Cranfield Defence and Security

Research Yearbook

Connecting Research and Resilience

It is my pleasure to introduce you to the Cranfield Defence and Security 2021-2022 Research Yearbook, which provides a tantalising glimpse at some of the diverse, innovative and impactful research completed by our staff and students. As research students are at the heart of our creativity, the great majority of the research examples presented here derive from PhD theses completed over the last year.

Cranfield University is well-known throughout the world as a centre for scholarship with purpose, which is actively applied to industrial and societal challenges. In the 2021 Research Excellence Framework (REF) assessment, 88% of Cranfield University's research outputs were ranked 'world leading (4*)' or 'internationally excellent (3*)'. Although the research featured in this publication stems from Cranfield Defence and Security, research in this sector extends across all schools of Cranfield University.

I hope you enjoy reading this book and that it inspires you to work with us, as a student, a company, or a government department, in Defence and Security research.

Professor Andrew Shortland
CDS, Director of Research

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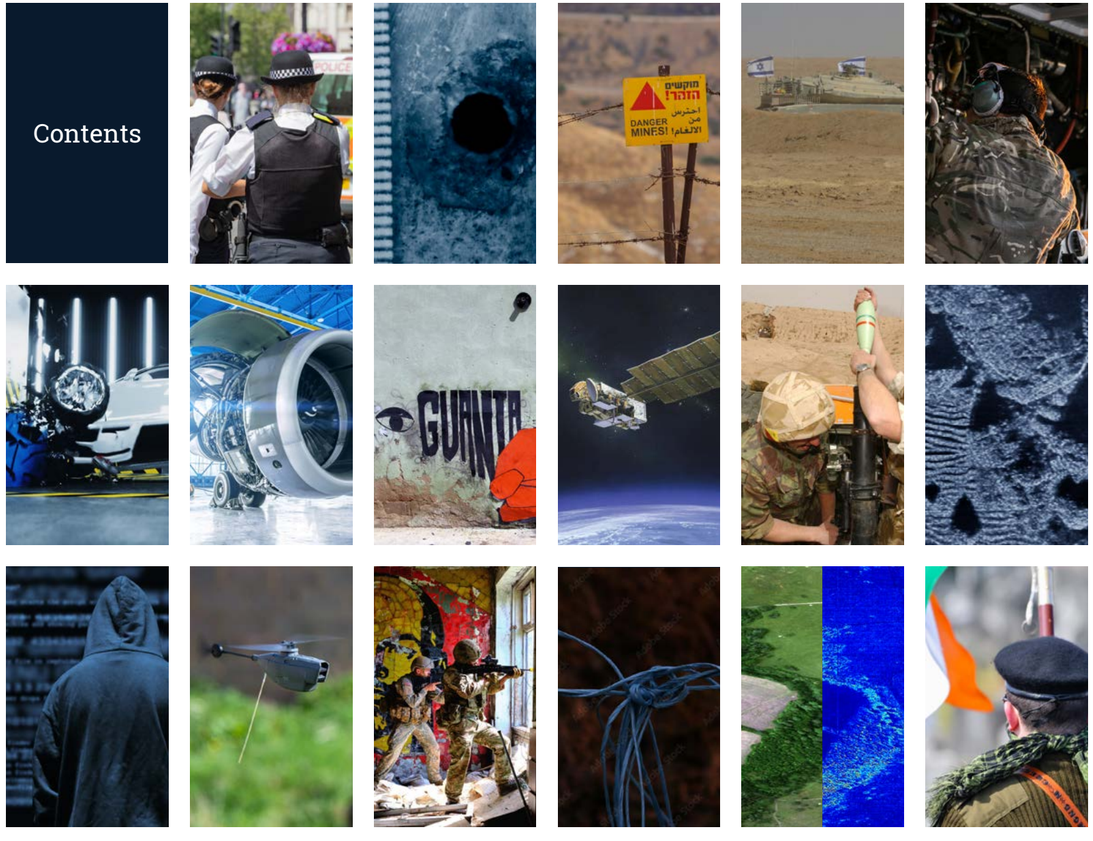

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Female police body armour: Improving comfort, protection, and testing

Within England and Wales, the wearing of body armour when on duty away from a police station is common place. The primary purpose of the body armour is to reduce the risk of a life changing or life ending injury.

Across England and Wales, there has been a steady increase in the number of female police officers to around 40,000 in 2020. The body armour worn by both male and female officers provides the same level of resistance to threats, but the design and comfort is different. The majority of previous research in body armour has focused on male anatomy with minimal work into female armour design and protection.

The research at Cranfield aimed to provide an insight into issues faced by female officers when wearing body armour, and how body armour testing can take into account the female form.

The first part of the research was a survey of female officers in England and Wales to establish the distribution of breast size and the bra type worn whilst wearing body armour and identify the areas of discomfort and rubbing, which play a significant factor in the comfort of the officer on duty. 2633 completed surveys were returned. The survey identified that the most common type of bra worn was an underwired bra, followed by sports bra. It also identified significant issues with discomfort while wearing body armour around the breast and lower back.

As a result of the initial work, a study was conducted to investigate

if bra type and the correct fit could improve comfort and how bra type could affect key measurements when sizing body armour. A selection of officers were professionally refitted for both an underwire and sports bra and measured using a 3D scanner. The officers wore the bras for a number of shifts and reported back on comfort. Over 80% of the officers who participated were resized for their bras with the majority reporting improvements in comfort when wearing body armour. Most noticeable was that the majority of officers were planning to wear a sports bra post the trial, which was a significant change. Key measurements also identified that sports and underwired bras do affect the positioning and shape of the breast which would have an impact on the fit of the body armour. This is key due to the body armour being designed to work when worn close to the body. Any airgaps can cause an increase in the risk of perforation from a threat.

The final part of this research investigated the materials that could be used for the testing of body armour. Historially these materials have been based on the male chest wall and have not considered female breast tissue. The materials investigated in this research have the potential to enable the developers of body armour to truly consider how body armour works with breast tissue, and hence reduce the risk of a serious injury and provide better protection for female police officers.

Research by
Dr Christopher Malbon, Dr Clare Knock
and Dr Richard Critchley

Internally bevelled entry wounds in sandwich bones; their genesis, impact dynamics and macroscopic and microscopic morphology

When pathologists investigate the causes of violent death, they may need to study trauma inflicted on bone(s) to aid in correct identification and interpretation. However, bone is a highly complex material. This research followed a review of the scientific literature on projectile impacts on sandwich bone which indicated that there was no consensus on the mechanism by which wounds form. Furthermore, the cone shaped wounds considered typical of projectile impacts were found to form at both low and high velocities, and there was no accurate method to determine the velocity of impact from a purely macroscopic assessment of the wound. Combined, these factors add considerable complexity to differential diagnosis. Hence the aims of this research were to facilitate the interpretation of cone shaped wounds by investigating the fracture processes present during their formation and to search for signatures of high-velocity impact. This involved a detailed examination of the impacts and wounds at different levels of magnification.

Using the facilities at Cranfield Defence and Security, specimens could be impacted by projectiles under controlled and reproducible conditions with velocities ranging from 10s to 100s of metres per second. High-speed video of the impacts, with subsequent examination of wounds by photography, micro-CT (computer tomography) and both optical and electron microscopy, underpinned the experimental approach.

One of the first outcomes of this research was a novel hypothesis on

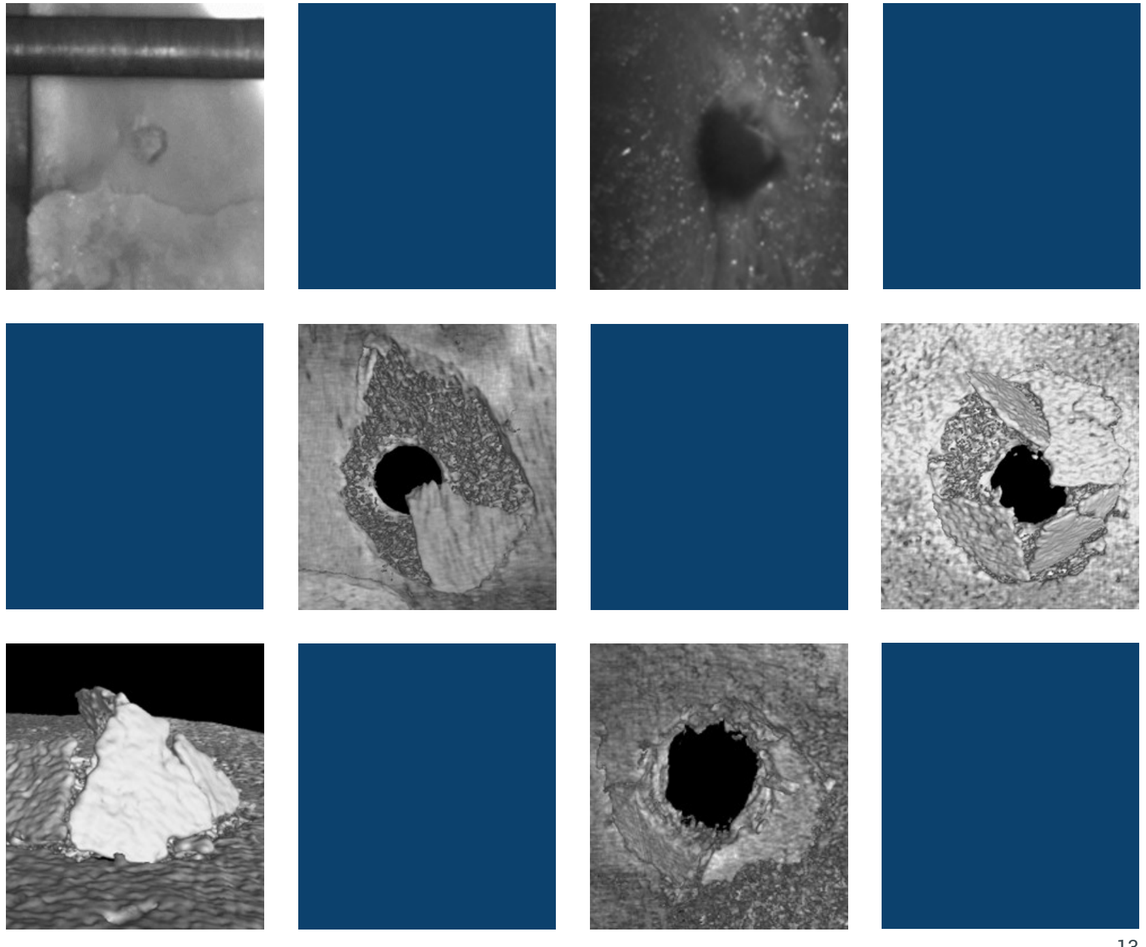
the processes involved in conoidal wound formation. This was further demonstrated by experimental evidence of cone cracking and the production and ejection of tri-layered conoids from the impacted bones. The morphology of these conoids was entirely consistent with published findings from archaeological and forensic case studies.

Additional support for the hypothesis was obtained by delving further into impact dynamics and the transfer of energy from the impacting projectile to the bones. The relationship between incident velocity and absorbed kinetic energy was found to be described by a power law. Comparison with other studies on different bone types enables one to see an important point, namely that the bone material and not the type of bone (shape, thickness etc.) is the dominant factor in energy absorption.

To further investigate the behaviour of bone under impact, electron microscopy was used to study the bone surface around the impact sites. At low velocities projectiles rebounded, creating concentric ring cracks around the compressed impact point, as is observed with conventional ceramics. (These ring cracks are the forerunners of the conoidal wounds.) At higher velocities, plastic deformation of bone around the entry point of the projectile was observed, this unusual behaviour is an indication that the mineral phase of bone undergoes structural modification.

The understanding garnered from this research has implications for forensic practice in crime scene reconstruction, from misinterpretation of the velocity of impact to trajectory determination. The latter is more complex than currently believed. In wider fields than forensics, the greater understanding presented in this work will be of benefit in the development and verification of both simulant materials and computer models.

Research by
Dr John Rickman, Dr Jonathan Painter
and Dr Rachael Hazael



Enhanced microwave imaging of the subsurface with application to humanitarian demining

Novel contributions have been made towards the evolution of the next generation of state-of-the-art Ground Penetrating Radar (GPR) for humanitarian demining application. We have pioneered the use of compact and full polarimetric antenna array as near-field sensors in monostatic, bistatic and multi-static GPR configurations.

Multi-perspective sensing in this way combined with new microwave imaging formalisms can provide significant performance enhancements over conventional GPR technology. At the GPR front end bespoke radio frequency antenna array, waveguide components, and microwave lenses were designed specifically for antenna near-field use near the ground. Antennas and components were fabricated using additive manufacturing and electro-plating processes to realise light weight, rugged, low cost, sensor arrays capable of production in the field. This was also the world's first ever application of a 3D printed antenna with dielectric lens integration demonstrated with subsurface imaging GPR.

The GPR system enabled full polarimetry data collection simultaneously in both monostatic and bistatic radar configurations. This enabled more sophisticated mathematical decomposition treatments to be brought to bear on the returned forward and backward scattered polarised signals. It has lead to a new paradigm in subsurface imaging, where objects can now be distinguished based not only on qualitative differences such as radar cross section level and synthetic aperture subsurface imagery, but

also on quantitative differences which characterise a wide variety of scattering mechanisms and provide new features to classifying buried landmines.

Opportunities for polarimetric sensing of landmines that exploit both spatial and temporal variations of the surrounding soil moisture level were also discovered. A unique form of temporal super resolution imaging was developed to provide cumulative differential phase interferometric imaging of the subsurface radar scene exposing buried objects and landmines in the ground. The approach was demonstrated to provide high resolution subsurface imagery with effective reduction of signal clutter and noise levels.

Research by
Dr Sebastian Wirth, Dr Ivor Morrow and Dr Daniel Andre

Image on page 16
A radar polarimetric antenna array scans different ground types for buried landmines (a TEM horn antenna illuminates the ground while two wideband loop antennas collect returned signals).

Breaking the mould of the orthodox approach to Security Sector Reform: A case study of Israel's civil-military relationship

Post-conflict Security Sector Reform (SSR) is a complex and difficult task which offers few historical examples of success. The practical challenges that SSR encounters are compounded by the western liberal democratic origins of the majority of the civil-military relations (CMR) theory from which it draws. By their nature, these theories are rarely well-suited to most contemporary post-conflict scenarios yet, since the requirement for post-conflict SSR shows no sign of diminishing, it is clear that an alternative approach is required.

This research offers a new perspective on the problem by advocating that the SSR programmers should make use of elements drawn from other less orthodox models in order to develop more appropriate objectives. In particular it argues that the Israeli system of CMR is a prime example of one such model, and in doing so for the first time an examination of the Israeli experience of CMR is used to directly inform the better understanding of post-conflict SSR.

Using a critical realist approach, the research presented a single case study to investigate the primary research question: How has Israel's CMR evolved since the state was founded in 1948? Thematic analysis was employed to evaluate data obtained from a series of semi-structured interviews conducted with influential Israeli elites. As part of this process a bespoke conceptual framework, CIPMIS, was constructed to ensure that the research covered all relevant aspects of CMR. The framework is named for the six separate, but related, factors that

it comprises: Cultural, Individual, Political, Military, Institutional, and Situational.

Interviews were conducted with over 40 key individuals in Israel working in a wide range of fields including politics, the military, the judiciary, the media and academia. These were then analysed and distilled into a 'thematic map', which is essentially a summary of the findings at an abstracted level. In this a unifying conception of Israeli CMR as being 'the same but different' is offered, reflecting the fact that, whilst often appearing on the surface to resemble a conventional western model, in reality Israel has so many historically, culturally, politically, and geographically unique elements to it that it cannot be templated.

The map shows that there are three overarching themes which address the critical concepts, these being:

- The peculiar nature of the permeable boundary between civilians and the military;
- The unconventional way in which the military engage closely with politicians behind the scenes, influencing government yet not running it;
- And, finally the effect that a constant background of violence has had on the development of Israeli CMR.

From this, three 'Big Ideas' emerged which, if adopted, could help to break the mould of the previously unfruitful, orthodox approaches to post-conflict SSR. They are: first, that culture and history must impact the design of all SSR programmes from the very start, not simply be bolted on afterwards; second, that more flexibility should be shown regarding military involvement in defence policy-making; and third, that if the benefits of more unorthodox approaches to SSR are to be realised, clear provision must also be made for the system to adapt over time.

Research by
Col (Retd) Dr Ian Westerman, Dr Bryan Watters and Dr Robby Allen

Image on page 21
The illustration visualises the three elements of the 'thematic map'. The helicopter represents the military influence with the sweep of the blades casting over two areas - a military/civilian population and government. The background depicts the shadow of violence that has been constant in the development of Israeli CMR.

Supporting operational decision making concerning aircraft structural integrity damage identified during maintenance

Military aircraft operations balance delivery pressures and engineering risks. Aircraft structural damage incurred in-service creates complex risk decision problems for managers deliberating maintenance activity such as delaying rectification to continue operations, or grounding an aircraft or entire fleet. A decision maker's consideration about a specific fault may be influenced by information such as the aircraft's historical and planned future usage profile or the presence of nearby defects. However, the choice reduces to: ground the aircraft with a known safe outcome; or fly the aircraft with some probability (p) of not returning safely.

Probabilistic risk solutions for p are possible for structural faults, which rely on a variety of fracture mechanics approaches coupled to methods for modelling uncertainty. These information intensive formal analyses require specialist knowledge or machinery beyond the capabilities of generalist engineering managers. In an operational context, aircraft availability demands also restrict the time, information, or resources to analyse structural risks in this way, rendering formal risk or decision analysis intractable. Consequently, aircraft maintenance decisions under operational constraints often compel decision-makers to use their subjective judgement in an unsupported way, for which no supportive aid has been identified in the literature. 'Unsupported' in this context means that there is no analytical or authoritative information that can be called upon in sufficient time to provide a solution. This is illustrated on a time axis plot, where

the decision horizon influences the accessible decision modes, extending the widely regarded Dual Process Theory of human reasoning.

For actors deliberating aircraft maintenance structural risks in such circumstances, a novel approach based upon heuristics, Toulmin argumentation and bounded rationality is proposed, which was informed by the results from a survey of engineering practitioners (n = 32) and case study analyses. These results indicated that practitioners were not necessarily able to represent structural faults in a complete risk form (inclusive of a meaningful likelihood of failure) and relied upon subjective judgement to form their evaluations of the fault. The solution is reliant upon decision-makers being able to arrange the available information around an argument structure, known as the Toulmin Schema. The decision aid also relies upon a heuristic, known as a Fast and Frugal Tree, to moderate the use of judgement for aircraft maintenance faults to only when necessary, when a sound argument can be formed and debiased.

Testing of the approach was carried out with twenty-one aircraft engineering decision-makers with experience of structural integrity risks, split into three groups, using realistic but fictional textual simulations of aircraft maintenance scenarios. One group used existing decision justification approaches and were compared with a second group who provided decision justifications using the novel approach. Users of the novel approach felt supported and were very confident in their justifications. The third group of raters comparing the two sets of decision justifications indicated preferences using Likert scales against the criteria: which is easier to understand, which is more transparent, and which gives the better justification. Analysis of the comparative results using Analysis of Variance (ANOVA) provided evidence that the novel approach enabled better decision justification and transparency compared to existing approaches.

The novel approach aids decision-makers compelled to use their unsupported subjective judgement, improving organisational resilience by improving robustness, stretching system process to handle surprises, and providing a clear record of the decision basis for post hoc review.

Research by
Squadron Leader Dr Richard Green,
Dr Ken McNaught and Dr Alistair Saddington

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Material strength evolution of FCC metals under high strain rates

Knowledge and understanding of the mechanisms and effects of high velocity impacts are vital to many different research areas; for example satellite or aeroplane protection in the aerospace industry, crashworthiness in the automotive industry, or armour systems within the military field. These different research areas focus on the safety of either people or electronics and therefore it is vital to understand how these materials are affected by high velocity impact or shock wave interaction.

This research investigated stainless steel 21-6-9, a face-centred cubic (FCC) material, where shock is loaded in partially recovered uniaxial strain flyer-plate impact experiments at varying impact pressures (6 GPa - 16 GPa). Samples were collected post impact via three differing recovery configurations:

- Standard or ‘free boundary’;
- Partial shock recovery, i.e. using both ‘momentum trapping’ and ‘soft recovery’ techniques;
- Finally, a traditional full recovery comparison with a 2 mm flyer impact.

These samples were then analysed using a suite of analytical techniques including X-ray diffraction, optical microscopy, hardness testing and compression after impact testing, to observe the material deformation characteristics in the simplified partially recovered shock and release condition compared to the more complex ‘standard’ release wave situation.

Results for the stainless steel 21-6-9 demonstrated the ability of

the partial shock recovery technique (hereafter called ‘partial-recovery’) to mitigate the reverberations compared to that of the standard samples. Upon analysis of the targets, it was observed that the dislocation density was generally lower for the partially recovered samples but varied with impact pressure for both the standard and recovered configuration. The twinning density to grain ratio obtained from optical microscopy showed a linear increase from 7 GPa at 4 twins per grain to 17 twins per grain at 16 GPa. Twinning density is indicative of a successful recovery, where a successful recovery is a reduction in reverberations in the sample and in a full recovery is a 1D shock. The dataset both verifies the use and success of the recovery technique as well as demonstrating the material’s characteristics under partial-recovery, while observing reverberation effects.

A recovery technique has been redeveloped for use in hydrodynamic gas-gun experiments, particularly on metals. This recovery technique could be successfully used in a number of different gas gun systems around the world, whilst currently being in use at Cranfield University. Stainless steel 21-6-9 has been characterised in different recovery states, with a plethora of hitherto unknown data provided, which can be inputted into predictive hydrocode modelling software for use in industries which have an interest in non corrosive austenitic steels. Furthermore, hardness testing and twinning density obtained from optical microscopy have been shown to be good predictors of the recovery behaviour of a metal, which provides a cost and time efficient method of obtaining preliminary results compared to the more traditionally used EBSD or TEM data. All of these factors combine to provide a significant benefit to the field of shock physics and engineering by enabling a greater understanding of the materials used with both financial and temporal benefits.

1. Control
Equiaxed grains with some twinning present.

2. Standard 7.0 GPa
Changes in grain size and shape with increased twinning compared to the control sample.

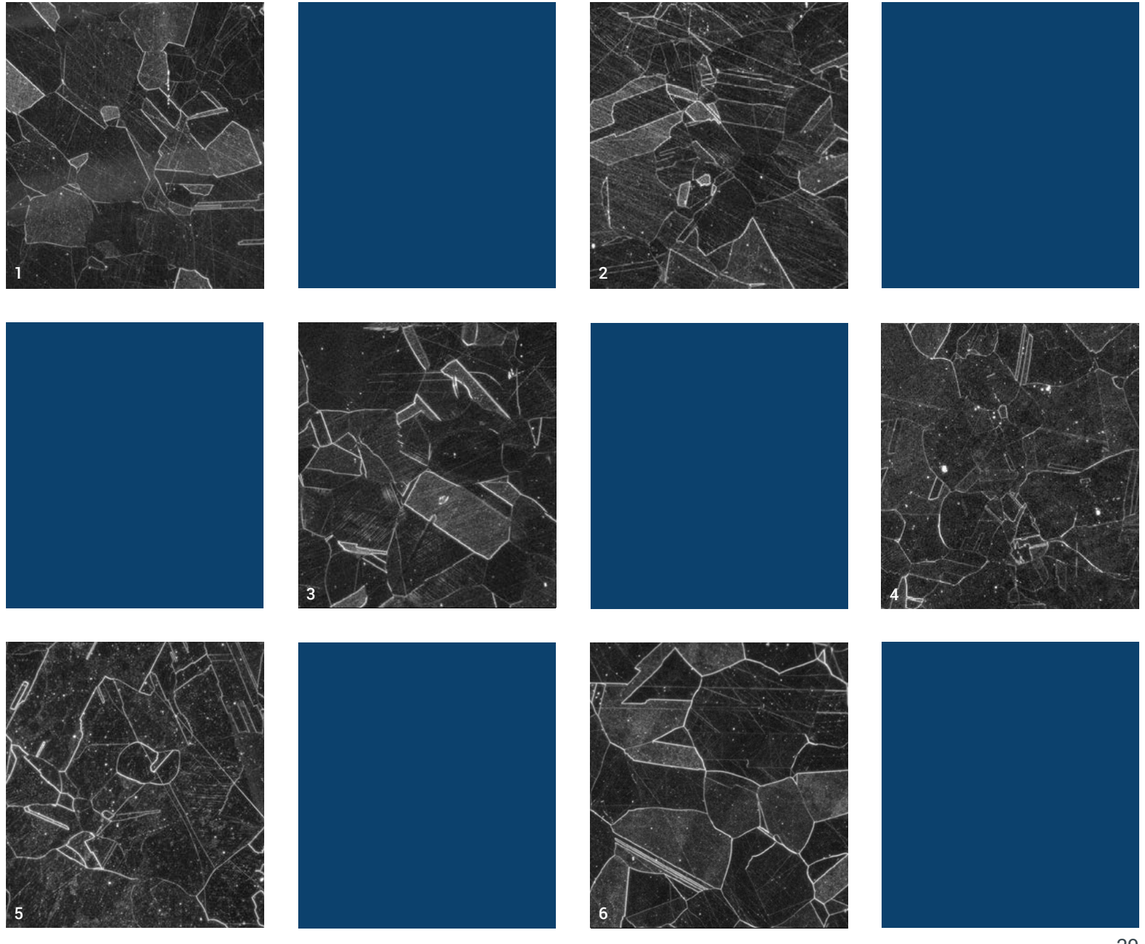
3. Partial recovery 7.0 GPa
The majority of grains are equiaxed with increased twinning compared to the control sample.

4. Partial recovery (2x2 mm) 7.0 GPa
An increase in twinning compared to the control sample with the majority of grains equaxial.

5. Partial recovery (1x4 mm) 7.0 GPa
An increased number of twins compared to the control sample with some variation in grain size.

6. Full recovery 7.0 GPa
Equiaxed grains with a similar number of twins as the control sample.

Research by
Dr Caitlyn Gilroy-Hirst, Dr Rachael Hazael
and Professor Jackie Akhavan



A novel approach for measuring the vibration properties of non-metallic materials

Modern engineering structures are composed of several different materials, such as plastics and metals. A major trend in engineering is to incorporate more non-metallic materials in designs, due to their favourable environmental and efficiency impacts. Aircraft design exemplifies this trend; in a span of just 25 years the use of composite materials has increased by 52%. In order to predict the response of a structure to vibration, it is necessary to know the properties of its constituent materials, for example, their response to stress and ability to damp vibrations. The research described here provides a novel experimental method for determining these needed properties.

The key properties that influence a material's vibration response are its Young's modulus and damping characteristics. For several materials, these properties depend on frequency and temperature. Thus, to maintain satisfactory behaviour of a structure over its full operational envelope, comprehensive characterisation is required. Such property data is the necessary input into computer simulations, which are an integral part of engineering design. The need for accurate property data in simulations was the primary motivation for the research.

The standard method of dynamic property characterisation is to use a Dynamic Mechanical Analysis (DMA) machine. These machines hold a material sample in grips, apply a sinusoidal oscillation and measure the resulting dynamic response. However, these machines are restricted to a small frequency range, often less than 100 cycles

per second. This is inadequate as modern engineering designs cover frequencies that start from a few cycles per second and can exceed 2000 cycles per second. Examples of such engineering applications include undersea piping and jet engines. These are safety critical applications, where it is important to have confidence that the material properties are correct over the full operational range of environmental conditions.

In order to measure dynamic properties over a given frequency range, material samples must be exercised at the frequencies and temperatures they will experience in operation. The experimental method developed uses the vibration of a beam to exercise material samples. In detail, the beam is excited at its natural frequencies, and is clamped at its root between two material samples. External vibration interference is eliminated by using inertial masses and a suspension system. Young's modulus may be obtained by observing how the material sample augments the natural frequencies of the beam. Damping, which is always difficult to measure, is determined from the decay of vibration following excitation. The method proves to be effective for a range of non-metallic materials which were tested for frequencies up to 2000 cycles per second and temperatures spanning -30 to +50 degrees centigrade.

The original objectives of the research have been achieved. It provides a new method for measuring non-metallic material properties which is now being examined by the engineering industry.

Research by
Dr Shabarish Sriraman, Dr Hugh Goyder
and Dr Clare Knock

An examination of morally embedded US governmental narrative allied to the approval and employment of selected counter-terrorism tactics

In the aftermath of 9/11, President Bush stated in a national television address ‘We will find those responsible and bring them to justice’. These words, reassuringly defiant and globally reaching, would set the course of the US in their pursuit of terrorists across the globe. Whilst US counter-terrorism initiatives may only appear to have been established since President George W Bush coined the term ‘Global War on Terror’, the initiatives actually date further back to the Nixon Administration and Executive Orders to establish a committee to combat terrorism world-wide in response to the 1972 Munich Olympic Games massacre. However, when a President publicly responds to a terrorist event, what is meant by ‘bring to justice’ or other words to the same effect? Does it create permission for an Administration to undertake morally unacceptable initiatives or commence illegal tactics? This research was designed to examine and better understand US Presidential communication in the aftermath of a terrorist attack.

The aim of the research was to examine whether Presidential Administrations create an obligation to the US public to respond to acts of terrorism when they are attacked either domestically or overseas by international terrorists or groups. The research reviewed specific counter-terrorism tactics that are employed by the US that perhaps attract the most criticism in the public domain: torture, extraordinary rendition and targeted strikes to either capture or kill a known terrorist. The research reviewed publicly available documents in relation to these tactics in the

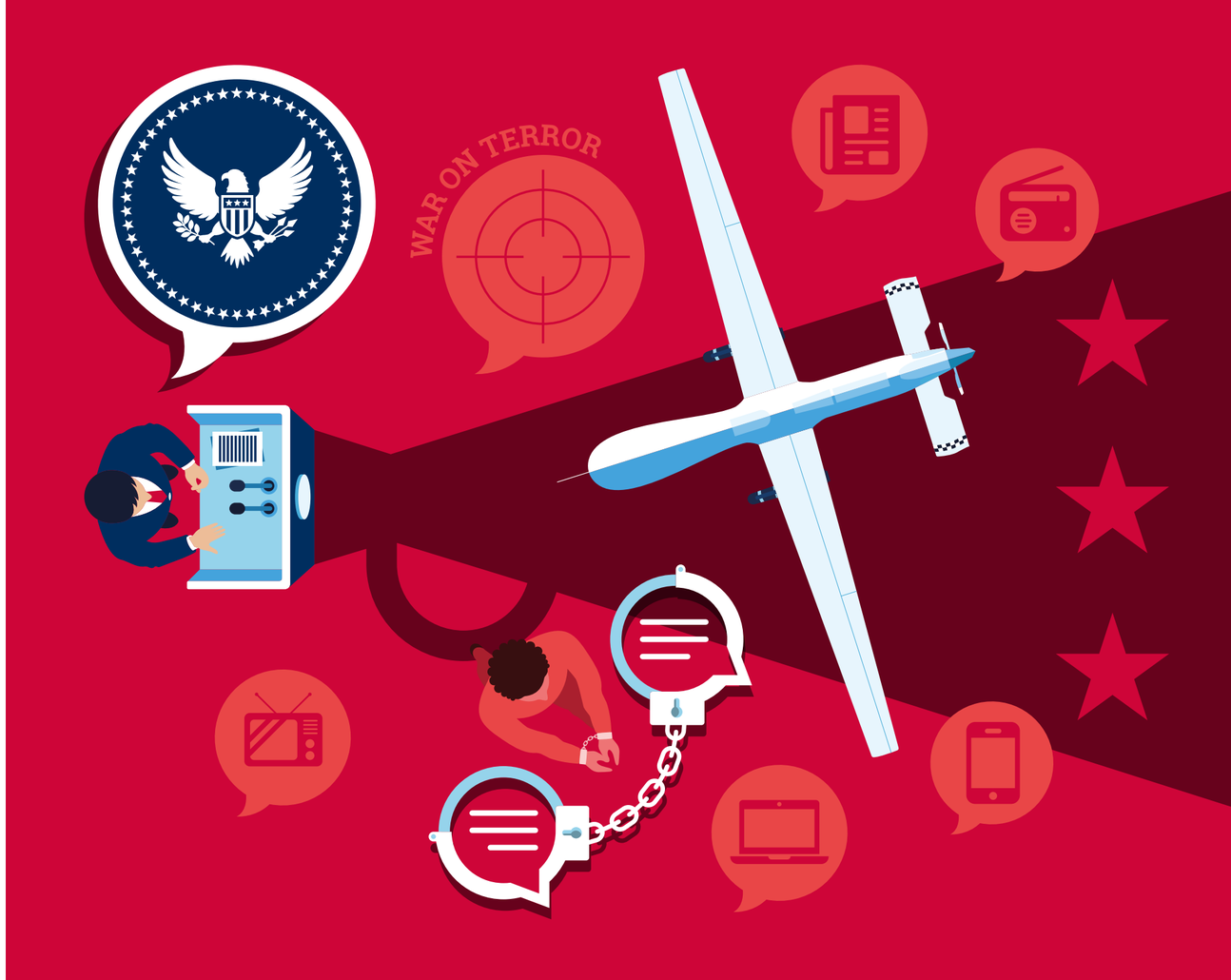
form of speeches, declassified Presidential Directives and National Security Strategies made by a US Administration from President Ronald Reagan to President Barrack Obama.

Analysis of the primary data was with the application of Speech Act Theory - a comprehensive field of social science dating back to 1950 where it has been used to measure the exact meaning of a person speaking. Although Speech Act Theory is generally only applied to verbal statements, the originality of this research was in the additional application of this theory to documents which was considered a valid means of communication between US Administrations and a third-party recipient.

The research reviewed known terrorist events over a 36-year period and then examined the response of each Administration when addressing the public, either in the immediate aftermath, or when those responsible for the terrorist attack were captured or killed. By applying linguistic analysis to what was communicated, the research revealed that there was a contract of response between the Administration and the US population and that this presented a self-generated pre-approval to utilise torture, extraordinary rendition and targeted strikes. It further identified that there is a complexity between the selection of words and medium of communication which affects the speaker-audience relationship which is ultimately not influenced by the severity of the terrorist attack resulting in those killed or injured.

The research was not designed to criticise US counter-terrorism policy but to use it as a framework to highlight that what is communicated, meant and acted upon can produce differing results; and that the chosen tactics may draw international disapproval, media condemnation or public criticism by the US population who have the right to voice their concerns against an Administration that employs morally unfavourable counter-terrorism methodologies.

Research by
Dr Benjamin Tripp, Dr Anastasia Filippidou
and Professor Andrew Silke



Multimodal navigation for accurate space rendezvous missions

Most of us today are familiar with the concept of autonomous vehicles, typically applied to self-driving cars which manufacturers hope to one day seamlessly deploy on the road without the need for human intervention. These vehicles are equipped with accurate sensors to perceive their environment, ranging from simple cameras to more complex radar, in order to successfully navigate it without risking any collateral damage. Our research is concerned with solving this estimation problem for the specific scenario of two spacecraft rendezvousing in orbit. In such a situation, one of which is controllable and carries the navigation sensors, called the 'chaser', is tasked with self-localising with respect to the other, termed the 'target'. This is known as spacecraft relative pose estimation: it is an integral part of rendezvous and needed for any further proximity operations such as docking.

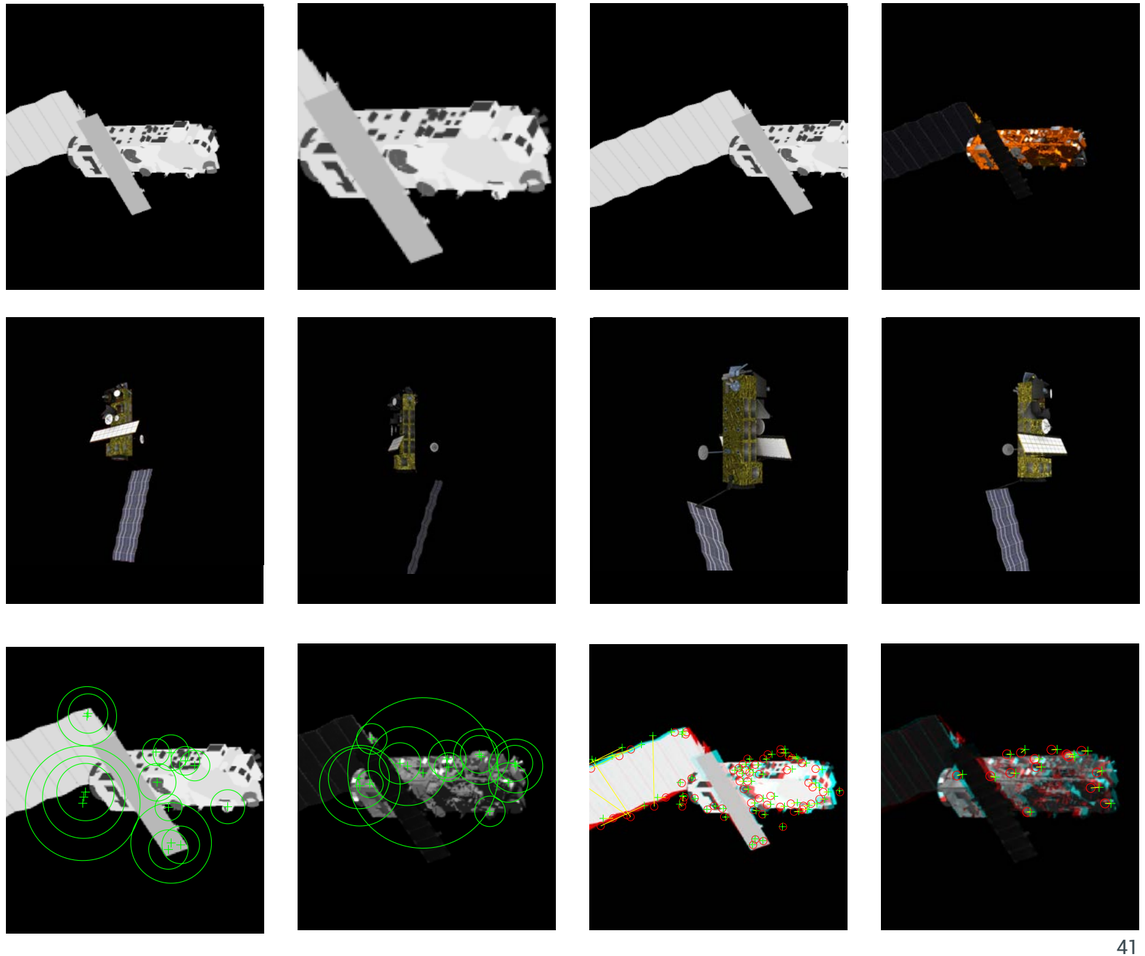
However, navigation in space is not as clear-cut as on the ground. For starters, because the two bodies are in orbit, they are free to not only change their position but also their orientation. These two quantities thus make up the pose, which must be estimated in full. Secondly, spacecraft have restricted power, volume, and cost budgets, which makes the widespread installation of costly active sensors hard. Passive ones such as cameras, on the other hand, are one of the cheapest and most available sensors, but require more complex image processing software approaches to get accurate results. This is investigated in this research to produce an accurate and fully image-based pose

estimation solution. Lastly, the space environment is very hostile towards typical image capture: satellites are often built with materials which reflect sunlight, causing glare at certain angles, and eclipse periods during the orbit can render the target nearly invisible. To tackle this, we propose to go beyond the visible and combine thermal infrared images to produce a multimodal approach. Thermal imaging largely depends on heat emitted by objects rather than on reflected light.

The research roadmap began with a straightforward task: data, data, data. Algorithms need examples to generate models, but annotated real image sequences of rendezvous in space are expensive to obtain. In collaboration with the European Space Agency, we upgraded the computer model of a target satellite with accurate material and thermal information to instead generate synthetic images using a realistic space camera simulator. The detection and tracking of interest points, or features, can be used to derive motion information from two-dimensional images. The next step consisted in selecting and benchmarking several feature detection algorithms on our rendezvous images, since these image processing routines were originally developed for ground applications. From this analysis, we developed two different pose estimation approaches: one based on classical machine learning involving feature matching with a codebook of the target on the visible spectrum; and the other rooted in modern deep learning for the unsupervised fusion of visible and thermal modalities.

The results of our research demonstrated improvements in terms of accuracy and computational complexity with respect to existing solutions in the visible (average errors of 2.5% for position and 1 degree for orientation), and our proposed multimodal fusion was successfully shown to mitigate the effects of visible imaging artifacts (average improvements per trajectory of 75% on position and 50% on orientation). The developed models were validated using experimental data acquired from laboratories in Cranfield University and City, University of London, UK, as well as in Thales Alenia Space, France, who sponsored this PhD.

Research by
Dr Duarte Rondao, Professor Mark Richardson
and Dr Alessio Balleri



The changing application of law in war: Aspects of the evolution of methods and means of warfare in international humanitarian law

International humanitarian law is the body of law that applies in situations of armed conflict to regulate the conduct of the belligerents and to provide for the protection of the victims of warfare. Methods and means of warfare is a phrase which, in international humanitarian law, refers to how soldiers fight (the methods) and what they fight with (the means). A very old body of law in general terms, with some of its rules dating back to ancient times, international humanitarian law nevertheless is a dynamic, evolving area, the interpretation and application of which can change in different circumstances.

Around the turn of the millennium the traditional paradigm of armed conflict was becoming ever more dominated by situations of non-international armed conflict on a spectrum of increasing complexity. The law, however, was - and still is - overwhelmingly weighted towards regulating conduct in international armed conflicts. With the increasing prominence of conflicts between regular State armed forces and their irregular opponents in foreign States, greatly amplified by the 9/11 terrorist attacks in the United States of America in 2001 and the subsequent 'Global War on Terror', but faced with the relative dearth of legal provisions specifically applicable in such conflicts, much of the discourse in international humanitarian law became concerned with the interpretation and application of existing rules from the law of international armed conflicts, but in the context of non-international armed conflicts. Over the same period, rapid military technological advances prompted

increasing discussion of whether the rules of international humanitarian law were ‘fit for purpose’ or needed amplification, development or revision in order to remain relevant.

The research focuses on several selected aspects of this general debate. The situation in Iraq from the coalition invasion in 2003 onwards is used as a case study for the applicable norms in evolving complex situations on the spectrum of armed conflict, whilst a specific example of targeting during Israeli operations against Hezbollah in Lebanon in 1996, barely otherwise considered in the academic literature, is analysed in light of the nature of the conflict and the applicable rules. The practical topics of the law concerning methods and means of warfare, and the particular rules concerning the use of specific weapons, are assessed critically in terms of their extension - accomplished, putative or merely aspirational - to non-international armed conflicts. Specific technological advances and their relation to particular rules of international humanitarian law are assessed, namely, the application of the notion of direct participation in hostilities in the context of cyberwar, and the use of ‘drones’ to carry out targeted killings of designated hostile actors.

The research affirms that the law is adequate to deal with these situations but that what is necessary is the consistent interpretation and application of the existing rules, which in the current polarised geopolitical context appears increasingly out of reach.

Research by
Dr David Turns, Dr Bryan Watters
and Professor Laura Cleary

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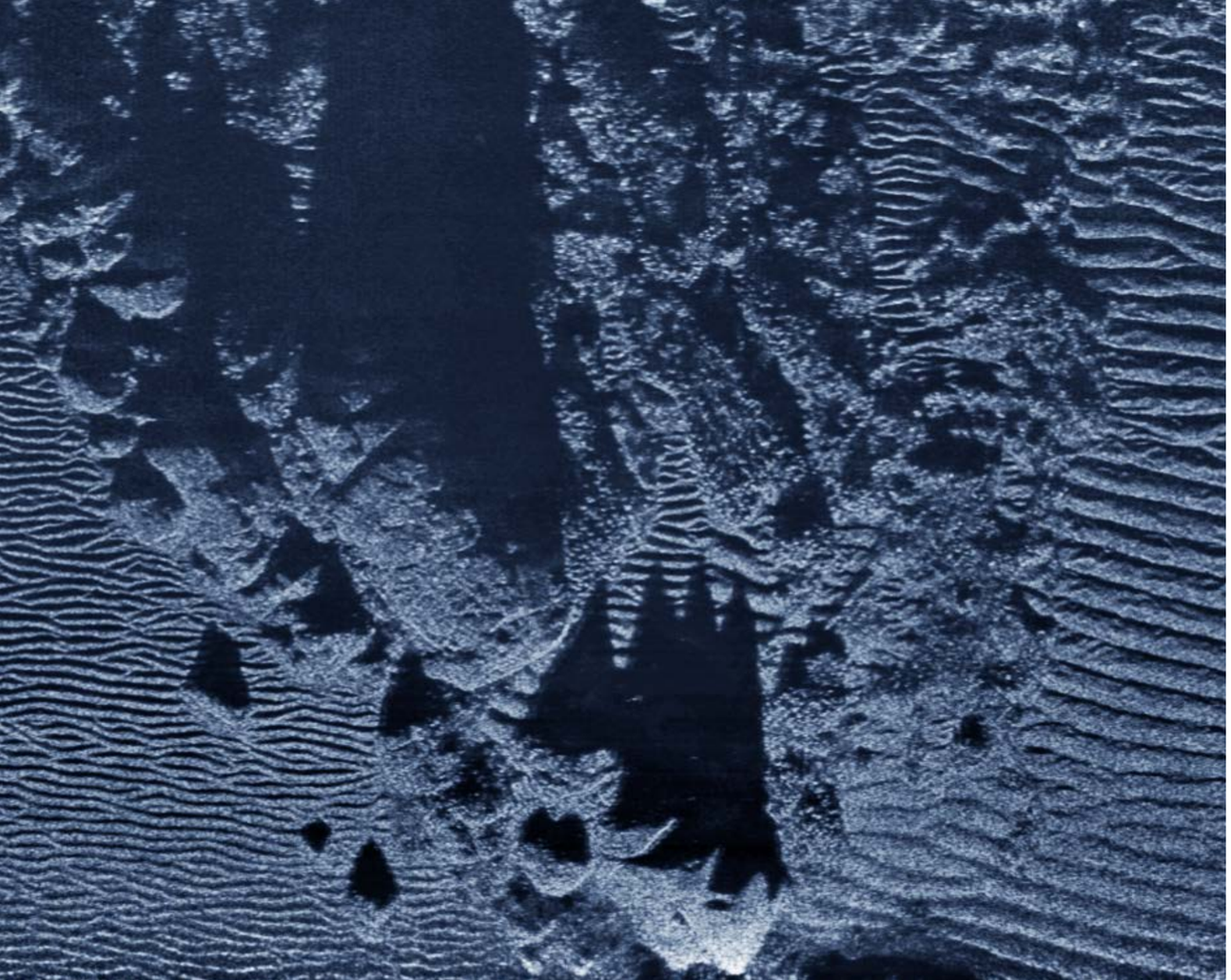


Towards a robust SLAM framework for autonomous underwater vehicle navigation

While mankind is sending probes to explore and map Mars, the depths of our oceans remain a comparatively remote and unknown environment. It is a complex and hostile place which requires significant and expensive means to carry out the surveys which would enable us to have a better understanding of it. However, the rise of marine robotics suggests an interesting development. Could we finally have the means to overcome this uncharted frontier?

Furthermore, the depth of the oceans will play an ever more critical part in the challenges faced by defence in this century. In particular, the ability to deploy extremely long-range autonomous systems would strengthen the capacity to protect itself against naval threats, either surface ships or submarines.

Such an autonomous system must be able to navigate without being able to perform a GPS relocation; at best the area can be GNSS-denied, at worst surfacing could compromise the system and leads to its demise. As a result, it must exclusively rely on its inertial unit and its perception of the environment, usually through active acoustic sensors such as sonar imagers while constantly remaining underwater. Typically, a map of its area of operation would be sufficient to recalibrate its position and correct a strong inertial drift. However, what can be done when the operational area is insufficiently mapped, as is the case with most parts of the oceans?

The purpose of our study was to focus on the development of Simultaneous Localization and Mapping (SLAM) algorithms

applied to the context of underwater navigation. They allow an autonomous agent to build a representation of its environment based on its own acquisitions and then use it for future reference.

One of the first aspects of our study was to consider the problem of performing side scan sonar image registration under a global context. Usually, such problems are addressed by a local approach where the inertial uncertainty is small enough to allow the use of image similarity metrics to handle the image registration. However, when the inertial drift dramatically increases, they become insufficient and even completely irrelevant with time. On the other hand, the underwater environment is poorly structured which greatly complicates traditional robotics approaches. There are few artificial features, and the potential natural landmarks are very similar which leads to ambiguities when performing data association.

Our study proposed a robust graph-based SLAM methodology that relies on recovering the correct topology of the scene. The objective is to rely on a set of metrics, both on the posteriori mosaic and trajectory, to deal with this highly ambiguous context. This data fusion methodology can naturally be extended to the context of heterogeneous acquisitions such as the use of bathymetric measurements to further enhance the robustness and resilience of the system. The main contribution of this study is centred on a novel data processing framework that can generate different graph topologies using robust SLAM techniques. One of its advantages is to facilitate the testing of different modelling hypotheses to tackle the data gap following the temporary breakdown and make the most of the limited available information.

Research by
Dr Mathieu Issartel, Dr Lounis Chermak
and Professor Mark Richardson

Agent-based modelling of offensive actors in cyberspace

Cyberspace is a challenging environment to operate within; the space is congested with many different actors, some malicious, some friendly and many third parties using the space for everything from international billion-dollar commerce to keeping in touch with friends and family. Therefore, defending and responsibly operating in cyberspace requires a sound understanding of the interactions between these many actors and the effects of any of our actions. Furthermore, when defending, we must understand the impact of defensive measures on those legitimately using cyberspace and how attackers respond to the defensive actions we take. Hence, attackers and defenders have a fundamentally adversarial and reactive relationship.

One way to model these complex systems is through agent-based modelling; in this process, we model different actors as small pieces of software that can interact with each other and their environment. But, of course, any such simulation depends on the accuracy and validity of these small software models.

Capturing the behaviours and creating these software agents can be very challenging with the diverse set of creative actors we observe in cyberspace. For example, malicious actors could be nation-states using advanced (and not so advanced) capabilities, highly skilled cyber criminals or low-skilled actors using tooling built by others.

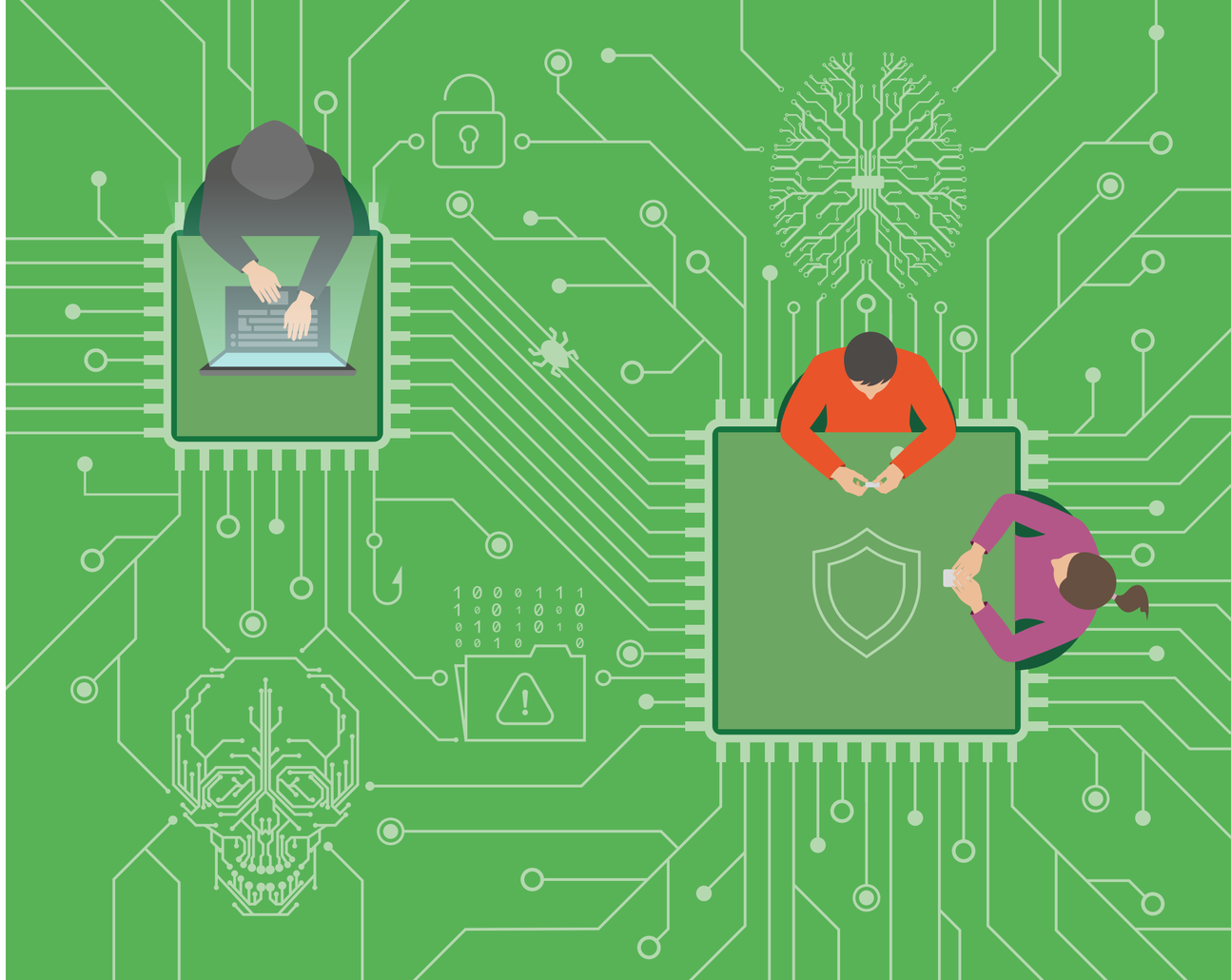
In this research, we created a board game that allowed players to act out fictional scenarios in an imaginary

world with fictional characters allowing players to behave in ways that they wouldn't in the 'real world' and outside of social norms and conventions. By metricating the game, we captured a diverse set of very rich behaviours, which we could automatically translate into these small software agents. We also measured the levels of impulsiveness and risk-taking associated with our players and could see the effect of these individual differences on the players' captured behaviours.

We found our player behaviours closely mapped to those observed in the real world, and our agents performed realistic and commonly seen steps resulting in natural-looking attack chains. However, we could also identify new interactions which led to some realistic but previously unseen attacks.

Most excitingly, a computer simulation allows us to create new realities and predict the steps attackers would perform to achieve their goals in this new reality; for example, what would we see with no sophisticated cyber criminals? With a significant increase in the number of hacktivists? Or with the 'down skilling' of high-end capability to low-skilled actors? Modelling these alternative, but plausible, futures allow us to explore optimal defensive strategies to defend and secure our cyberspace.

Research by
Dr Tatjana Sidorenko, Dr Duncan Hodges
and Professor Mark Richardson



Development of a K-band FMCW flexible radar prototype for detection and classification of nano-drones

The technological transformation towards unmanned aerial vehicles began with the transition from full-size aircraft to large remotely controlled and unpiloted aerial platforms. Referred to as drones, their size has been significantly reduced over time to provide unmanned solutions that have become more portable, more affordable and easier to operate. These changes mean drones are no longer restricted to the military, and they have become a technology readily available to civilians for both commercial or private use.

The smallest type, nano-drones, are already an existing technology. Insect-like in size, they have the capability of intrusion to provide intelligence and potentially violate secure establishments and public privacy rights. As such, they may soon provide a tool for stealthy surveillance and become a plausible defence and security threat.

Smaller drones are characterised by a low Radar Cross Section (RCS) and, as a result, detecting them with conventional radar becomes a challenging task. Increasing the radar operating frequency, and thereby shortening the wavelength, is a possible way to increase the target RCS. However, at the same time this reduces the radar maximum detection range as attenuation due to atmosphere and dissipation losses grow with frequency. As the radar performance is usually evaluated by the ability to detect a specific target at a given range, it is important to compromise between the operating frequency and the detectable range.

One of the techniques that have been deployed in micro-UAV detection is the extraction of micro-Doppler signature. Micro-Doppler signatures are Doppler signatures induced by micro-motions of the target, like the rotation of the propeller blades. As micro-UAVs hover or move at a relatively low speed, they are often characterised by a small main body Doppler return. However, small rotating or vibrating parts of micro-UAVs can largely contribute to the micro-Doppler. Despite the increasing research focus on these techniques for detection of drones, the existing literature lacks detailed investigations focussing on the detection of nano-drones, that is drones of a size comparable to insects.

This research investigated the design and development of a K-Band Frequency Modulated Continuous Wave (FMCW) radar prototype for nano-drone detection. The resulting FMCW radar prototype consists of connectorised components operating at a carrier frequency of 24 GHz and offers high parameter selection flexibility. Experiments have been undertaken in order to evaluate the system's performance. Results showed that an Arcade PICO Drone Nano Quadcopter, smaller than 5 cm, could be detected, and that its micro-Doppler signature could be extracted from the data.

Research by
Dr Safiah Binti Zulkifli, Dr Alessio Balleri and Professor Mark Richardson

Image on page 54

A novel dual-spin actuation mechanism for small calibre, spin stabilised guided weapons

Long-range weapons have been an integral part of warfare throughout human history. Modern warfare is increasingly taking place in built-up areas, with a high density of civilian populations and structures in which the possibility for unacceptable collateral damage is extremely high. The term ‘guided weapon’ encompasses a family of ranged munitions which are equipped with a control mechanism, able to purposefully modify the munition’s trajectory during flight. The higher munition accuracy provided by guided weapons results in a lower likelihood of collateral damage, a larger probability of achieving a successful target effect with the first round and a correspondingly lower economic and logistical burden. The advantages of conventional guided weapons are numerous and proven on the battlefield. As a result, they are now well established in modern arsenals.

The physical hardware (components and subsystems) used in guided weapons is complex and must be resilient to extreme flight conditions. As a result, these components and subsystems are relatively large and expensive. The research was focused on small calibre munitions which often have a high spin rate imparted on them to improve their accuracy, and this high spin rate is contradictory with the established methods used for controlling large calibre guided weapons (conventional); at least given the current position of the control technology. This work has established a novel method of projectile control which addresses these issues and conducts a systems-level analysis of the underlying actuation mechanism.

The projectile design uses two sections, which are connected by a bearing but allowed to spin independently of one another. This ‘dual-spin’ design is geometrically identical to conventional small calibre projectiles and is designed to be used interchangeably with conventional ammunition. The front half has an asymmetric aerodynamic profile, and the back section contains the control and guidance electronics and actuators. Control is enacted by intelligent physical locking and unlocking of the two halves at opportune moments in the projectile’s rotation, to subtly impart lateral motion towards the target.

A seven degree of freedom model has been developed to model the projectile, aerodynamic perturbations and coupling moments. This was validated using firing range data.

A mathematical framework has been constructed to model the actuation mechanism and an associated guidance law, which is responsible for generating instructions for projectiles’ actuators during the fast approach to the target. A parametric investigation is undertaken to investigate the breadth of control permitted by the guidance law. It was then improved by using a genetic algorithm optimisation method.

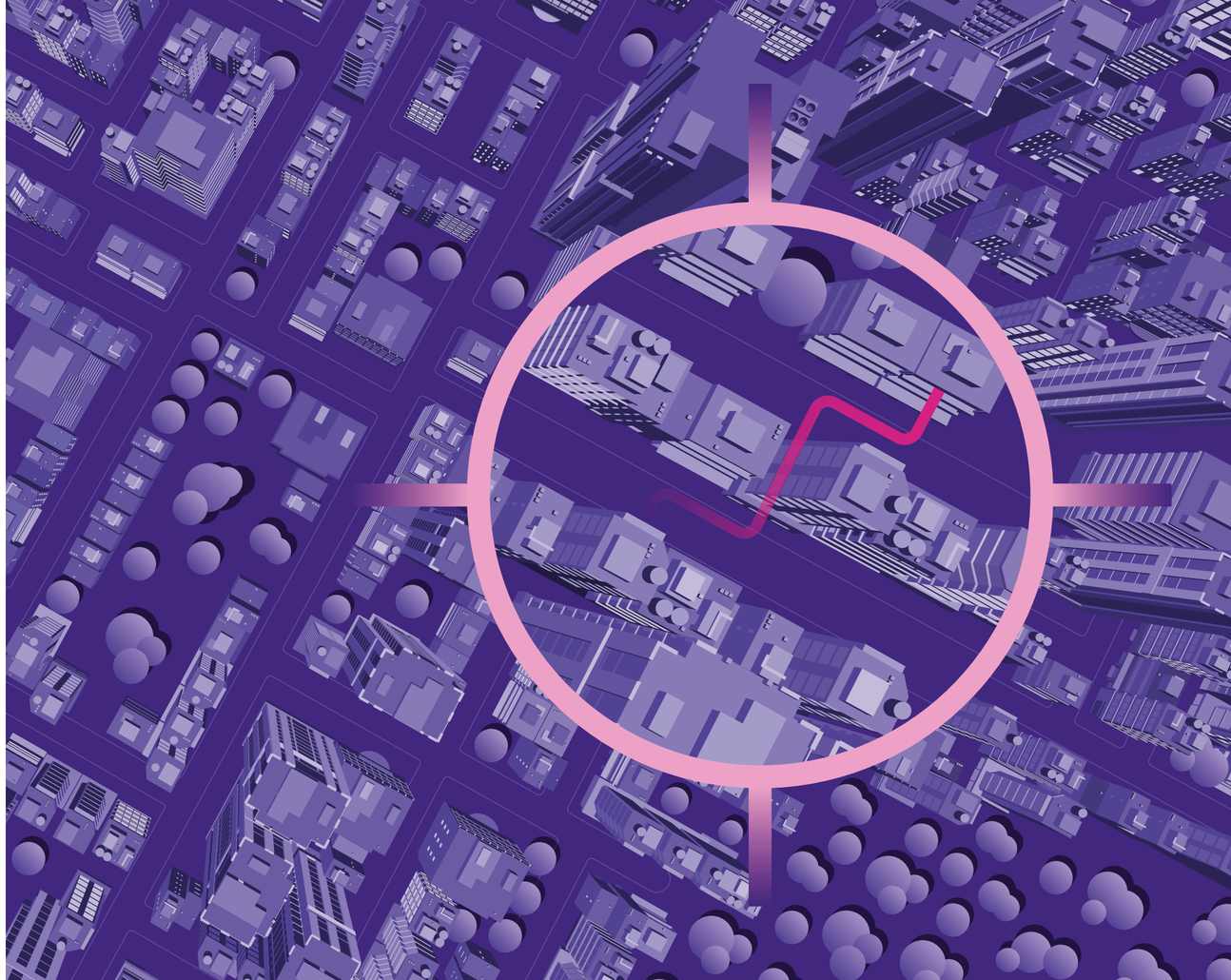
Alongside this, two variants of deep neural networks were used to create an independent actuation mechanism framework and guidance law. Both the bespoke and AI guidance laws were then compared against several traditional and well-established methods, using Monte Carlo simulations. CAD models of the novel projectile were produced and used for aerodynamic analysis. Finally, the novel design and accompanying guidance algorithms were compared against a classic ballistic in computer simulations. The novel design was shown to reduce the impact grouping area by 80%.

The research was published in the Journal of Aerospace Engineering (IMECHE) and Defence Technology (Science Direct).

Research by
Dr James Norris, Dr John Economou and Professor Amer Hameed

Technical support for this research was offered by Mr Simon Parker of BAE Systems. The work was funded by BAE Systems and an EPSRC Industrial Case Award.

Image on page 58



Cutting a Gordian Knot? Understanding the relationship between culture and process, environment, and people in military planning

This research focussed on the experience of military planning; in particular, why practitioners, when in real operations, appear to find it difficult to use the structured planning processes.

Conducted by Colonel Nicholas English, a review of military-specific literature reveals that the human experience of military planning is relatively underdeveloped in comparison to the more technical facets. It addresses that gap through a comprehensive analysis of planning and decision-making research, exposing a rich, multi-disciplinary body of knowledge that relates planning strategies with complexity, 'wicked' problems, and psychology. His analysis develops three key themes: culture and process, real-felt environment, and people. These form the foundation for a revelatory case study of real-world planning during the Joint Aviation Group (JAG) deployment to Afghanistan in 2014.

The study draws together the key themes to propose that the difficulty experienced by individuals is grounded in the inter-relationships between the military socio-cultural norms and expectations, people's naturalistic behaviours, and their perceptions of the environment. Building on evidence developed in the case study, the frameworks position the dissonance felt by individuals in the gaps between their constructed context and their experienced environment. Dissonance then has a wider effect on performance, acting as the trigger for behavioural adaptation and as an indicator of impending instability, particularly when relative complexity

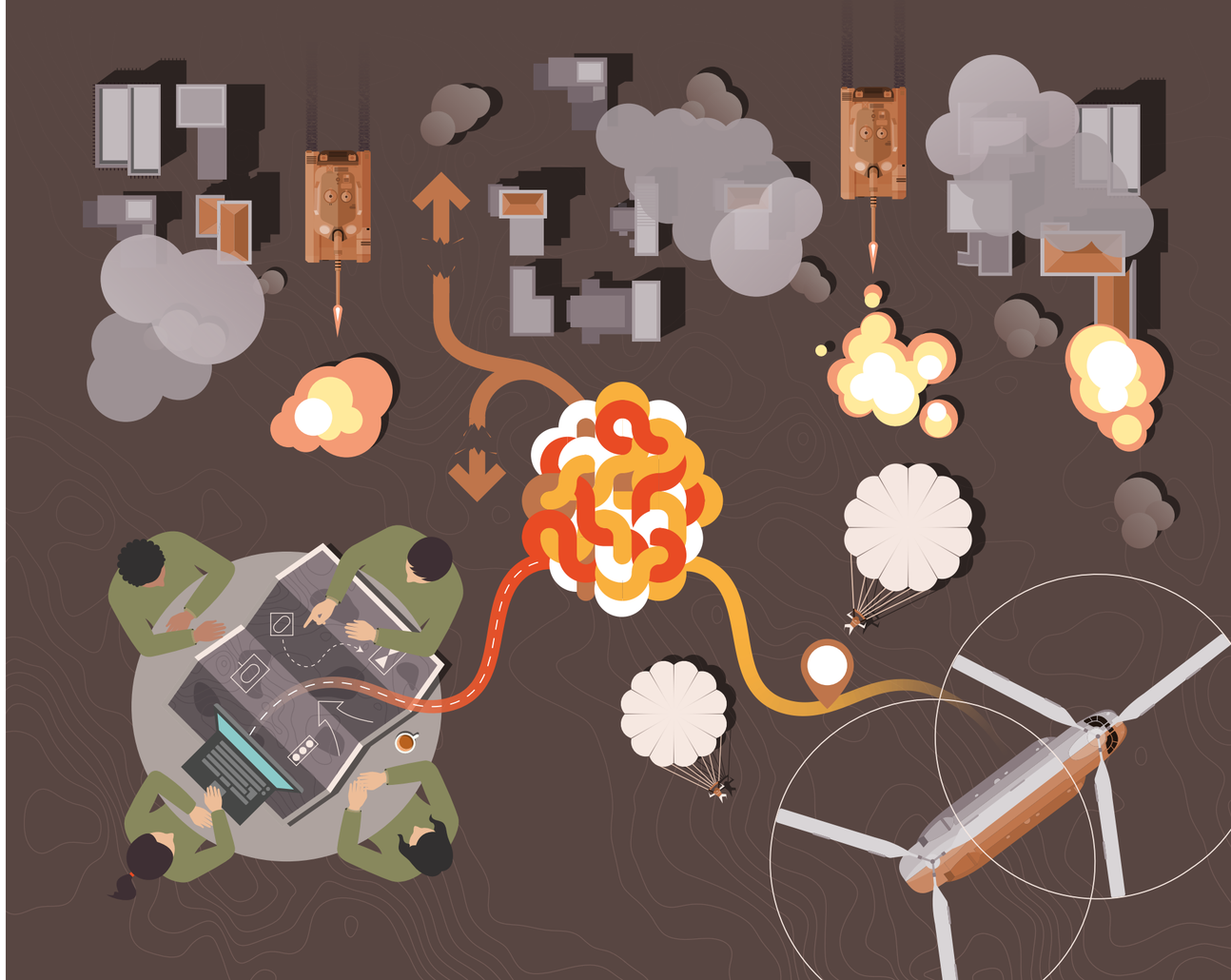
is high. The research proposes frameworks that link planning strategies and contextual complexity with stability and robustness, to put forward explanations for the behaviours observed in military operations.

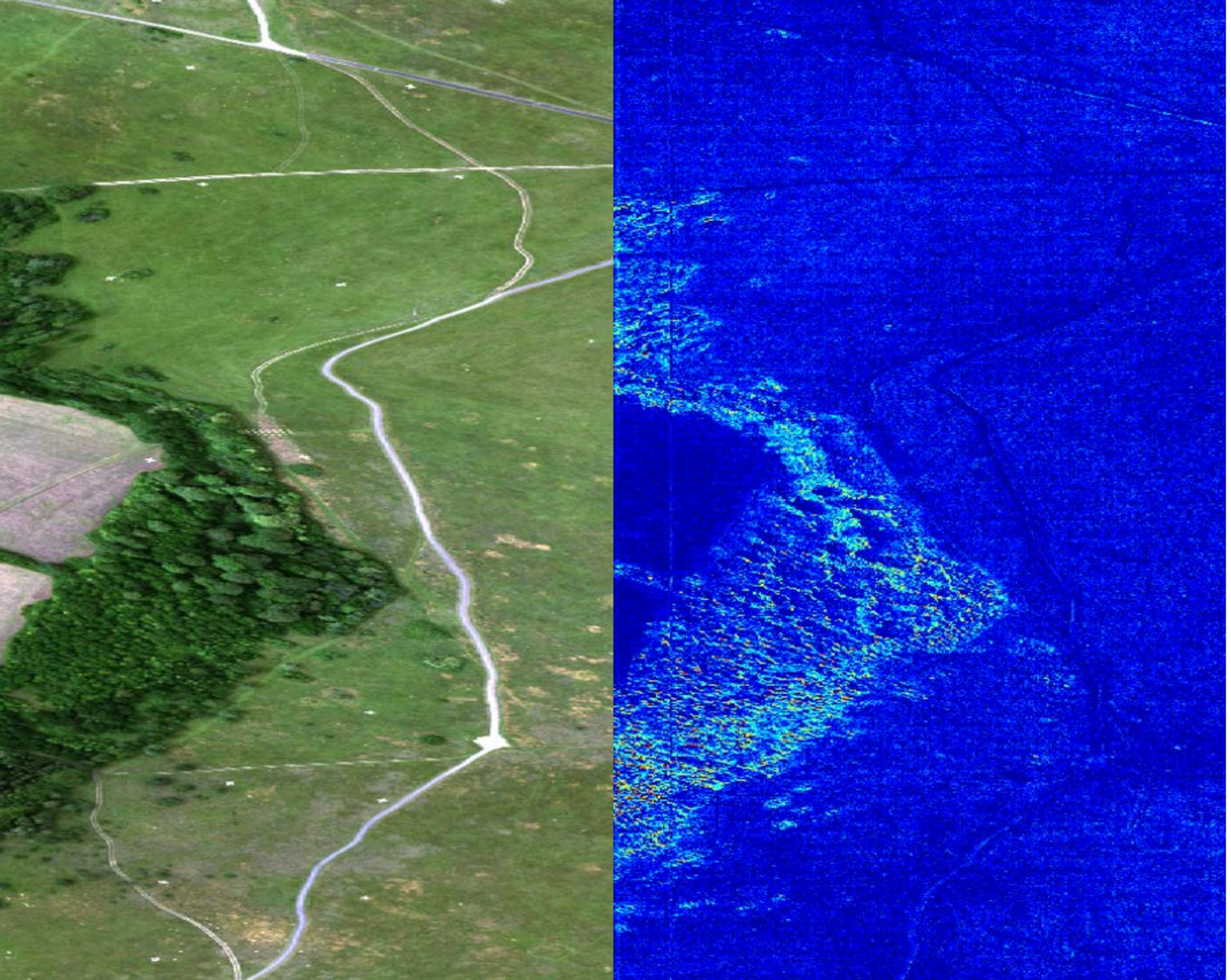
Nick collected his data in an individual and unique setting. He captured personal accounts from a live operation as part of the JAG operations in Afghanistan in 2014, while being himself immersed in that same operation as an attack helicopter command-pilot (prior to that, he was deployed on combat operations in Afghanistan three times between 2006 to 2008). The stakes were high and quite often literally a matter of life and death for those involved. The core of his study developed from his direct experience as a military planner and commander.

The military tenet at the heart of collective training is that following a planning process is the key to rapidly understanding the environment, generating an optimal plan and defeating the adversary through the application of tempo, momentum and use of force. However, Nick's lived experience of military planning proved somewhat different. Many found it difficult to use a rational, analytical, reductive process to address 'real world' complexity. This difficulty manifested in different ways for different people, which they broadly described as a sense of dissonance or tension, sometimes manifesting as counter-productive behaviours. The 'shiny products' planning process wasn't just simply failing, it appeared to be impacting people's intellectual thinking, behaviour and emotional state. The analytical planning processes, that had been the focal point of so much training, were mostly forgotten and variants emerged that focussed on activity rather than desired/ expected outcome.

Nick's dissonance-based frameworks, developed through lived experience and a carefully crafted 'real life' case study, now stand as a potent reminder. The research recommends a number of strategies for military practitioners and doctrine developers to restore a sense of reality in order to improve robustness in military planning when operating under a complex range of environmental conditions.

Research by
Col Dr Nicholas English, Dr Lorraine Dodd
and Mr Jeremy Hilton





Enhancement and validation of the CameoSim hyperspectral scene simulator

Hyperspectral scene simulation is a powerful technique designed for assessing the detectability and vulnerability of targets without the need of laborious experimental trials; regardless of whether the targets are embedded into a variety of scene backgrounds, atmospheric conditions, sensor characteristics, ambient temperatures and illumination sources.

The research project's main objective was to assess the reliability, limitations and accuracy of CameoSim, a Commercial Off-the-Shelf (COTS) military grade hyperspectral scene simulator originally designed and produced by Lockheed Martin for military applications. Subsequent objectives have included the improvement of the effectiveness accuracy of CameoSim for assessing the vulnerability of targets in the scene. The project utilises data collected by DSTL in 2014 from a real hyperspectral image (HSI) known as the 'Selene' scene as the template. It simulates the scene by using the original and enhanced versions of the CameoSim package to validate both the spectral integrity as well as the target detection statistics of the simulated scene against that of the ground truth real data.

This project was fully funded by DSTL between 2015-2019 to support three PhD students, and the original CameoSim package has been enhanced through their three research projects:

- 3D simulation with enhanced cloud modelling and target injections through a Matlab GUI interface.

- Material allocations through compressive sensing techniques.

- Migration of CS from the Linux into the Windows platform.

In essence CameoSim is a physics based scene simulator, which compiles modules for facilitating the modelling of radiances of the observer under various geometries of solar or artificial irradiances, atmosphere conditions and viewing geometry conditions through the MODTRAN data base.

It was found that the CameoSim in its original form is not capable of simulating hyperspectral scenes accurately, and which exhibits spectral /statistical error of ~300% with respect to the ground truth (GT). The large simulation error is caused by CameoSim's 'material classification' feature which is found not able to allocate material species correctly for the scene to be simulated. After replacing the original 'material classification' module by an external material map, the simulation of the reflectance scene achieves a mean spectral error of 7.2% with respect to the GT. This encouraging result suggests that the enhanced CameoSim package will be able to simulate any scenes in any locations over the globe by using the 8-band or 16-band of satellite images as the input data.

Four journal papers have been published under this scene simulation project.

Research by
Dr Murat Gunes, Dr Peter Yuen
and Dr David James

This project was fully funded by DSTL between 2015 - 2019 to support 3 PhD students.

Image on page 66
The 'blue' coloured picture (right) is showing the % error of the simulation with respect to the ground truth (left) when the simulation was done using only 32 WV3 satellite imaging bands.

The tipping point of terror: The psychological drivers of escalation from sympathetic to active involvement in violent extremism in Northern Ireland

The ‘specificity problem’ is one of the longest running unanswered questions in research on terrorism. This problem focuses on the fundamental question as to why do only a few people radicalise when many appear to have been exposed to at least some of the same causes of radicalisation? Leading scholars have referred to this as the ‘greatest mystery’ currently facing terrorism research.

This research has sought to help answer that question by examining two groups in Northern Ireland: the first composed of seventeen former paramilitary members and the second composed of twelve paramilitary sympathisers. The sympathisers acted as a control group as both came from similar areas and had very similar backgrounds.

The research focused on identifying and examining differences and similarities between the two groups. Semi structured interviews, questionnaires and psychometric tests were completed by all participants, allowing the research to explore factors which were distinctive of those who became actively involved with paramilitary groups versus those who had not.

Importantly, the results found no differences between the two groups on a wide range of factors normally associated with radicalisation, including for example the number of family members killed during the conflict. On the contrary, only a small number of significant differences were found between the two groups. For example, involvement in rioting as a youth, higher levels of community isolation and less

exposure to other communities were among the few factors associated with individuals becoming directly involved with a paramilitary group. The research results overall represent an important step forward in efforts to finally resolve the mysteries around the ‘specificity problem’.

Research by
Dr Emma Yialto-James, Professor Andrew Silke and Dr Anastasia Filippidou

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