond (10^{-15}s) range. With such short pulses, lasers with high peak power can be easily achieved. These fs lasers can be used in several defence applications such as remote sensing, and have great impact on systems such as navigation, secure optical communications, chemical sensing, lidar and range finding.

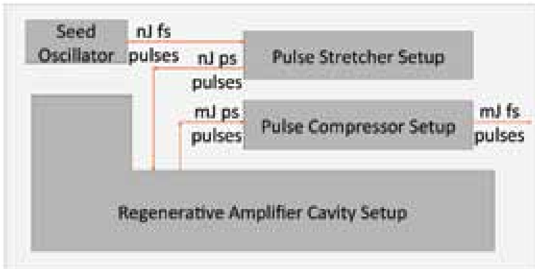


FEMTOSECOND LASERS

In spite of numerous attractive features, the extensive deployment of fs laser in the future battlefield ultimately lies in its size and cost. There are several types of fs laser sources: solid state bulk lasers, fibre lasers, dye lasers, and semiconductor lasers.

Solid state bulk lasers have the advantage of producing high quality ultra-short pulses, and have been used extensively for advanced applications such as optical clocking, supercontinuum generation, time-resolved spectroscopy, and optical parametric generation. By focusing the fs pulses, nonlinear propagation of the laser pulses can be achieved. This process is commonly known as filamentation. Filamentation can generate broadband white light continuum with a wavelength spectrum covering the absorption band of many pollutants. Filaments can propagate through hostile conditions such as rain, haze and turbulent atmospheres. Another potential application of filamentation is in lightning protection and triggering.

Figure 1 Basic architecture of Yb-based Regenerative Amplifier



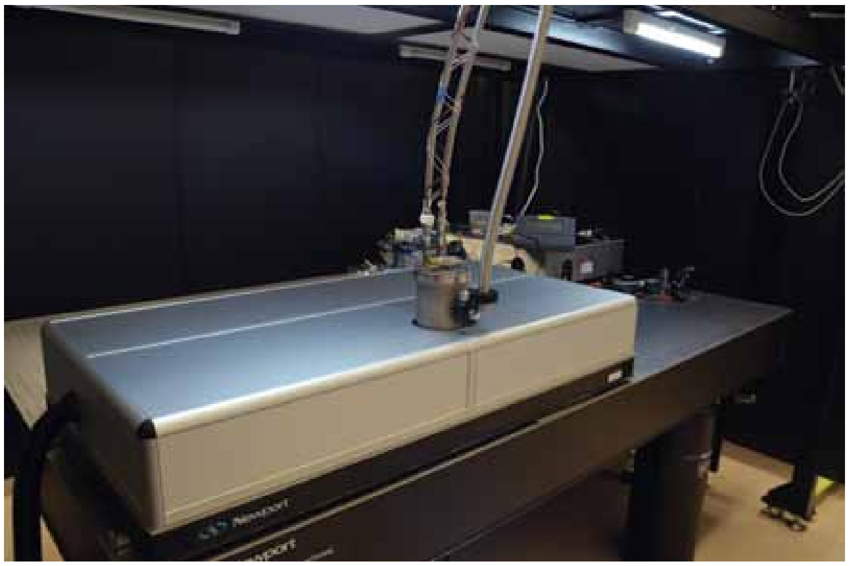


Figure 2 Yb-based Regenerative Amplifier fs laser

FEMTOSECOND LASERS

DSO has established a scientific collaboration with Vienna University of Technology (VUT) in developing high energy or high average power fs laser. The current technology that has been developed is a Yb-based cryogenic-cooled fs laser with pulse energy of more than 6mJ, operating at a 1000Hz repetition rate. The emitted wavelength is centred at 1030nm and the pulse width is ~200fs. This corresponds to a laser system with >6W of average power and >30GW of pulsed peak power. The laser system comprises a seed oscillator, a pulse stretcher, a regenerative amplifier and a pulse compressor. The seed oscillator generates sub-nJ fs pulses. These sub-nJ fs pulses are stretched to ps pulses using the pulse stretcher. The regenerative amplifier amplifies the nJ ps pulses to more than 6mJ of energy. And finally these amplified ps pulses are compressed back to fs pulses using the pulse compressor. The complete laser setup sits on a 120cm x 60cm optical breadboard. The size of this Yb fs laser is approximately two to three times smaller than the typical Ti:Sapphire fs laser.

Figure 3 Filamentation formed by focusing the fs pulses in air

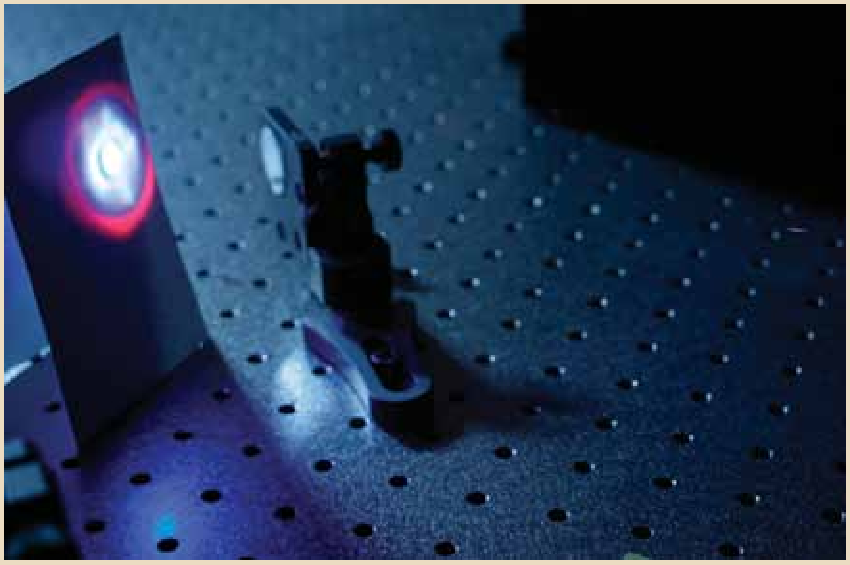


Figure 4 Bright white light generation from filamentation in air


IB LASER

MID-INFRARED LASERS

Mid-Infrared (MIR) generation refers to the generation of laser sources that emit wavelengths within the MIR range of 3-5μm. The atmosphere consists of various different molecules that can absorb certain wavelengths.

MID-INFRARED LASERS

However, there is a certain wavelength range that is not absorbed by these molecules. These wavelength ranges are commonly known as atmospheric windows, and the MIR wavelength range of 3-5μm is one of them. This gives rise to a strong motivation to generate MIR wavelengths for several atmospheric applications, such as remote sensing and detection.

In DSO, MIR generation is achieved using a nonlinear optical conversion process known as Optical Parametric Oscillation (OPO). This is an energy down-conversion process where a high energy photon splits into two photons with lower energies. In terms of wavelength, a shorter wavelength interacts with a nonlinear crystal, forming two longer wavelengths when the necessary conditions, known as phase-matching, are met. To generate MIR wavelengths, a Ho:YAG pulse laser emitting at 2.09μm is used to pump a Zinc Germanium Diphosphide (ZGP) nonlinear crystal. The ZGP crystal (Figure 1) is an attractive nonlinear crystal for MIR conversion because of its high nonlinearity, wide transparency range in MIR, high thermal conductivity and sufficient birefringence to provide phase-matching over the entire MIR range. ZGP is a ternary (comprising three elements) semiconductor, and its single-crystal form is typically grown via melt-growth. This process involves melting pre-synthesised polycrystalline materials, and its re-solidification process is carefully controlled to yield a large single crystal known as a boule. As the melting point of ZGP is >1000°C, the volatile zinc and phosphorus components can vaporise, separating them from the melt as it is heated to the melting temperature. This makes the control of the elemental proportions a key challenge in ZGP crystal growth.

The main challenge for the laser engineer using ZGP crystals for MIR generation, is the requirement of a pumping laser source emitting at a wavelength >2μm. This is because the transparency range of ZGP crystal begins from 2μm onwards. Previous work done in DSO made use of the OPO technology to convert the mature 1μm Nd:YAG laser to 2μm. This process involves an additional OPO stage to achieve MIR wavelengths, thus lowering the conversion efficiency of the laser. Currently, direct generation of 2.09μm is achieved by a high energy pulsed Ho:YAG laser pumped by Tm-based fibre laser (see Figure 2). The laser system operates at 100Hz repetition rate and emits pulse with <20ns pulse width. With this laser, a few mJ of MIR pulses are generated in DSO's ZGP OPO configuration. Such high energy MIR laser pulses are not available commercially and are the results of DSO's efforts to explore the MIR laser technology area.

Figure 1 Ho:YAG laser pumped by a Tm-based fibre laser

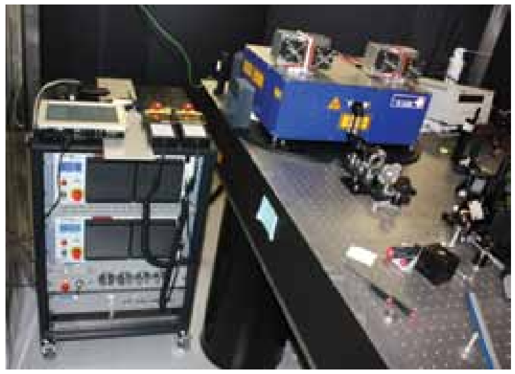


Figure 2 A ZGP crystal (bottom) harvested from a typical ZGP crystal boule (left)

FIBRE LASERS

About 10 years ago, DSO decided to explore a new direction in our laser research – iode-pumped fibre lasers. These lasers have the potential for compactness, air-cooling, very high efficiency and near diffraction-limited beam quality.

FIBRE LASERS

One of fibre laser's great advantages is its tunability. Unlike other rare earth-doped laser sources, the host material for fibre lasers is glass, and usually silica glass. Glass provides broader absorption and emission spectra for rare earth ions due to its strong inhomogeneous broadening, leading to a wide emission bandwidth, as well as less constraints on the pumping laser stability. For example, the emission of Ytterbium fibre laser is tunable over 1~1.15-micron, while Thulium fibre laser is tunable over 1.7~2.15-micron. Moreover, fibre lasers coupled with nonlinear optics, such as Optical Parametric Oscillators (OPO) and Stimulated Raman Scattering (SRS) emission, have further extended the spectrally tunable range from near Infrared (1~2-micron in wavelength) to middle Infrared (3~5-micron in wavelength). Therefore, much effort has been focused on the development of tunable laser sources based on high power fibre laser and nonlinear optics.

In recent years, DSO has been collaborating with the Nanyang Technological University (NTU) on wideband tunable fibre lasers. We are investigating various novel approaches towards a spectrally tunable, fully-fibre solution so as to lead to compact and ruggedised fibre lasers. The aim is to make use of the spectrally-wide stimulated emission of rare earth doped fused silica fibre materials in the 1 to 2-micron wavelength regime.

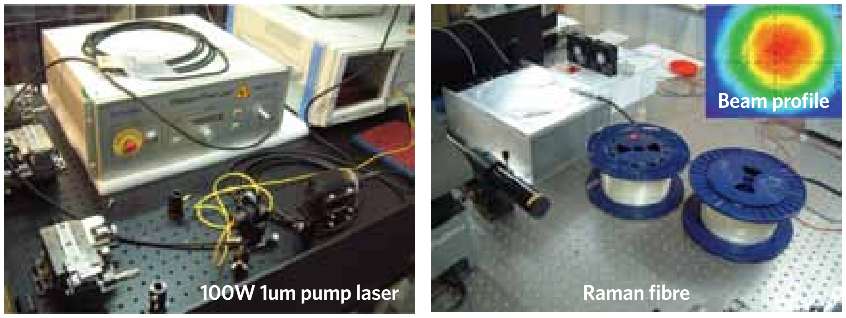
Through the collaboration, we have gained in-depth understanding of different schemes of tunable laser sources with either continuous operation or high peak power, as well as a broad tuning range with true all-fibre solution. Currently, there are very limited choices in the commercial market that can provide us with such specifications in a compact, all-fibre based device.

Thulium-doped fibre lasers have also gained much interest in recent years because of its possible applications in the medical, defence, ranging and atmospheric sensing areas. It is critical for the laser source to be wavelength-tunable, in order to precisely match each of the specific operating wavelengths. An all-fibre solution is also critical as the lasing wavelength stability and tuning range is not restricted by the free space optics, so that it is compact, flexible and ruggedised at the same time. We have successfully demonstrated, to the best of our knowledge, the first time a broadly wavelength-tunable, all-fibre CW thulium-doped ring laser, using a fibre Sagnac loop filter constructed with a piece of High Birefringence (HiBi) fibre. We have also successfully demonstrated continuous tuning of more than 47nm, from 1924nm to 1972nm.

Pulsed fibre lasers based on Q-switching are also of great interest for applications such as range finding, remote sensing and optical instrument testing. Compared with conventional passive and active Q-Switching techniques that have been widely studied for fibre lasers, Fibre Bragg grating (FBG)-based Q-Switched fibre lasers are attractive due to its fibre compatibility, good repeatability, low loss and cost. We have demonstrated that a narrow linewidth single-longitudinal-mode operation, can be obtained from a long length unidirectional fibre ring laser system, by the proper utilisation of high finesse twin FBGs based Fabry-Perot etalon. When this FBG Fabry-Perot etalon and narrow bandwidth apodised FBG are integrated into the fibre ring laser with matched operation wavelength, a stable single longitude mode laser output with narrow spectral linewidth without modes competition and hopping can be generated. We have successfully demonstrated the 25nm wavelength tunable highly polarised ytterbium doped fibre ring laser by using 45° tilted FBG. The output power of this fibre laser is about 6mW.

In addition, fibre laser pumped nonlinear devices, such as OPO and SRS have further enhanced the tunability of fibre lasers. The team has successfully developed a 13W cascaded Raman fibre laser at 1.54 micron in wavelength (see Figure 1), beating the previous record of 8.5W. We have also indigenously designed and developed a 7.4W Thulium-doped fibre laser operating at 1.9 micron wavelength (see Figure 2). Both of these wavelengths are in the eye-safe region and coupled with the rugged and compact fibre architecture, these lasers are potentially very useful in remote sensing applications.

Figure 1 Record power 13W 1.54um Raman fibre laser



The team has successfully developed a

13W

cascaded Raman fibre laser at 1.54 micron in wavelength, beating the previous record of 8.5W.

Figure 2 Fibre laser lasing

RESEARCHING THE FUTURE

Dr Teo Kien Boon Programme Director Emerging Systems Division Years in DSO: 16	**Wu Rui Fen** Principal Member of Technical Staff Emerging Systems Division Years in DSO: 16

THE PROGRAMME DIRECTOR

With a doctorate in physics, Dr Teo Kien Boon is well equipped to oversee his programme's work in the physical sciences. Work that ranges from lasers and optics, to advanced materials and quantum technologies for defence applications. However, Kien Boon's greatest challenge does not only lie in helping researchers overcome technical obstacles. More often than not, it comes from finding the right people who have a passion for R&D, and putting them together to build the right teams.

"In the programme, we try to inculcate a healthy sense of respect for one another. It's about recognising and valuing the diversity of talented people that we have so that we are able to tap on collective wisdom, overcome obstacles and achieve common objectives. This also requires great teamwork, and to ensure this, the whole team usually meets potential hires to see if there's chemistry!"

How successful has this been? Researchers from Kien Boon's programme have broken world records in laser performance; garnered numerous DSO awards for innovation; filed patents for their work; and won recognition through the prestigious Defence Technology Prize.

One such researcher who has managed to achieve all of the above is Ms Wu Rui Fen, a Principal Member of Technical Staff in Kien Boon's programme.

THE RESEARCHER

What area of research are you involved in, and what's the secret to your success?

My work in DSO is in the field of nonlinear optics and lasers. As for my secret, I don't actually have one. I think as Kien Boon mentioned, if you have a passion for what you do, success will come naturally.
Also, as one of the more senior staff, I get to work with many junior researchers. Seeing them grow and achieve in their work is a great source of satisfaction and drive for me. Of course, it also helps that my work involves lots of surprises – good and bad! This keeps it interesting as no two days in the lab are the same!

You've won many awards, so we know about the good surprises. Can you share about the bad ones?

In R&D, setbacks are inevitable. But when that happens, perseverance is the key. One recent example was when my team was working on a fibre laser. We had just gone through three months of painstaking work to build the laser, only to find out that there was a tiny defect in the optical fibre in our laser module! This tiny defect was serious enough to degrade laser performance by almost two orders of magnitude. Imagine that, three months of hard work defeated by a tiny defect! At the time, I felt like a mother who had to abandon her child! However, cooler heads in the project team prevailed, and upon closer examination, we found out that it was possible to overcome the defect by using a certain type of high temperature conductive tape that would be stable to 250°C. After three days of searching, we managed to source for one that was only available overseas. Once we got our hands on the tape, I was too nervous to even go near the laser to repair it. A colleague with steadier hands than mine had to do the job! In the end, it worked and we managed to attain the original laser performance. You can't imagine the relief and satisfaction I felt at that moment! This is only one example. There have been many others like it in the course of my work!

For someone who has had many achievements in her work, what's next?

Well, much of my work today is in emerging technology areas, so most of it is done within the lab. In the future, I hope to take these technologies out of the lab and into the field. I'm sure that this will bring about many engineering issues that have to be overcome, but I'm also sure that the team will be more than game for it!

DROGUE CHUTES FOR SHIP DECELERATION

The idea of using drogue chutes (see Figure 1 overleaf) was conceptualised to answer the Republic of Singapore Navy's (RSN) quest for a means to arrest the parasite momentum of potentially hostile large vessels.

DROGUE CHUTES FOR SHIP DECELERATION

The concept (see Figure 2) was to use clusters of chutes, entangled around the bow of the hostile vessel and deployed behind the stern of the vessel, to provide sufficient drag forces to reduce the momentum of the vessel.

In order to establish the feasibility of the concept, scaled testing (based on Froude number) was conducted to address the main technical risks identified such as the drag coefficient of such drogue chutes underwater, performance of chutes in cluster deployment, coupled with interference of ship wakes and bottom effects in shallow littoral waters. To study the drag coefficient of the chute in isolation from other interferences, 1/8th scaled ribbon chutes (see Figure 3), were towed behind the vessel using a long tow line. The interference of the 'ship wakes' on the chute's drag when deployed at various trailing distance astern was also studied. Figure 4 shows the amount of wake created when the chutes were deployed astern with short trailing distance. Lastly, the impact of the separation distance between chutes in the same tow line was studied.

The findings showed that the drag coefficient per chute is strongly dependent on the trailing distance and separation distance between the chutes. Increasing the trailing distance and the canopy separation distance would affect the C_d significantly, hence the efficiency of the overall system.

Extrapolating from the performance of the scaled system testing, the use of drogue chutes as a means to create additional drag to reduce the momentum of hostile vessels to a sufficient level was assessed to be feasible, together with its deployment from a packed condition (see Figure 5).

With the positive results from the scaled testing, DSO will be moving into full scale testing in the next phase.

Figure 1 Illustration of the concept on the typical usage of drogue chutes deployed astern of fighter jets versus the proposed usage of drogue chutes for large ships

Figure 2 Illustration of the proposed deployment of drogue chutes for large ships in plan and side view. Towline and chutes are submerged in water

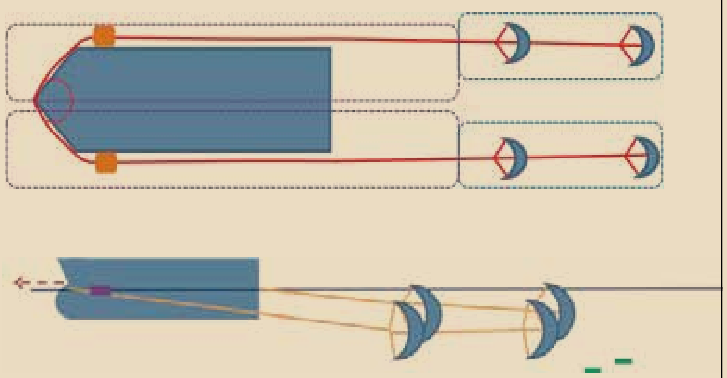


Figure 3 Ribbon chute used for trials

Figure 4 Photo of a wake created by chute with short trailing distance

Figure 5 Packed Deployable 1/8th Scale System with two ribbon chutes in each bag

GRAPHENE RESEARCH

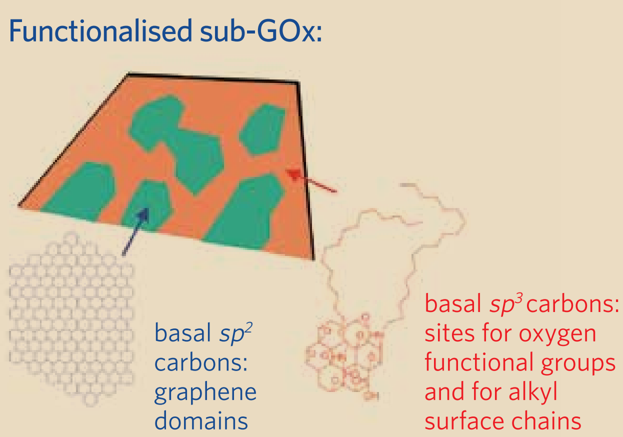
Graphene is a single layer of graphite, comprising two-dimensional honeycomb structures of *sp*^{2} carbon atoms. It is considered as the building blocks of many carbonaceous materials such as graphite, fullerenes and carbon nanotubes.

GRAPHENE RESEARCH

A single sheet of graphene does not exist naturally, and it was only in 2004 when Nobel Prize physicists, Andre Geim and Konstantin Novoselev, managed to isolate a single layer of graphene through repeated mechanical exfoliation of graphite using a scotch-tape. This pristine single layer of graphene exhibits interesting behaviour closely related to that of high energy physics, yet allows experimentation under room conditions. Since then, graphene research took speed and a supernova of scientific research activities on this amazing material was born.

DSO embarked on graphene research in 2008, in collaboration with the Organic Nanostructured Device Lab (ONDL) of the Physics Department in The National University of Singapore (NUS). The predecessor of graphene, the carbon nanotube, which was discovered in 1990, was hallowed as a wonderful material useful as nonlinear optical limiters, enhancing mechanical and electrical reinforcement in composites. However, carbon nanotube suffers from poor processibility, thereby delaying the realisation of the full potential as predicted. Graphene, on the other hand, was found to be solution-processible, giving rise to various configurations and materials systems for application assessment. The ONDL group in NUS was able to chemically exfoliate graphite stacks, partially oxidise them and plant functional groups to the single sheets, resulting in single sheet dispersion of graphene-like material. This material, though unlike the pristine graphene isolated by Andre and Konstantin, was found to demonstrate band-like transport behaviour (see Figure 1).

Figure 1 Chemical structure of sub-GOx

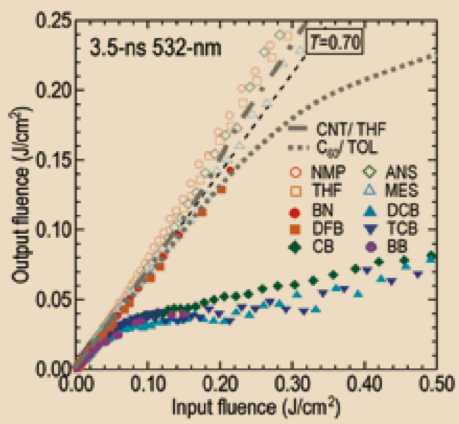


The DSO team then started studying the nonlinear optical properties of chemically-derived graphene through a collaborative effort with NUS and Cambridge University. This has led the team to discover a surprisingly strong matrix dependence nonlinear optical limitation in this material system, when excited by a green pulsed laser (see Figure 2). Heavy atom solvents are ideal, with such dispersions demonstrating very strong nonlinear optical behaviour at laser fluences five to 10 times lower than that observed in other carbon systems such as fullerenes (C60) and single-wall carbon nanotube (SW-CNT). This unusual behaviour was attributed to a new mechanism (unlike that of carbon nanotube) involving the formation of localised excited states through interaction with the environment. These excited states were probed using a laser and found to be rather long-lived. The joint team subsequently filed a U.S. Provisional Patent in December 2010 on this discovery and published the work in Nature Photonics.

Such chemically-derived graphenes are also useful as fillers in composites to increase the mechanical strength, as well as thermal and electrical conductivity. They form very homogeneous dispersions even at high concentrations, which is not possible for other carbonaceous composite systems. With increased interaction area with the surrounding matrix, this magical two-dimensional material can still yield surprising properties.

Such chemically-derived graphenes are also useful as fillers in composites to increase the mechanical strength, as well as thermal and electrical conductivity.

Figure 2 Optical limiting curves of sub-GOx dispersions in various solvents measured using 532nm pulsed laser. NMP: M-methylpyrrolidone; THF:tetrahydrofuran; ANS: anisole; MES:mesitylene; BN: benzonitrile; DFB: 1,2-difluorobenzene; CB: chlorobenzene; DCB: dichlorobenzene; TCB:trichlorobenzene; BB: bromobenzene; C60: fullerene; SW-CNT: single-wall carbon nanotube



RADIO FREQUENCY ELECTRONICS MINIATURISATION

The emergence of more compact and capable military platforms has opened up new opportunities for inserting high value payloads.

RADIO FREQUENCY ELECTRONICS MINIATURISATION

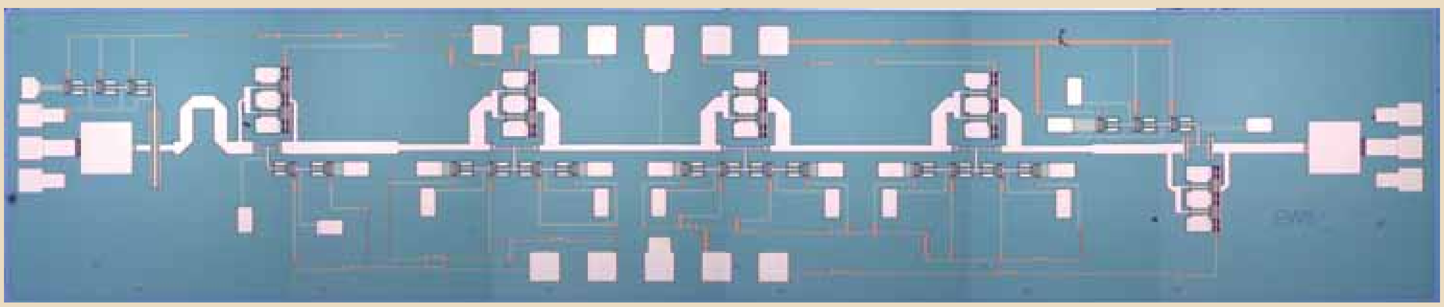
Since many of these payloads require increasingly complex Radio Frequency (RF) front-end sub-systems, it is important for DSO to build up the know-how in RF hardware miniaturisation technologies. Specifically, the ability to customise the design of RF hardware based on Monolithic Microwave Integrated Circuit (MMIC) and RF packaging technologies is essential for DSO to harness them for our own defence requirements.

The rapid advancements in compound semiconductor technologies for RF and microwaves applications have enabled high-performance RF/microwave circuits to be implemented on MMIC chips with very small sizes. An example of such an MMIC is a Digital Controlled Attenuator (DCA) designed by DSO, measuring only 5.6mm x 1.2mm. (see Figure 1).

A Digital Controlled Attenuator (DCA) is a common microwave component that is used in many system applications. DCAs are used to increase the RF receiver's dynamic range by attenuating incoming signals according to their strength. They can also be used to equalise imbalances in the signal amplitudes within the multi-channel receivers. However, a compact ultra-wideband DCA that is required by a system application was not available as a Commercial-Off-The-Shelf (COTS) item. In order to achieve optimal system performance across the entire bandwidth, a customised DCA was thus designed in DSO.

The DCA of interest requires relative amplitude attenuation from 0 dB to 32 dB in 1 dB step, operating across more than a decade of bandwidth. The design uses a set of switched-resistor networks (see Figure 2), and its design approach has the advantages of good temperature stability and a simple control circuitry. Implementing the DCA design using MMIC technology reduces the overall size of the DCA, and it also minimises the parasitic effects, thereby enabling it to operate over the required wide bandwidth.

Figure 1 Micro-photograph of the fabricated DSO 5-bit DCA



The design for the switched-resistor networks varies slightly depending on the attenuation level, but essentially they are based on the well-known switched Tee resistive network. It consists of a through path and a lossy path where the series and shunt switches are used to direct the input signal to flow between them (see Figure 3). The relative insertion loss between the two paths constitutes the relative attenuation level of the switched network. The main design task is to select the appropriate resistance values, and the dimensions of the microstrip lines interconnecting the switches. This ensures that the overall network attenuates the signal level accurately in the lossy path, and exhibits low loss in the through path across the entire frequency range. This can be achieved by ensuring that the impedance matching condition is satisfied across the required bandwidth.

The critical step in this design process is to ensure that the device models used to represent the transistor switches are accurate. These models should be physical to account for all the intrinsic and parasitic elements presented by the device. Although the MMIC foundry provides the nonlinear transistor model, its accuracy is inadequate for this application. In this case, DSO extracted the dedicated device models to ensure its accuracy. These dedicated models were adapted from the proven 13-element equivalent circuit model for the microwave field effect transistors.

Figure 2 Simplified schematic of a 5-bit DCA

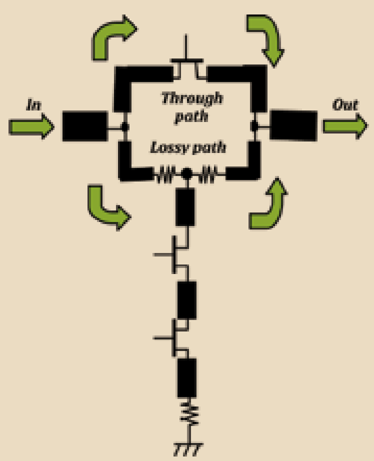
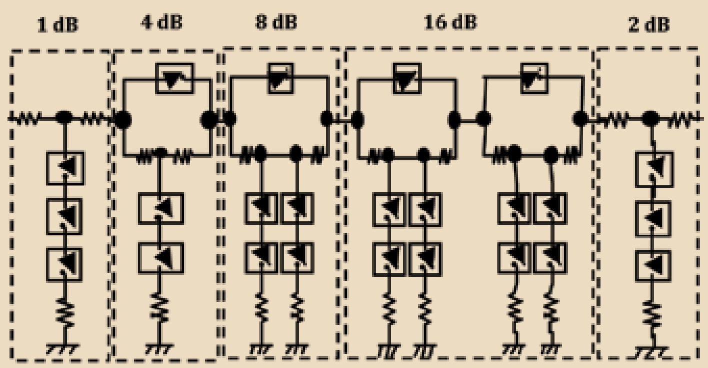


Figure 3 Schematic of the 4-bit attenuation switched network



RADIO FREQUENCY ELECTRONICS MINIATURISATION

The final DCA design is derived by cascading the switched-resistor networks with the interconnecting microstrip lines. The dimensions of these microstrip lines are optimised in the computer-aided engineering design tools, to ensure a better match in impedance between the adjacent stages, thus minimising signal reflection. Plotting all the 32 states of the measured relative attenuation of the DCA at room temperature, it shows that they are distinct and exhibit no crossing of states across the entire frequency band, validating the accuracy in the design (see Figure 4). At an elevated temperature of 95°C, the measured results for the same DCA (see Figure 5). This shows that all the relative attenuation levels vary little at the elevated temperature, confirming the robust temperature stability of the DCA. The DCA was subsequently tested as part of an integrated RF subsystem, and it achieved the overall expected performance, further confirming the validity of the design.

RF packaging technology enables a high density of RF circuitries such as filters, power dividers, and baluns to be packed in a very compact size. It makes use of multi-layer substrate technology, where multiple layers of low loss dielectric materials are stacked together, with patterned metal layers to form a higher functional level RF subsystem. One example is a customised Switched Filter Bank (SFB) developed by DSO, where it integrates multiple filters together with switches to achieve high selectivity and fast-switching RF channels (see Figure 6). The performances of the three RF channels selected by the SFB are also measured (see Figure 7).

Figure 4 Measured relative attenuations of the 5-bit DCA at 25°C

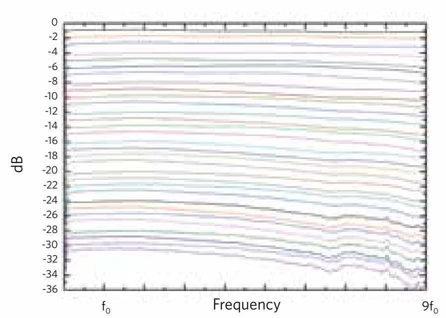


Figure 5 Measured relative attenuations of the 5-bit DCA at 95°C

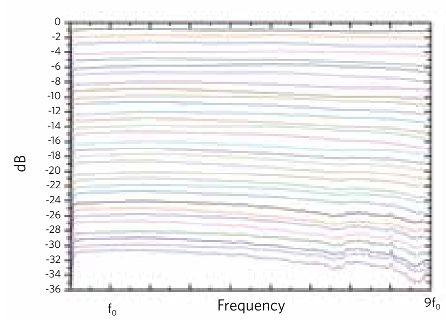
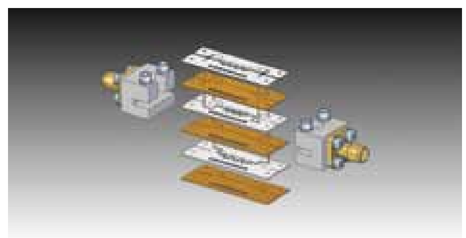


Figure 6 SFB with vertically stacked filters



Example of a Custom-designed RF Switched Filter Bank (SFB)

Customised SFB filters are stacked vertically in multi-layered Printed Circuit Boards (PCB) to reduce the footprint required. Since the filters are now embedded within the PCB, the outer layers of the PCB are freed up and may be populated with other components. Transition Vertical Interconnect Accesses (VIA) which carry signal from one layer of the PCB to another are required in such an SFB. The challenge of RF engineers would be to ensure a good isolation between the PCB layers, in addition to being impedance matched.

Circuit and electromagnetic (EM) simulation tools are extensively used to design and simulate a filter performance before it is fabricated. Whether the simulation will capture the expected filter performance accurately is determined largely by the attention put into the details at this stage. Filter designers have to ensure that material properties, three-dimensional details of the physical filter structure and the enclosure design are modelled accurately. For example, it is often necessary to carry out separate experiments to study the dielectric constant of a substrate material, and the resultant dimensions of a design fabricated using a specific fabrication process. A good understanding of the mechanics behind the simulation software used is also important. While most of today's EM simulation software is smart enough to automatically select an optimum setting when executing the simulation, a more accurate set of results could generally be obtained by manually tweaking the software settings. However, a compromise needs to be struck between model accuracy and simulation time. The layout capture of the embedded filter in the EM software (see Figure 8), and its simulated RF current densities (see Figure 9) can be used to confirm the proper design of the filter.

The work on the DCA and the SFB has demonstrated DSO's capability in harnessing the advanced RF technologies to customise the design of RF components and subsystems to our own requirements. This capability forms an integral part of the technological edge that DSO can contribute to the SAF.

Figure 7 Measured performances of the SFB

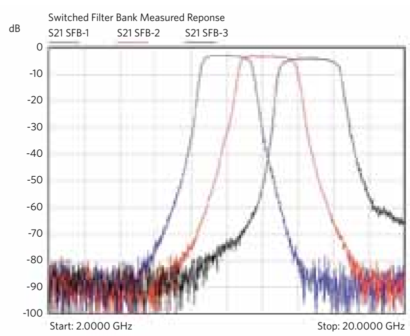


Figure 8 Layout view of the filter

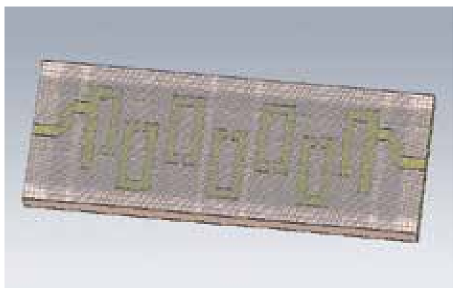
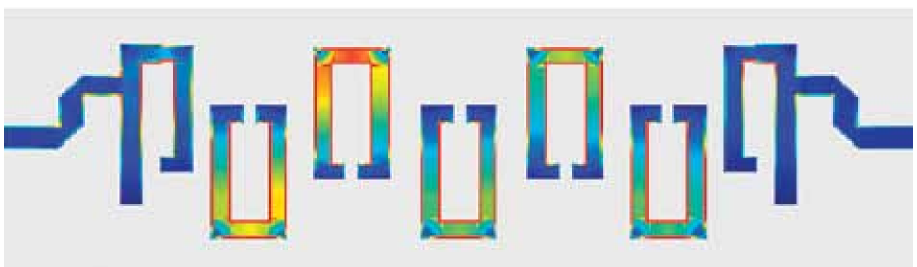


Figure 9 Simulated RF current densities flowing in the metal-strips of the filter



SMALLER IS BETTER

Dr Vincent Leong
Laboratory Head
Electronic Systems Division
Years in DSO: 21

Clocking close to a quarter of a century of research work at DSO, more than half of which were spent researching on Monolithic Microwave Integrated Circuits (MMIC), a Radio Frequency (RF) hardware miniaturisation technology, Dr Vincent Leong is a rightful guru in this field.

Back when he was on an Industrial Attachment (IA) in a U.S. company, a young Vincent was suitably inspired by a principal engineer's practical interpretation of RF knowledge and creativity in designing its components. He was fascinated by how volatile the characteristics of RF and Microwave signals can be when they're propagated through different mediums and frequencies, and challenged himself to design the optimal circuit pattern which would bring out the best characteristics.

The more he worked in this area, the more interested and inspired he was, so much so that he went all the way and pursued a doctorate in microwave engineering from the University of Massachusetts Amherst.

Any form of research would not have been without its challenges, and for Vincent, his main challenge was in the design of the Digital Control Attenuator (DCA), a microwave component used in many system applications. This design needs to achieve precise attenuation levels, and the device model needs to be accurate in predicting its performance.

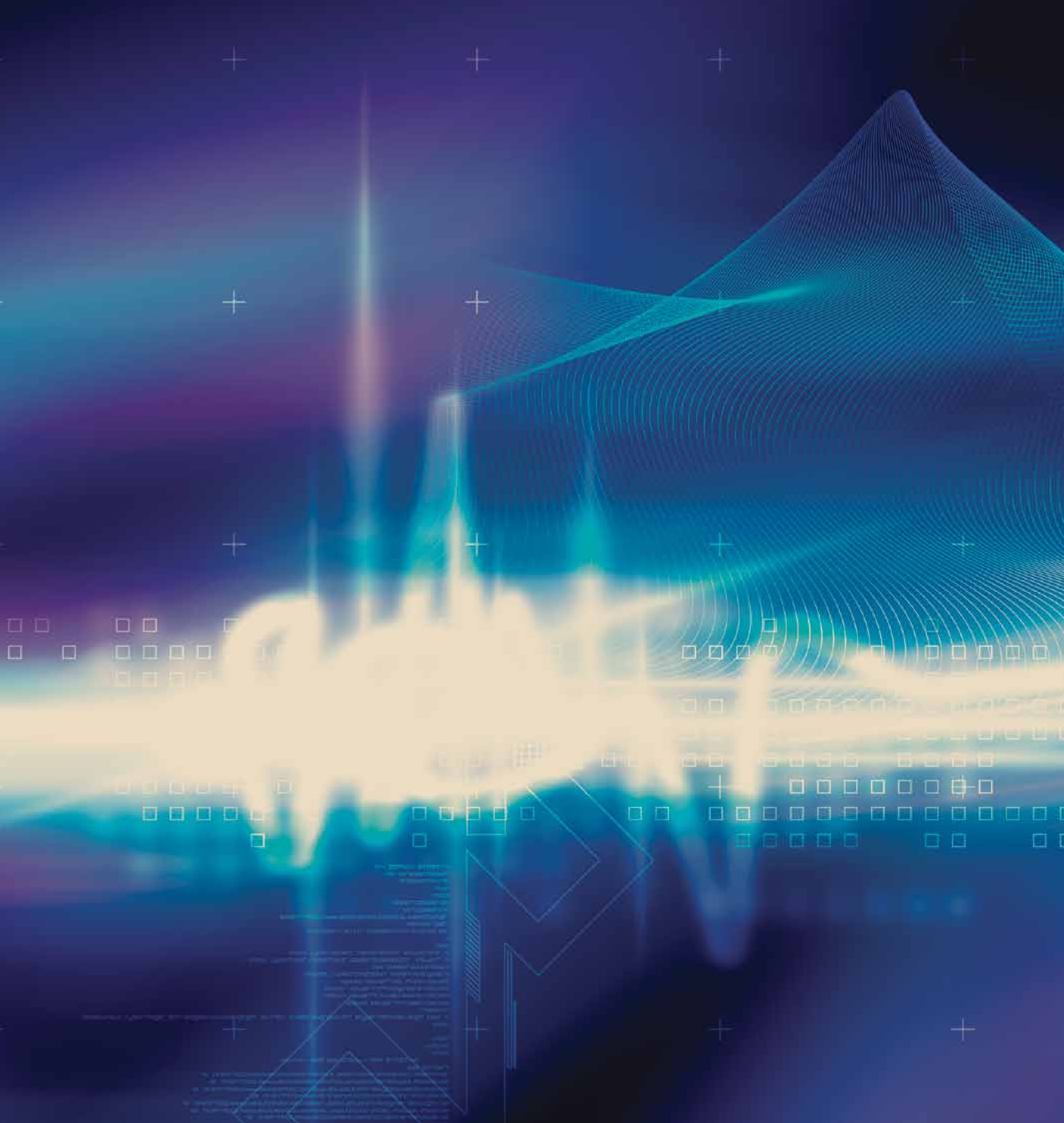
Once, Vincent and his team assessed that the model provided by the foundry was not good enough for that purpose, and without that assurance, they decided to extract their own model instead.

"That was a challenging decision to make as most designers would rather play it safe and rely on what was given by the foundry."

They decided to take on the challenge and successfully extracted a model which worked just as well, if not better than the one provided by the foundry.

Such dedication and team spirit have yielded results and gained recognition, with his team winning the 2007 Defence Technology Prize Team (R&D) Award for their research in MMIC.

There's no stopping him now. With a wealth of expertise under his belt, Vincent hopes to continue his work in this area with a team of dedicated researchers, leveraging on each other's strengths to advance DSO's mission.



SOFTWARE DEFINED RADIOS

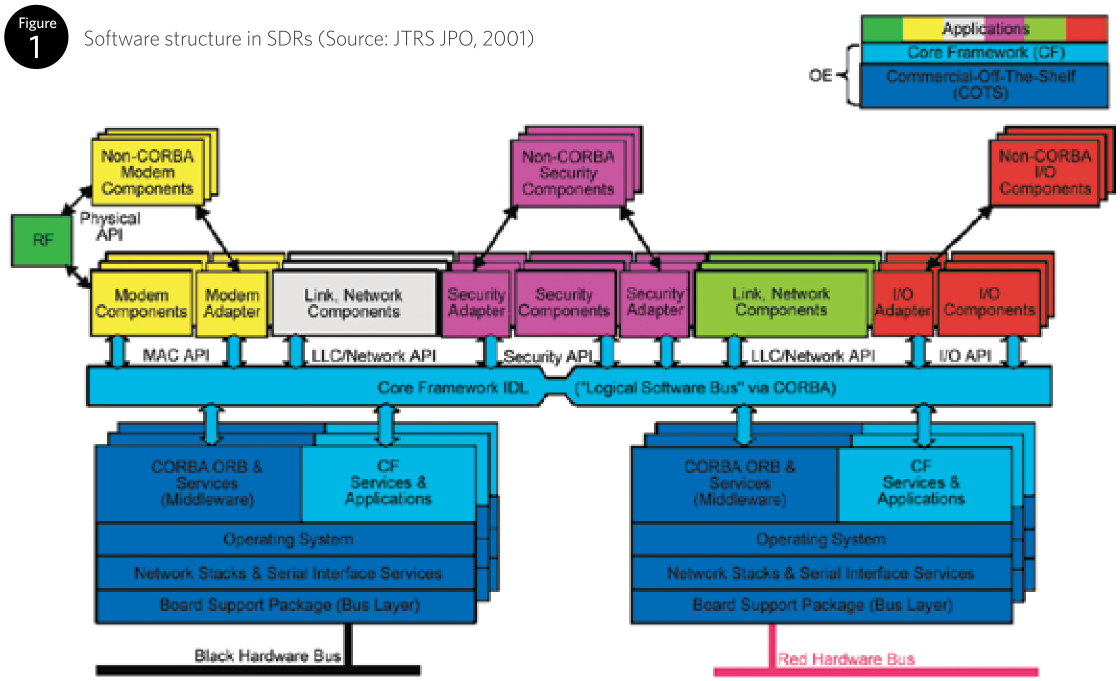
Software reconfigurable Software Defined Radios (SDRs) offer a good platform to conduct research on advanced wireless networking algorithms.

SOFTWARE DEFINED RADIOS

The standardised common architecture in SDRs, known as Software Communications Architecture (SCA), facilitates the porting of waveforms across SDRs provided by different radio vendors. SCA is an open architecture framework that tells waveform designers how the hardware and software elements are to operate in harmony within an SDR. It interconnects the various software components located in the General Purpose Processor (GPP), Digital Signal Processor (DSP) and Field Programmable Gate Array (FPGA). Collectively, the various software components make up the waveform.

Tactical waveforms especially developed for use in the terrestrial environment need to be able to handle frequent link breakages due to terrain masking and foliage, and to operate in an environment with high interference.

Figure 1 Software structure in SDRs (Source: JTRS JPO, 2001)



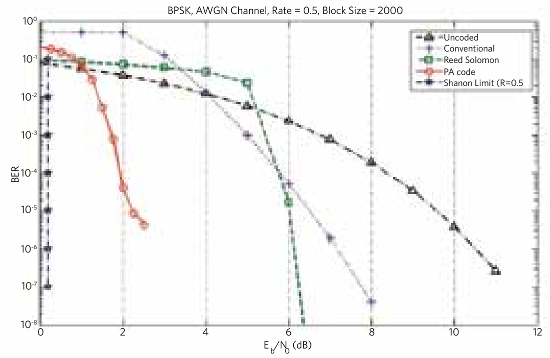
Adaptive Coding and Modulation

Most waveforms are designed to operate in a fixed modulation scheme. Typically, this results in the waveform being configured at the lowest transmission data rate (i.e. the most robust modulation scheme) to meet the worst types of range and channel conditions. DSO has designed a scheme that automatically adapts the modulation scheme, and hence the transmission data rate, based on the assessment of the channel conditions. The scheme allows the waveform to transmit data at high data rates in good channel conditions. This greatly enhances the throughput performance and reduces the end-to-end delay of delivered data packets. In poor channel conditions, the scheme switches to lower, but more robust, data rates to maintain the communication link.

To support a hybrid scheme that combines adaptive coding and modulation, DSO has developed a real-time reconfigurable Product Accumulate (PA) encoder and decoder (codec) implemented in FPGA. PA codes are a class of error correction codes with a well defined structure, which allows flexible rate and length adaptation, while maintaining good Bit Error Rate (BER) performance which is comparable to the well known turbo code. Figure 2 shows the performance of various classes of error correction codes. The PA codes achieve better BER performance than conventional codes such as Reed-Solomon or convolutional codes.

DSO has studied various design tradeoffs needed for the FPGA implementation of PA codes. For example, the interleaver conventionally used in PA codes is not suitable for FPGA implementation. After evaluating several classes of algebraic interleavers that allow easy reconfiguration and have low storage requirements, Quadratic Permutation Polynomial (QPP) based interleavers were used to strike a good balance of BER performance, reconfigurability and ease of implementation in FPGA. A three-stage pipeline structure to the codec was designed to maximise throughput, and a PA type-I codec was developed by DSO to achieve real-time reconfiguration, low resource requirements and high throughput while maintaining good error correction performance.

Figure 2 BER performance of various classes of error correction codes



A three-stage pipeline structure to the codec was designed to maximise throughput, and a PA type-I codec was developed by DSO to achieve real-time reconfiguration, low resource requirements and high throughput while maintaining good error correction performance.

SOFTWARE DEFINED RADIOS

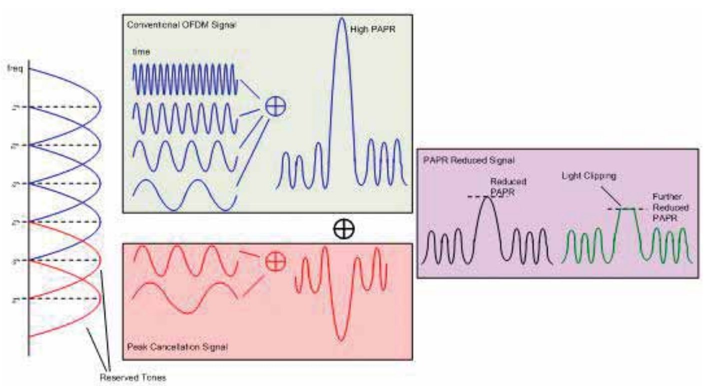
Orthogonal Frequency-Division Multiplexing (OFDM): A Multi-carrier Modulation

In a conventional single carrier system, information is modulated onto one carrier using frequency, phase or amplitude adjustment of the carrier. As higher bandwidths are used, the duration of data symbols become shorter, causing the signal to be susceptible to impulse noise and multipath effects. OFDM overcomes this problem by splitting the high data rate serial bit stream into many lower rate parallel streams, each modulated on orthogonal subcarriers. As each subcarrier has a lower information rate, OFDM is able to combat severe degradation of the communications link caused by multipath propagation whilst staying robust against interference. Given its many advantages, OFDM has been adopted as the choice of modulation for many new wireless technologies being used and developed today, such as Wi-Fi and 4G cellular systems.

Associated with this multi-carrier modulation is a phenomenon known as Peak-to-Average-Power-Ratio (PAPR), which requires large power amplifiers. DSO has designed a scheme to reduce the PAPR through a combination of a Tone Reservation technique with a Clipping technique. Through manipulating reserved tones (i.e. selected sub-carriers), followed by some light clipping of the resulting signal peaks, this scheme is able to effectively reduce the PAPR with minimal signal distortion.

Another challenge in deploying OFDM on mobile platforms is the effect of the platform movement that leads to Doppler shifts and spreads in an urban environment. For highly mobile platforms, these Doppler shifts and spreads severely degrade communications performance. DSO has designed a technique to mitigate the inter-carrier interference caused by Doppler spread through a judicious placement of pilot symbols to aid in channel estimation and equalisation. This technique increases the signal-to-interference (SIR) ratio compared to conventional OFDM systems, and results in improved BER performance under rapidly changing channels, without incurring any significant additional overhead or computational complexity.

Figure 3 PAPR reduction using Tone Reservation and Clipping



Dynamic Spectrum Access

Typically, when new wireless systems are deployed, they are allocated unused frequencies from the shared spectrum. With the increased use of wireless tactical systems, spectrum scarcity will become a critical problem in the near future, especially when wider bandwidths are needed to support the ever increasing throughput requirements.

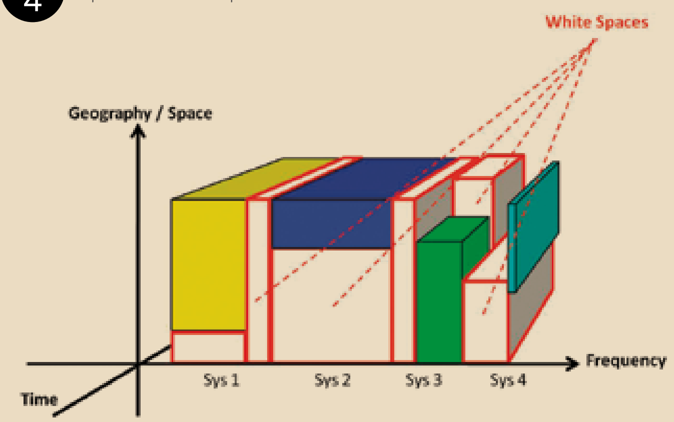
Significant amounts of unused frequencies or 'white spaces' may be available even when the spectrum has been heavily allocated, as the wireless systems may not be operating everywhere, or at all times (see Figure 4). Terrain masking and buildings in an urban setting will limit the transmission range, allowing the same frequencies to be reused in another area without causing interference. Network throughput can be increased by supporting multiple concurrent transmissions within a multi-hop network. Dynamic Spectrum Access (DSA) exploits these 'white spaces' to resolve the spectrum scarcity issue.

The ability of DSA to increase time-spatial-frequency spectrum reuse efficiency also helps to overcome network capacity that is usually interference-limited. This, in turn, helps to increase the effective network throughput and provides for a flexible and scalable network. In the operational perspective, this also means increased flexibility and timeliness of mission planning. In addition, the agility of the DSA waveform to adapt to its changing environment also equips the network with the inherent ability to recover from intentional or unintentional interference. This is necessary to overcome the increasingly challenging environment of high tempo, mobile ad-hoc operations/networks.

DSO has developed and demonstrated an infrastructure-less prototype DSA networking waveform (commonly known as cognitive radio, or CR) on a software programmable platform in the UHF band.

SDRs offer a flexible, programmable platform that allows DSO engineers to research and prototype advanced waveform algorithms, and test their performance under various conditions. Tactical waveforms incorporating cutting edge features that offer significant leaps in connectivity, robustness and throughput performance are critical in the next generation communications infrastructure.

Figure 4 Spectrum white space



SCENTMATE: A PORTABLE NERVE AGENT DIAGNOSTIC KIT

Chemical agent threats have been demonstrated in war and in terrorist attacks to be an effective unconventional weapon to achieve mass casualty outcomes. In August 2005, the Scotland Yard thwarted a planned Sarin nerve gas attack by Al-Qaeda on the House of Commons and the London underground.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SCENTMATE: A PORTABLE NERVE AGENT DIAGNOSTIC KIT

This was a reminder of the Tokyo subway Sarin attack that took place 10 years ago in March 1995, where the initial mass hysteria and surge in 'worried-well' people seeking medical attention overwhelmed hospitals' emergency medical service departments. The need to attend to all people seeking medical attention stretched and fatigued medical responders. Today, potential response efforts to terrorist incidents involving chemical attacks still represent a major challenge.

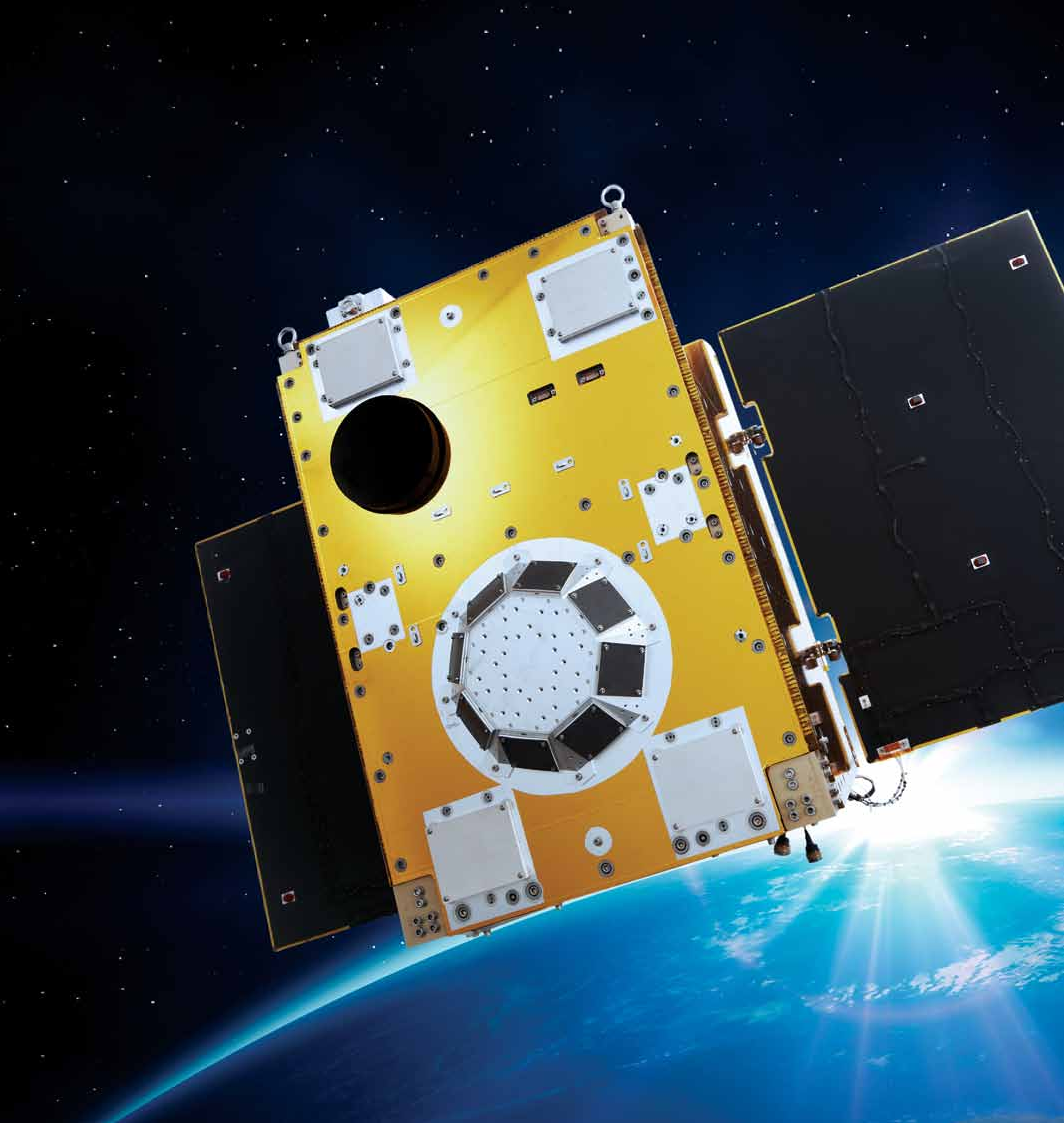
Current field diagnostic devices require prior pre-exposure measurements of a human biomarker such that post-exposure reduction of this biomarker can be used to confirm exposure to nerve gas. This requirement restricts the applicability and use of such diagnostic devices during unexpected terrorist incidents. This is because it is difficult to obtain and track the baseline pre-exposure reference value for every single member of the public. Therefore, an effective diagnostic capability plays a critical role in reducing nation-wide panic, and contributes to the prevention of unnecessary strain on existing medical facilities. By enabling early differentiation of actual nerve agent casualties from the 'worried-well' population, timely medical intervention is achieved and the adverse psychological impact posed by chemical agents can be avoided. To meet this challenge, scientists from DSO's Chemical, Toxins, Radiological and Nuclear (CTRN) programme developed and patented the Scentmate test kit (see Figure 1). This portable test kit can diagnose mild and asymptomatic exposure to nerve gases such as Sarin and VX. Both nerve gases have been used in the past during terrorist attacks in Japan. Scentmate requires only a single drop of blood for performing the analysis, and is able to screen 96 people in the field within an hour at a sensitivity level equivalent to that achieved in the laboratory. With Scentmate, DSO has effectively brought a laboratory diagnostic capability into the field where it is most needed.

The innovation behind Scentmate is its ability to confirm asymptomatic nerve agent exposure without the need for comparison against a pre-exposure biomarker reference level, making it the first in the world. Cholinesterase is a blood biomarker found in the human body that nerve agents bind to. Current diagnostic applications detect the reduction of this biomarker following nerve gas exposure by referencing it against the individual's pre-exposure baseline level. This requires arduous and costly nation-wide baseline screening efforts. In comparison, the Scentmate test kit diagnoses by direct detection of nerve agents released *in-situ* from the blood biomarker. Hence, the individual's pre-exposure biomarker baseline is not required. The derivation of this seemingly simple procedure represented a major technical challenge that revolved around the concomitant application of chemical(s) to release the nerve agent from the blood biomarker, and to permit it to reattach to a similar surrogate biomarker present on the assay device. The ability of this regeneration chemical to inhibit the surrogate assay biomarker further complicated the assay procedure. DSO resolved this challenge by discovering an apt chemical procedure that permitted regeneration and assay of the nerve agent while removing interferences from the treatment chemical(s).

SCENTMATE: A PORTABLE NERVE AGENT DIAGNOSTIC KIT

Figure 1 Scentmate portable test kit

...scientists from DSO's CTRN programme **developed** and patented the Scentmate test kit. This portable test kit can diagnose mild and asymptomatic exposure to nerve gases such as Sarin and VX.



X-SAT - SINGAPORE'S FIRST INDIGENOUSLY BUILT MICROSATELLITE

The X-SAT is a microsatellite project developed by the Centre for Research in Satellite Technologies (CREST) – a joint establishment between the Nanyang Technological University (NTU) and DSO. Wholly developed at CREST in NTU by a team of NTU and DSO researchers, the X-SAT represents a valuable learning opportunity for both organisations in the area of satellite engineering. The following pages highlight some of the development work undertaken by the team.

X-SAT - SINGAPORE'S FIRST INDIGENOUSLY BUILT MICROSATELLITE

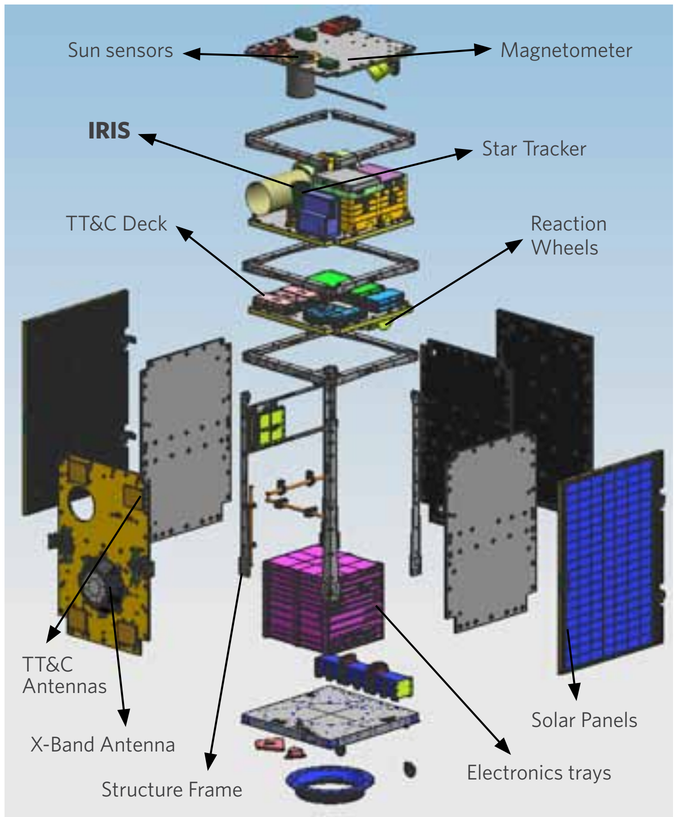
The name 'X-SAT' was chosen to symbolise the essence of the microsatellite's experimental and exploratory nature. The X-SAT weighs 105kg, has a primary electro-optical (EO) earth observation mission, and two other secondary missions. The primary mission EO payload developed by Satrec Initiative of South Korea is called IRIS, with three multi-spectral bands and a ground sampling distance of 12m. The secondary payloads include an NTU-developed payload called PPU (Parallel Processing Unit), and a space-borne precision GPS receiver from the German Aerospace Centre (DLR).

The development approach consisted of a three-model development philosophy: the Engineering Model (EM), Qualification Model (QM) and Flight Model (FM). Such an approach was deemed essential in mitigating the risk of developing a satellite.

X-SAT: Overall Configuration

The overall design configuration of the X-SAT is shown in Figure 1. The EO camera (IRIS) and the star tracker is mounted on a special deck, called the 'optical deck', to harmonise performance in terms of pointing direction for imaging and attitude control. The Telemetry, Tracking and Control (TT&C) components are deemed to be sensitive and as such, are mounted on a separate dedicated deck. The rest of the electronics modules, such as on-board-data-handling, attitude control interface and power modules are stacked together in the form of 11 trays.

Figure 1 Overall satellite configuration



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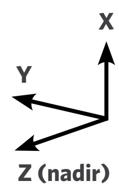
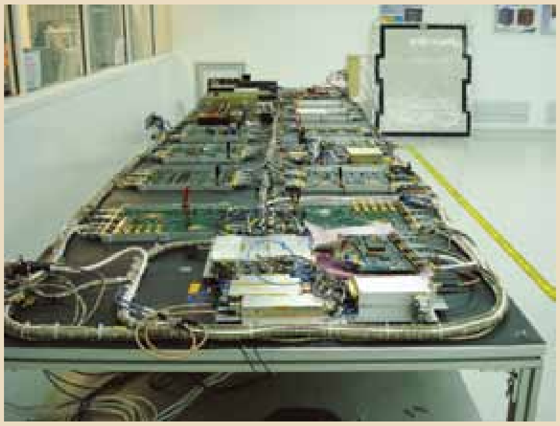


A mechanical frame was designed around the integrated electronics modules to provide the structural integrity. This greatly facilitated the assembly and integration of modules such as the solar panels.

Figure 2 Engineering Test Bed Setup in CREST



Source: CREST

A mechanical frame was designed around the integrated electronics modules to provide the structural integrity. This greatly facilitated the assembly and integration of modules such as the solar panels. The base-plate of the satellite was designed to have good stiffness as it had to be interfaced with the satellite's separation ring (IBL-298), provided by the Polar Satellite Launch Vehicle service provider – the Indian Space Research Organisation (ISRO).

The X-SAT experimental microsatellite has a body-mounted fixed solar panel and two deployable solar panels which are each held by one metallic string. During in-orbit testing, this string is cut by pyrotechnic cable-cutters. The Li-ion battery is located near the base of the microsatellite and wrapped by a thermal blanket (not shown in Figure 1). The thermal blanket provides passive temperature control during the X-SAT's operation in space. The various attitude control actuators such as the reaction wheels and magnetic torquers have been mounted inside the satellite, while sensors such as the sun-sensors have been mounted on the surface.

Command and control of the X-SAT is carried out by a TT&C 6.1m antenna system at the Research Techno Plaza in NTU. The reception and processing of the imagery data is carried out via the 6.5m X-Band antenna system at the Centre for Remote Imaging Sensing & Processing (CRISP) in the National University of Singapore (NUS).

Engineering Test Bed (ETB) Setup

The ETB is a setup that integrates all the electronics and electrical modules of a satellite in a two-dimensional (2D) table. The X-SAT's ETB is illustrated in Figure 2. Due to its 2D setup, the ETB is often referred to as a 'flat satellite'. For the X-SAT, the ETB 'evolved' from the EM to the QM, and finally to the FM's actual hardware and software.

The ETB enabled the testing of all modules at an integrated system level in the X-SAT. The modules were brought to the ETB table to be integrated one by one into a complete satellite. This enabled progressive testing of system level functionality and performance. The X-SAT development team also used the ETB to progressively develop and test the flight and ground software through the EM, QM and FM phases.

After the launch of the X-SAT, the ETB was used to check software codes before uploading it to update the on-board flight software. This helps to ensure the robustness of the new flight software, and prevents any accidental malfunction of the in-orbit microsatellite.

X-SAT - SINGAPORE'S FIRST INDIGENOUSLY BUILT MICROSATELLITE

Fail-safe Design

In order to create a robust microsatellite, the X-SAT was designed to handle single point failure, and redundancy design at the level of the modules or subsystems was implemented. In addition to redundancy design considerations, safe-hold mode features were also incorporated, particularly in the attitude determination and control, using a combination of hardware and software. The safe-hold mode design is the last line of defence for the microsatellite to deal with incidents or anomalies during satellite operations in orbit. During the safe-hold mode of operation, the microsatellite shuts off the power to non-essential modules and keeps itself safe by spinning slowly to allow the solar panels to receive solar energy. All these are done while waiting for the intervention of ground operators. These features are critical for the safe operation of the X-SAT in orbit. After the launch of the X-SAT on 20 April 2011, there were several incidents that took place during the first two months of operations. The safe-hold modes design features kicked in to 'save' the microsatellite during this period of in-orbit test activities when the team was learning how to operate a low earth orbiting satellite.

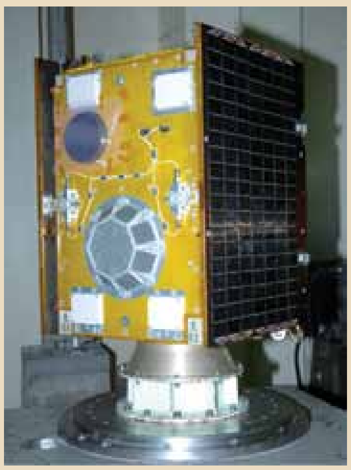
Centre of Gravity and Moment of Inertia Analysis and Measurement

The launch service provider requested a very tight cylindrical tolerance for X-SAT's Centre of Gravity (CG) control to avoid uncontrolled tumbling during separation from the launch vehicle. An accurate CG prediction would enable quicker detumbling of the microsatellite so that it can deploy its solar panels faster, whereas an accurate Moment of Inertia (MOI) prediction would allow better control of the microsatellite through its Attitude Determination and Control (ADCS). This was achieved through good configuration control and proper generation of Component Breakdown Structure (CBS). Accurate mass captured in the CBS can be loaded into a detailed CAD model for accurate prediction of the CG and MOI. This is shown in the measurement in Figure 3.

Structural Analysis

Accurate structural analysis was performed to ensure that X-SAT could survive the harsh environment during the launch. The structural analysis consisted of the optimisation of the structural mass, normal mode and dynamics analysis. A high number of elements and nodes were required for accurate Finite Element (FE) modelling. Figure 4 illustrates the predicted and measured results.

Figure 3 Centre of Gravity and Moment of Inertia measurements



Source: CREST

CG Measurement	Requirement	Theoretical	Measurement
CG in Y-Axis	5mm	-1.94mm	-1.29mm
CG in Z-Axis	5mm	-1.10mm	-2.23mm
CG in X-Axis	<450mm	314.2mm	319mm

MOI Measurement	Axis		
	X	Y	Z
Theoretical CAD Results	5.21 kgm^2	8.09 kgm^2	7.76 kgm^2
Measurement Results	5.44 kgm^2	8.64 kgm^2	8.51 kgm^2

Thermal Design and Analysis

The thermal control subsystem maintains and controls all the satellite components within allowable temperature limits for all operating modes of a satellite when it is exposed to the orbital thermal environments. In the X-SAT, a passive thermal control scheme was implemented in the form of thermal surface finishes. Surface finishes included asaluminum paint; Kapton; black paint and chromate; MLI (Multilayer Insulation); thermal isolators; and conductors.

A commercial thermal analysis software package with SINDA/G as a main solver was used to build the thermal model and perform the analysis. A total of 186 Rod, 3934 Plate, 1338 Solid, 270 Mass and 21 Beam elements were used to model the entire geometry of the X-SAT.

A total of 11 loading cases, including 'worst hot', 'worst cold' and payload operations were analysed to find a feasible thermal design scheme. The typical temperature profiles of X-SAT in orbit for 'worst hot' and 'worst cold' cases are shown in Figure 5.

The thermal analysis indicated that all the modules and components were controlled within their respective operating temperature limits.

After the launch of the X-SAT, temperature telemetries of major modules such as the battery, solar panels and IRIS were obtained to check their thermal health status while in orbit. It was observed that all the modules operated within their respective temperature limits.

Quality and Reliability Processes

Satellite development requires a well-planned and controlled manufacturing and assembly (M&A) process to achieve quality and ultra high reliability. The X-SAT's M&A was modelled with reference to the European Cooperation for Space Standardisation (ECSS[1]) standard that demands more stringent workmanship requirements, tight control of soldering activities and reworks, and a Electrostatic Discharge (ESD) safe and controlled work environment. The ECSS standard was implemented with a comprehensive M&A plan to ensure proper design, selection of material, process control, good workmanship and proper work environments.

The M&A activities involved more than 30 processes with the development of numerous travellers and route cards to produce the QM and FM. The X-SAT's M&A team was trained and certified to ensure they were equipped with the knowledge and skills to execute the various M&A activities. Satrec Initiative was also engaged to review and confirm the M&A set-up and processes. In addition, the team had many hours of training in assembling pre-QM/FM prototypes, to prepare and accustom themselves to the process flow, workmanship and documentation required for satellite manufacturing.

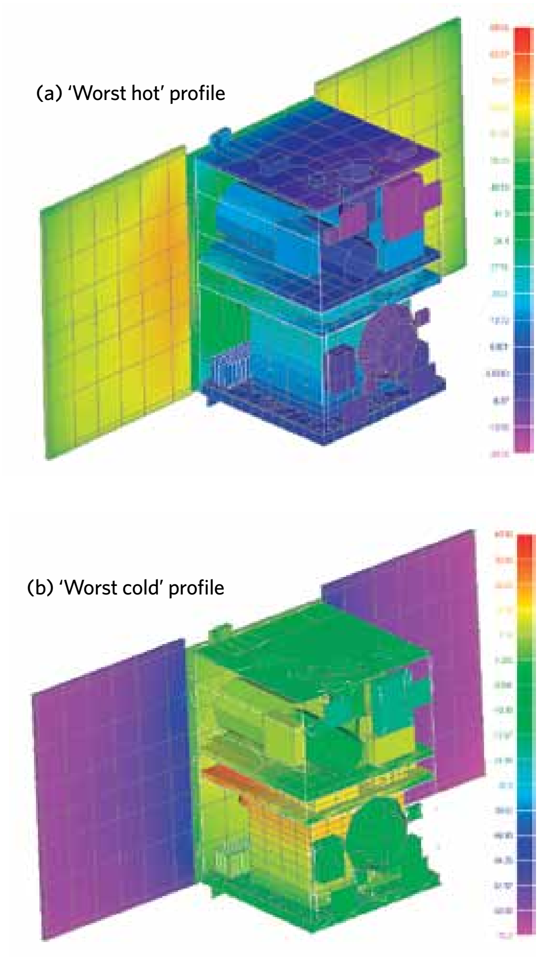
[1] A European Space equivalent of IPC standards.

Figure 4 Predicted and measured results of structural analysis

Description	Pre-Test	FM Test	% Diff
Frequency-Lateral Z	68.4 Hz	62.3 Hz	8.9
Frequency-Lateral Y	71.2 Hz	67.5 Hz	5.2
Frequency-Optic Deck	100.2 Hz	104.8 Hz	4.6
Frequency-Longitudal X	133.6 Hz	135.0 Hz	1.1

Source: CREST

Figure 5 Temperature profiles of the X-SAT in orbit



Source: CREST

X-SAT - SINGAPORE'S FIRST INDIGENOUSLY BUILT MICROSATELLITE

Satellite Software

Satellite software is used to control the operations of the satellite. This software resides in both the space segment and ground segment computers.

In the space segment, the satellite bus architecture with subsystems designed with redundancies is highly robust to withstand the harsh environments caused by a Single Event Upset (SEU). This allows the satellite to operate autonomously most of the time. To support scalability for various hardware subsystems, the architecture was highly distributed. On-board Computers (OBC) were connected to several microcontrollers over the Controller–Area Network (CAN) bus.

The OBC Software architecture design adopted the layered design approach to abstract the software application from the underlying hardware architecture, thus ensuring portability. The OBC Software's main functions of housekeeping and command execution, payload operations, ADCS and system monitoring are supported by the OBC Software Application Layer Interface. This software application provides facilities for tele-command execution, telemetry requests, and large data transfers. The OBC Data Link layer abstracts these tele-commands and telemetry requests into software messages, serial messages and Controller Area Network (CAN) messages. The Bus Abstraction Layer provides the communication backbone for exchanges of software messages and delivery of CAN and serial messages to the final destination.

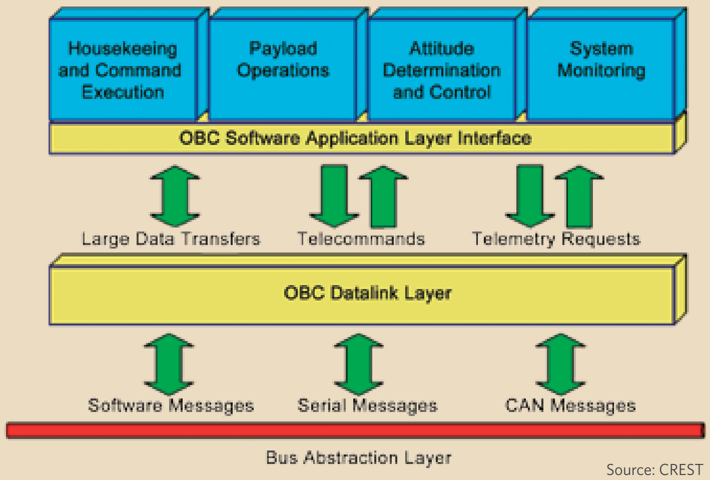
Real-Time Executive for Multiprocessor Systems (RTEMS) is the real-time operating system used by the OBC software to manage the real-time requirements of the ADCS function. This is the most critical software function as it maintains the stability and control of the satellite throughout its life.

The ground segment comprises two major parts - the NTU Mission Control Station (MCS) and the NUS CRISP Ground Station (CGS). The MCS is responsible for tasking the microsatellite to execute its missions and monitor its health. The CGS is responsible for receiving the images and processing them into usable and recognisable ones.

The MCS Software uses the Service Oriented Architecture (SOA) to realise a distributed yet highly reconfigurable ground station. Different MCS configurations were used to support the testing of the 'flat' microsatellite in NTU and the assembled one for overseas qualification testing and launch preparation.

Software technologies such as Microsoft Windows Communication Foundation (WCF) and Windows Presentation Foundation (WPF) have greatly simplified and reduced the MCS Software development time. A domain specific language was adopted in the MCS development to provide a uniform framework for operators and subsystems engineers to control the different subsystems for testing, mission executions and satellite health monitoring. The developed language effectively eliminated the need for the operators and subsystems engineers to have detailed knowledge of the inter-operability of the sub-systems when tasking a mission, or the precise commands to use.

Figure 6 Satellite bus architecture



Source: CREST

Figure 7 Satellite image of Singapore taken by the X-SAT

Source: SaRC

X-SAT - SINGAPORE'S FIRST INDIGENOUSLY BUILT MICROSATELLITE

To implement this, a grammar was developed using ANother Tool for Language Recognition (ANTLR) that generated the needed Lexer and Parser (an interpreter for the language) into C# codes that were incorporated in the tele-command Graphical User Interface (GUI). This was used by the operators and subsystems engineers to send tasks to the satellite.

Software reliability is a key attribute in complex and mission critical software. As such, robustness and stress testing employing regression unit testing with NUnit and FxCORP testing tools were employed throughout the development.

The launch of the X-SAT took place successfully on 20 April 2011 at 1242hrs, Singapore time. Immediately after launch, the X-SAT went into spinning motion. At this high body rate of around 6deg/sec, solar panel deployment was unsafe. To de-tumble the satellite into a slower spinning motion of less than 0.3deg/sec, X-SAT made use of the principle of electromagnetic effects. Electric currents through magnetic torque rods mounted in the three axes of the satellite interacted with the Earth's magnetic field to produce torques. The torques slowed down the spinning motion of the satellite till its body rate was small enough for the safe deployment of its solar panels.

The sun sensors mounted at specific locations on the microsatellite determined the sun-direction with respect to the satellite body axes. In the sun-tracking mode, on-board reaction wheels orientate the satellite's solar panels to face the sun to receive maximum solar energy. In a single orbit, the satellite is nominally pointed towards the sun's direction all the time, except during the 10 to 12 minutes of imaging operations.

The first contact with the satellite was successfully established by the TT&C ground station of NTU on 20 April 2011 at 2206hrs, Singapore time. This was a historical moment for the project team as the first signal from our own satellite in space was captured! In the subsequent three weeks, main in-orbit tests were carried out and a complete Singapore image was captured on 11 May 2011 (see Figure 7). Thereafter, further tests to check all the redundant units' functions were satisfactorily carried out. The conduct of secondary missions, namely, the experiment of DLR GPS RX and PPU were also successfully completed in September and October 2011 respectively. The satellite has since been placed in the normal operating mode of the imaging mission.

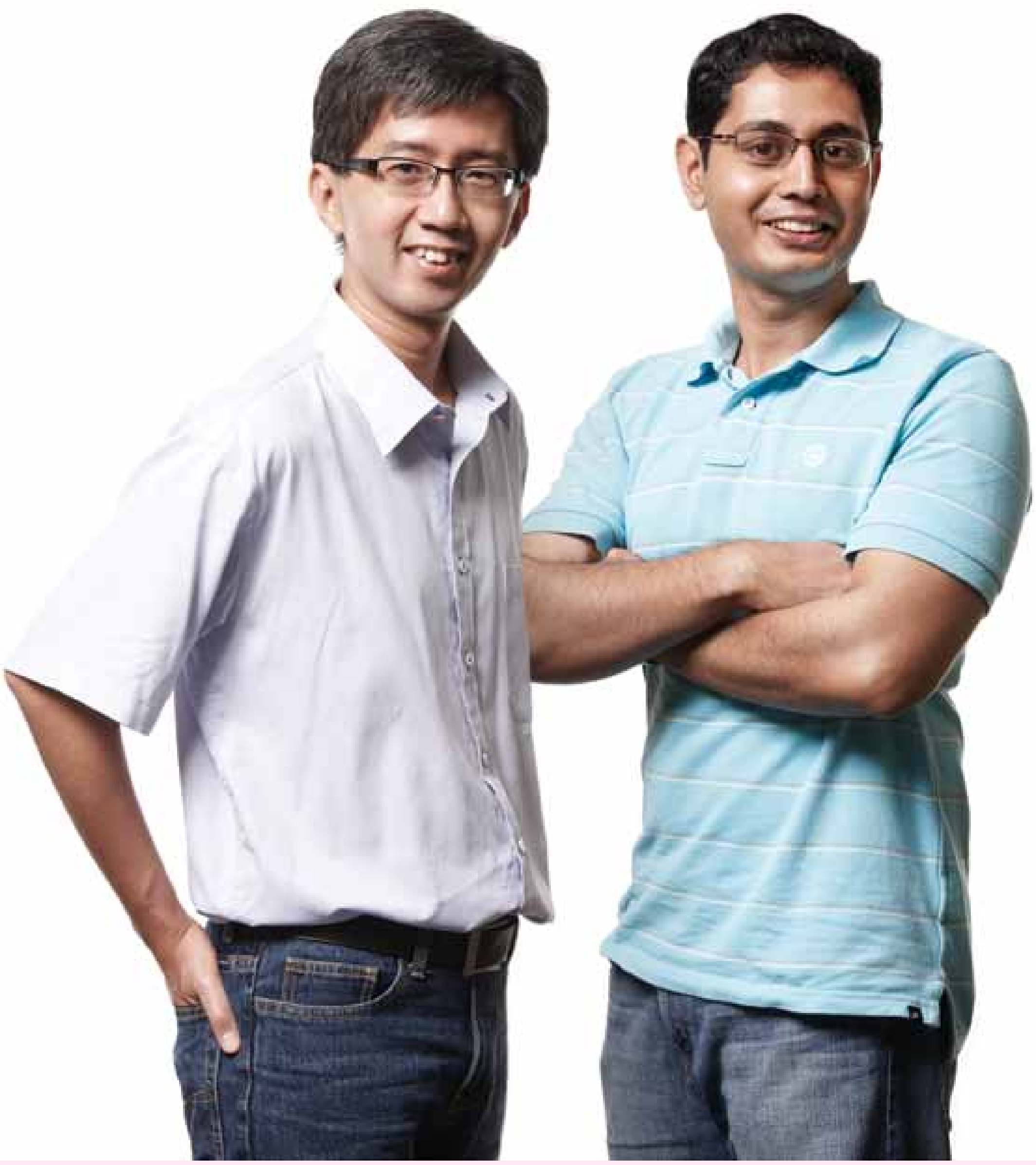
Singapore Technologies Electronics (Satellite Systems)

Singapore Technologies Electronics (Satellite Systems), or STE (SS), had its beginnings in the Centre for Research in Satellite Technologies (CREST) – a collaboration between NTU and DSO formed in 2001 with the purpose of building and launching Singapore's first indigenous experimental microsatellite, the X-SAT.

After the successful development and launch of the X-SAT in April 2011, STE (SS) – a JV between Singapore Technologies Engineering, DSO and NTU – was announced in May of the same year. STE (SS) marks a major milestone in the development of an indigenous high-tech satellite industry. The JV leverages on the research and systems engineering expertise from both DSO and NTU to undertake research, development and manufacturing of products and services for advanced earth observation satellites.

Together with the global marketing reach and expertise of STE, the JV will develop satellite technologies in Singapore and take these into the global market. Currently, the JV is working on the development of a more advanced earth observation satellite .

THE FINAL FRONTIER



Philip Teng Principal Member of Technical Staff Networks Division Years in DSO: 14	**Chantiraa Segaran** Member of Technical Staff Quality Division Years in DSO: 5

In 2001, the Centre for Research in Satellite Technologies (CREST) was jointly set up by the Nanyang Technological University (NTU) and DSO to build the X-SAT – an experimental microsatellite that would serve as a learning opportunity to build an in-country capability in satellite engineering. Developing and sending a satellite into space is an enormous endeavour. One that requires expertise from a multitude of engineering disciplines to build a complex system that can withstand the harsh environment of space. Among the many who contributed their expertise were Philip Teng and Chantiraa Segaran – two men who played important roles in the joint development of the X-SAT and sending it into the final frontier.

Tell us more about what each of you was responsible for in the development of the X-SAT.

Philip Teng (PT): I was part of an NTU and DSO team working on the development of mission and safety critical software for the X-SAT. The flight software controls the on-board operations of the satellite and consists of different subsystems and modules that have to be integrated and tested during the Engineering Model phase.

Chantiraa Segaran (CS): My responsibility was in the area of reliability engineering which entailed performing reliability analysis and quality assurance to ensure that the X-SAT's systems are able to perform their required functions under stated conditions, for a specified period of time. I assisted the electronics designers from NTU in component selection, materials selection and qualification, environmental stress screening and component failure analysis. Such activities are important as the X-SAT has to withstand the harsh environment of space. If something fails in space, there's no way to repair it!

Not many people have the opportunity to work on something in such a niche area. How did each of you get started?

PT: After I came back from my overseas postgraduate studies in 2003, there was an opportunity to get involved in satellite engineering. I was keen to apply my knowledge of software engineering in this niche area that few people have the privilege of participating in. Needless to say, I jumped at the opportunity!

CS: I was quite lucky in that the opportunity to work in the area of satellite engineering was offered to me when I joined DSO. Like Philip, I jumped at the opportunity! To me, it represented a unique and exciting challenge in which I could apply my knowledge and skills. I think very few people in my position would have turned down such an opportunity. You would have to be a bit crazy to do so!

The X-SAT is Singapore's first indigenously built microsatellite, and doing anything for the first time is challenging to say the least. What were your greatest challenges?

PT: As I mentioned, I was part of the team developing the X-SAT's flight software. The team comprised many talented people from both NTU and DSO who were responsible for different modules and subsystems. The challenge lay in bringing the entire system together for integration and testing to make sure that it works. This involved endless intensive planning, meetings, reviews and testing sessions! At times my determination was sorely tested but as a result, I think I developed a healthy dose of patience!

CS: I mentioned that I jumped at the opportunity to work in this area. However, as a young engineer, the prospect was also quite a daunting one! I didn't have much practical experience and I was tasked to provide quality assurance support for a complex system – a satellite! However, I was lucky to have many NTU and DSO colleagues from other engineering disciplines who were always willing to give technical advice, and a supervisor who conducted daily knowledge sharing sessions. These things helped tremendously in overcoming the challenges I faced in the project. And in the end, seeing such a complex system being put together – basically from scratch – was an awe inspiring experience.

The successful launch of the X-SAT must have been a satisfying moment for both of you. Take us through the experience.

PT: I think 'satisfying' is putting it too mildly! Developing the X-SAT required tremendous effort from everyone involved. A lot of testing was necessary to ensure that everything would work as intended. However, all this was done on the ground. Space is a totally different environment. Once the satellite is up there, how can you be sure everything will work? There is no way to bring it down for repairs! You only get one shot – either it works or it doesn't. The moments just before the launch were tense. I'm sure everyone involved had similar thoughts running through their heads. Would anything happen to the launch vehicle the X-SAT was in? Would the X-SAT be able to withstand the launch? Would it separate properly from the launch vehicle once it was in space? Once separated, would all its systems work properly?

The defining moment was when we managed to make first contact with the X-SAT at the Mission Control Station in NTU.

CS: Yes! First contact with the X-SAT was a significant moment. That first signal from the satellite meant that all our hard work had paid off. Singapore had sent its first satellite into space! At that moment you could literally see the relief and joy on the faces of everyone in the room! Plenty of cheering and high-fives were involved!

DSO BIG IDEAS (dBi)

DSO BIG IDEAS (dBi)

Innovation is the cornerstone of any R&D organisation, and DSO is no exception. 'Innovation' is central to what we do and is one of our key core values.

Launched in 2005, the DSO Big Ideas (dBi) annual competition aims to promote the inquiring and innovative spirit among our staff. Over the past seven years, the competition has received a positive and steady increase in participation and the number of awards won.

Staff may also use the bottom-up innovation funding via INnovative Projects (INP) resources to develop their new ideas and concepts. The Big Ideas Sessions (BIS) are hosted by the CEO and Division Directors each year, so that staff can have a better appreciation of the important and unresolved issues facing the SAF and/or DSO.

The dBi competition is open to individuals or teams, with individual winners and each team member awarded $500, up to a maximum of $5,000 per team. The winning ideas are presented at the annual DSO Technology Showcase to the MINDEF and SAF leaders, and more significantly, these ideas are provided funds for further development. To date, 17 of the 41 dBi winning ideas have been adopted and transited to the SAF operations.

The winning ideas cover technology areas in Advanced Electronics, Antenna, Cryptography, Laser and Optronics, and Communication and Protein Engineering. Some of these winning ideas are described below.

TSI TDOA Geo-location Method: Time Synchronisation Independent (TSI) Time Difference of Arrival (TDOA) geo-location is a novel and unconventional concept that can achieve very high precision geo-location, without the need for precise time synchronisation between sensors.

Shared Aperture Broadband Antenna Array: In the area of Antenna systems, a technique to achieve dual broadband arrays with dual polarisation by stacking one array onto another was developed. This can significantly reduce the form factor, allowing high performance antennas to be installed on small platforms.

Crypto Guardians and Unity in Diversity: It is increasingly difficult to evaluate the security aspect of high performance commercial technologies. This is largely due to the immense complexity and the lack of full disclosures. The use of guardian logics that unify and guard diversified components in a communication security architecture was proposed. This idea is robust in enhancing the communication security resilience against fault and other exploitations, in a complementary and non-conventional way.

TRUE RANGER: Based on the quantum randomness of photon detection and random bits extracted using a novel algorithm, TRUE RANGER is a physical generator of random numbers that are unpredictable.

PolarFour: PolarFour is a compact, simultaneous polarimetric and hyperspectral camera. It employs a Polarisation-based Fourier transform hyperspectral imaging technique, which provides broadband spectra information of the scene. This winning design reduces the size and weight by an order of magnitude compared to the conventional Michelson interferometric imaging technique.

Source-Channel Coding for Video Data Links: Wireless transmission of compressed videos is challenging under noisy and fading conditions, as compression formats often contain critical segments that cause decoding failures when corrupted or lost. Using a joint source-channel processing scheme that exploits the relationship between the video and channel-coding layers, the innovative approach demonstrated significant improvements in the video quality, as compared to current solutions.

CLRTECH – Lectin Mediated Destruction: A method was proposed to alter the region common to all antibodies, so as to confer the ability to engage innate lectin recognition pathways which promotes the destruction of viruses. If successful, this may enable 'virus binding' to be the only requirement for neutralisation, and eliminates the need for the laborious selection of naturally neutralising antibodies – the minority components of a larger antibody pool.

CEO'S EPILOGUE

The logic of the late Dr Goh Keng Swee was irrefutable.

Given Singapore's small geographic size and population, there is no way we can outnumber, out buy or outrun any potential adversaries.

The conclusion from this was a powerful one. The only way to defend against any aggressor is to surprise and defeat them with our own unique capabilities.

From our early days 40 years ago, DSO has steadily built up capabilities in all domains of importance to the SAF. Today, innovations from DSO are slowly but surely transforming the island into the 'lethal' red dot.

This has not been easy.

The need to develop local capabilities, the role of DSO and the vision of Dr Goh resonate with every generation of leadership within the Ministry of Defence (MINDEF) and the Singapore Armed Forces (SAF).

However, building local capabilities takes time and bears considerable risk. It is always very tempting to choose a solution from an established industry overseas. This is especially so when we are starting out from the very beginning, whereas the alternatives have track records to boast of.

We are fortunate that generations of leadership in MINDEF and the SAF have given DSO the time, resources and support to experiment, learn and develop.

We cannot take this for granted. We need to stay relevant to the SAF. This means that we must maintain our deep mastery of the latest advances in science and technology. We must have a good understanding of the SAF's operational environment and strategic considerations. And we must ensure that what we conceptualise, we deliver.

We take immense pride in our achievements. Over a short span of 40 years, a small group of Singaporeans have come together to create the technological edge for the SAF; the edge that will mitigate the strategic vulnerabilities we face as a result of our small geographic size and population.

Today, our innovations are being integrated into the SAF, invisible to most due to the strict security measures imposed on these.

While this commemorative book will not be able to show the full breadth and depth of what we do, we hope that it will be able to provide a sampling of DSO's diverse R&D work, reach out to a wider audience, and give you a glimpse at the deep passion of our research scientists and engineers.

This commemorative book is also dedicated to the staff of DSO, past and present, who have chosen to serve the country with us.

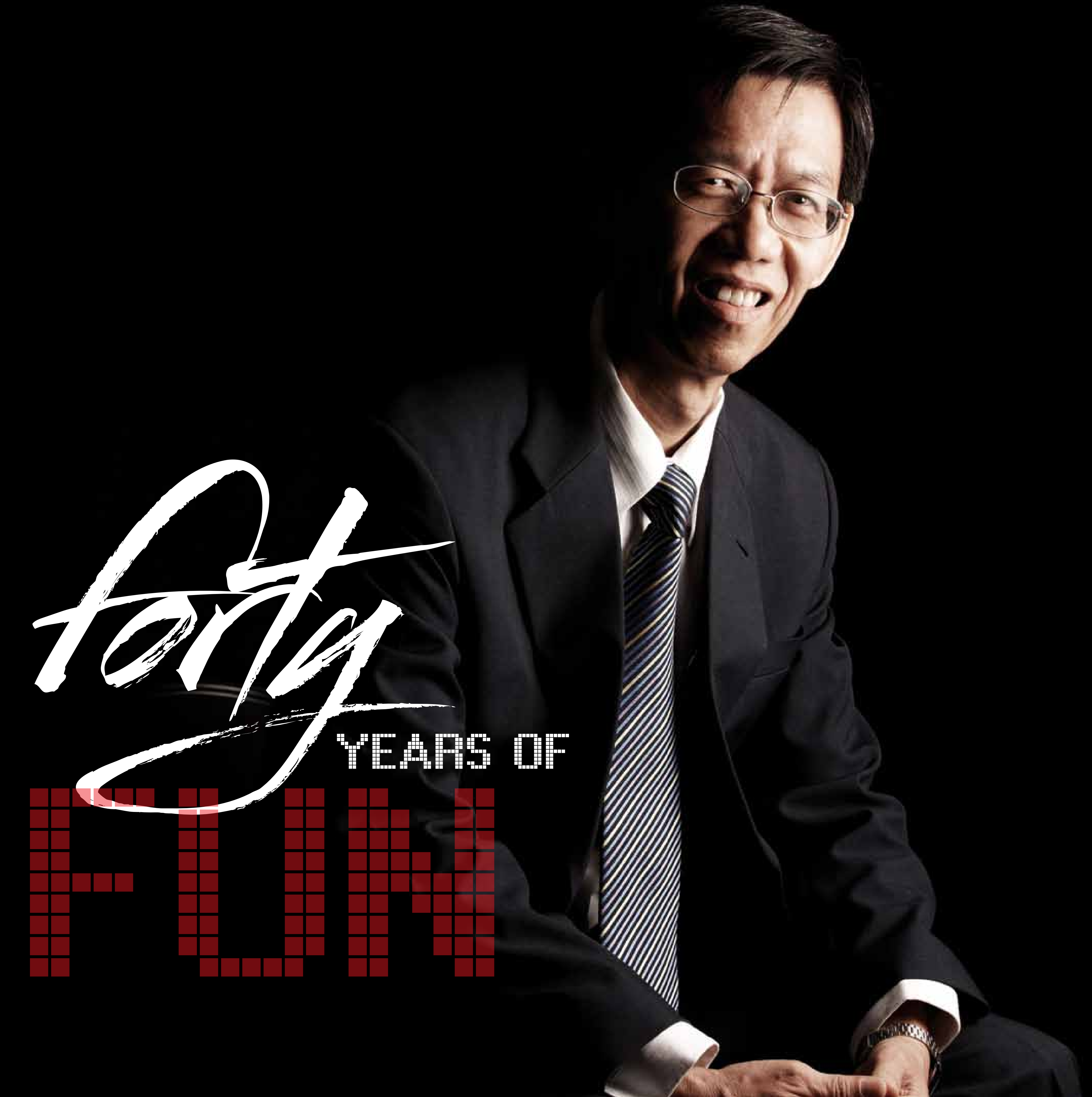
We owe our success to these many Singaporeans who have dedicated their life and work to build this national institution from scratch.

While the true full contribution of our people will remain unknown, each of us is proud to have contributed to our nation's defence and security. Indeed, it is the nation's needs that brought us here, and the Pride Within that keeps us going.

As we celebrate our 40th Anniversary, we look forward to the future with confidence and eager anticipation. We have a good team - competent, passionate, focused - and will continue to deliver our best, as we have done for the past 40 years.

Mr Quek Gim Pew
Chief Executive Officer
DSO National Laboratories

SERIOUS



forty YEARS OF FUN

DSO 40TH ANNIVERSARY CENTREPIECE AND DIVISION TREES

DSO's 40th Anniversary

Defence R&D is a serious business. There is no room for mistakes as it is a matter of life and death in the battlefield. However, innovating serious technology can be fun as well, especially when we get the chance to change the rules of the game and make the competition irrelevant. This is why DSO is celebrating 40 Years of Serious Fun.

But our 40th Anniversary is more than a celebration of serious fun. It is also a celebration of DSO's firm belief in nurturing our people – people who have in turn, shaped DSO into what it is today.

The DSO Centrepiece

In recognition of this belief and the unique spirit of our people, staff across DSO got together to specially design and hand paint this unique 1.3m x 1.6m artwork, currently on display in DSO's Science Park premises.

GROWING OUR OWN TIMBER

The tree is a powerful symbol of growth.

Over the past 40 years, DSO has grown from a three-man outfit into one of Singapore's oldest and largest R&D organisations. With its branches reaching up to the sky and roots deep into the ground, this artwork symbolises DSO's growth and firmly rooted belief in nurturing our people.

Individually pieced together by DSO staff, the tree trunk represents our connectivity and unity, whilst the specially designed 40 flourishing leaves highlight our collective creativity.

DSO 40TH ANNIVERSARY CENTREPIECE AND DIVISION TREES

Our Division Trees

Inspired by the creative influence of the DSO Centrepiece, staff from each Division injected their artistic talent into the creation of their own Division Tree, representing how each Division contributes to DSO's growth.

DEFENCE MEDICAL AND ENVIRONMENTAL RESEARCH INSTITUTE@DSO (DMERI@DSO)

DMERI conducts research in the areas of Biomedical, Human Sciences, Environmental Protection and Chem-Bio Defence. Our research enhances the safety, survival and performance of our national defence forces.

The graphics burnt on the leaves illustrate the various disciplines that we harness to protect the SAF against chemical and biological warfare agents. They also represent our research in combat care, human effectiveness, biotechnology and bioengineering. The tree trunk is formed by the names of all staff in DMERI, and symbolises the achievements of our Division, and the unifying ethos of our people.

"...question with imagination
answer with science..."

EMERGING SYSTEMS (EG) DIVISION

EG Division focuses on the research and development of a broad spectrum of capabilities that are critical to the SAF. These include antenna design and electromagnetics, as well as next-wave technologies in the areas of lasers and advanced materials.

Our young tree is a symbol of strong growth and signifies the Division's spirit of learning, and freedom to push the boundaries of science and engineering. The stems emerging from the base of the light bulb represent the many new ideas flowing from the Division. The fresh vivid leaves represent the varied experiences and youthful spirit of our people, who are both passionate about their work, and about nurturing younger generations of research scientists and engineers.

ELECTRONIC SYSTEMS (ES) DIVISION

ES Division develops electronic defence capabilities and enabling technologies to enhance the survivability and mission effectiveness of the SAF.

The leaves on our Tree of Life represent the diversified knowledge that our people possess, while the branches of the tree signify our unity and interconnectivity. The growth and achievements of the Division – represented by the trunk – are firmly rooted in DSO's 40 years of history.

Together with the other Divisions in DSO, we seek to provide shelter and protection for the land that will support us for years to come.

FINANCE AND ADMINISTRATION (F&A) DIVISION

Our Centrepiece is made up of a hand representing the trunk and branches of a tree, and 40 hearts representing its leaves.

The five fingers of the hand are symbolic of the five unique departments in our Division, united through the palm of our hand. Through our work in corporate framework and infrastructure, we provide strong anchorage and unwavering support to the operations of the organisation, and ensure that DSO flourishes in her capability development.

The heart on the palm signifies that we are serving with passion, and we are proud to have contributed to the 40 years of hard (heart) work for the defence and security of Singapore.

GUIDED SYSTEMS (GS) DIVISION

GS Division harnesses engineering knowledge and technologies to deliver a broad spectrum of unique guided system solutions to the SAF.

The big strong tree that is deeply rooted symbolises our maturity, developed over the years from a strong foundation in science and engineering

The intertwining roots reach upwards to form the trunk and pointed branches, representing new technological breakthroughs.

The acorns hanging from the branches represent the fruits of our labour. They are protected by the acorn's hard shell which symbolises the secretive nature of our work. But, like the aerial flight vehicle manoeuvring up the tree to reveal GS at the centre, our "delicious secrets will also be revealed when the time is ripe".

INFORMATION (INFO) DIVISION

INFO Division develops capabilities and technologies that enable the SAF to effectively use information on the battlefield. The various programmes in the Division are represented in our Centrepiece.

Information Exploitation is represented by the roots searching for nutrients, while Information Assurance is symbolised by the bark protecting the tree against the harsh environment.

The different directions that the branches explore as they grow are symbolic of our Manned-Unmanned programme, while Operations Research and Critical Infrastructure Vulnerability Assessment are represented by the red lines optimally distributing nutrients to where it is needed.

The leaves and fruits illustrate the aesthetic aspect of Human Factors Engineering.

Finally, the twigs connecting the leaves to the branches depict the support that our Software Laboratory provides to all in the Division.

DSO 40TH ANNIVERSARY CENTREPIECE AND DIVISION TREES

NETWORKS (NW) DIVISION

NW Division delves into the development of robust communication systems and technologies for the SAF's assured connectivity in the battlefield.

The tree trunk represents the unique, creative and passionate individuals from NW. The branches and leaves symbolise communications and network connectivity, which collectively, are our common areas of focus. They also represent the synergy derived from our collaboration with other Divisions and partners.

The black diamonds symbolise state-of-the-art technologies and systems developed for the SAF, while the arrows depict their transformation into dual purpose cutting-edge capabilities. In total, our tree which symbolises growth and vitality, sits on the firm ground, which represents the solid foundation built up over the years, and sturdy support from customers.

ORGANISATION DEVELOPMENT (OD) DIVISION

OD focuses on change and risk management, and the provision of IT infrastructure to enable productive, responsive and collaborative engagement among our staff, customers and collaborators. The Lego bricks represent our staff's brick-by-brick contribution to DSO.

The Compass and Rings represent the Plans and Collaboration Cluster in charting DSO's direction and link-up with our collaborators and customers. The Shield represents our Security Department's role in our defence against security threats. The Safety and Health Department is represented by Helmets, protecting us against workplace mishaps and hazards. The Corporate Information Cluster is represented by Computers, for the provision of our enterprise IT infrastructure.

Collectively, we enable a sturdy DSO to bear fruits despite the uncertainties and changes in our environment.

PEOPLE DIVISION

Engagement is what the PEOPLE Division is all about.

We are zealous in establishing DSO as an employer of choice, attracting new talent, while nurturing our people. We reach out and shape DSO's future by cultivating a passion for science and technology in Singapore's youth.

"PEOPLE", inscribed on the tree trunk reminds us that people lie at the heart of DSO. The different materials used to make this flourishing tree embrace the unique qualities that we possess, and the ability to synergise our efforts to connect with individuals, within and outside the organisation.

Passionate. **E**nergetic. **O**riginal. **P**rincipled. **L**ike-minded. **E**nterprising.
We are proud to be the **PEOPLE** of DSO.

QUALITY DIVISION

Our Goal:
Quality is when DSO solutions work the first time, every time.
We deliver quality solutions by working closely with our people and partners.

Our People:
Passionate, Perceptive, Persevering
Like a woodpecker, we passionately identify and remove bugs without damaging the tree; we are perceptive in spotting and resolving quality related issues; and we persevere in upholding the quality standard.

A healthy tree, our DSO, delivers high quality fruits!

SENSORS (SR) DIVISION

SR Division always delivers accurate, comprehensive and timely surveillance capabilities. Over the years, we have extended our coverage to all four domains – land, air, sea and space.

The different species of birds represent the distinct differences in the job nature of our programmes and labs, as well as our sensing capabilities in day or night.

The colourful, strategically arranged leaves embody the heart of Sensors – our vibrant people, who are persistently striving ahead and contributing to our key sensing capabilities.

Like the branches which are constantly reaching up and stretching out, we aspire to achieve greater heights, and will continue to grow and develop technological surprises for our customers!

This book is dedicated to all DSO staff, past and present, who have chosen to serve the country with us.

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