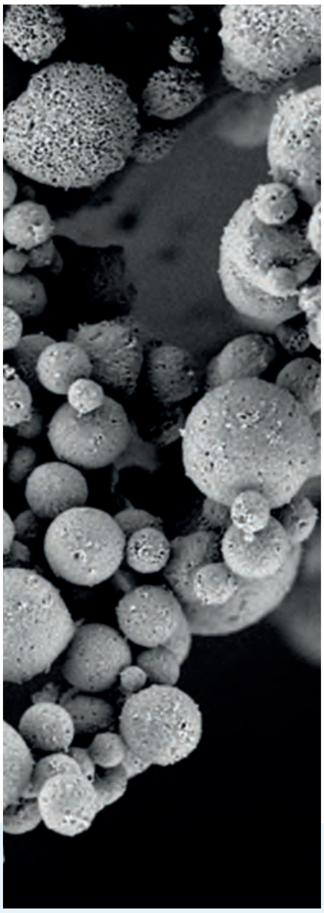
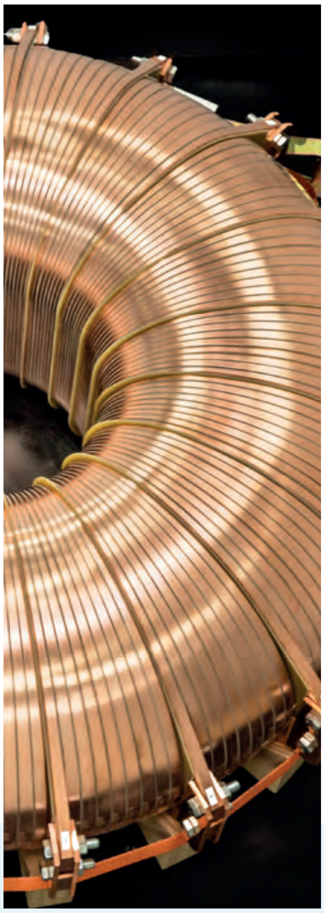
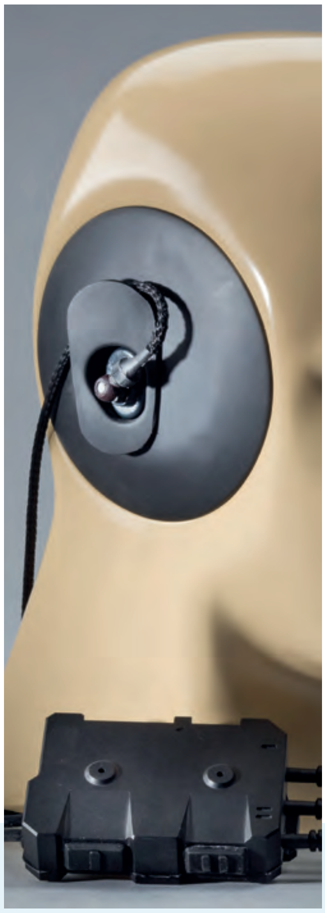
French-German Research Institute of Saint-Louis



Annual Report 2017–2018

Content

ISL

French-German Research Institute of Saint-Louis

Annual Report 2017–2018

Preface

European cooperation in defence has been over the past decades a fixture in political stances, interspersed with fewer and fewer collaborative armaments projects. Hypocrisy, lip service? Issues are admittedly complex: differences in strategic priorities or understanding of strategic autonomy, various doctrines of use, industrial considerations, etc. But a common European effort is dictated by necessity.

On their annual French-German meeting of ministers in July 2017, the German Chancellor Angela Merkel and the French President Emmanuel Macron have acknowledged that the development of a common European Defence Technological and Industrial Base (DTIB) is a solution for overcoming the problem of limited resources and a way to support greater military cooperation. And they have paved the way for a common future in ground and air combat systems.

Accordingly, both nations heralded during the 2018' Berlin Air Show (ILA 2018) the signature of the High Level Common Operational Requirement Document for a future joint fighter project. A lesser staged, but similar event had taken place months before to launch a common French-German project on a joint Main Ground Combat System (MGCS).

Ever since, the French-German Research Institute of Saint-Louis has played a key role in the subsequent efforts in order to make this perspective a reality. How could it be otherwise? From long-range detection/identification of incoming threats, to protection of the personnel and on-board high-end equipment, to the destructive power of the future MGCS, our Institute has a decades-long experience in many of the challenges that need to be tackled in such a project. Our expertise – independent from the expertise of the industry – has provided a significant contribution to these early stages of the cooperation that is being built. Our know-how and our innovations are available for the coming technology development and demonstration program.

On a broader front, ISL scientists and engineers bring disruptive technologies to life, focused on the needs of the end-users. Indeed, our clear focus allows us also to bridge the gap between innovations developed by the academic community in a civilian perspective and defence applications. With its co-located and mixed teams of experts of several nationalities and all ways of life, and as a hub for many partnering academic research and defence industry teams, our Institute acts as a force multiplier in the domain of defence research & technology, leveraging cultural and topical complementarities.

These complementarities are first and foremost evidenced by the wide multidisciplinarity and high interdisciplinarity of our teams. ISL's four main research topics (materials research including explosives, flight techniques for projectiles, new electric effectors such as eye-safe lasers and electric guns, and protection technologies) rest on a broad range of competences. Breadth of the research portfolio and depth of the research investigation are often opposed. But ISL's unique mix proves to be surprisingly efficient. Our scientific portfolio, our facilities ranging from complex simulations to free-field testing, our comprehensive approach nurture a wealth of tangible solutions. ISL acts as a R&T one-stop shop, unique in Europe, to the benefit of the frontline soldiers and first responders. This report illustrates selected scientific achievements.

ISL's output has earned in the past year recognition from the international scientific community and the defence communities, as well as from various personalities, confirmed by the numerous prizes and awards granted to several ISL research teams. None of these results could have been achieved without the active and proactive collaboration of the entire ISL staff: we praise them for their dedication to our institute – we dare say also on your behalf.

We have however no time to rest on our laurels. The ISL 2020 project has brought since 2012 a huge transformation of our institute, but it is drawing to its end, while the external context has also changed. This requires to genuinely reconsider how to serve you better, not only through trimming here and expanding there, but also with a thorough review of our constraints, opportunities, drivers and orientations. Doing this, we may well bring forward some disruptive scenarios: this is our DNA! This task is underway, in close collaboration with ISL's Board of Directors, and is slated to last a few more months for the sake of comprehensiveness.

We will report on this in our next Annual Report. This intense phase coincides also with an important anniversary for our Institute. The ISL Convention (the French-German treaty creating ISL) was signed 60 years ago in March 1958 by both Ministers of Defence and was ratified by both Parliaments in June 1959. We invite you to save the 27th and 28th of June, 2019 to celebrate with us 60 years of peaceful and fruitful cooperation, and to wish our "60-years young" institute a promising future. For the time being, we suggest you follow us for a pleasant journey through several ISL highlights, with the golden thread of a MGCS perspective!

Dr.-Ing. Thomas CZIRWITZKY   Christian de VILLEMAGNE

Facts and figures

Staff

per 31.12.2017

94 scientists

33 PhD students

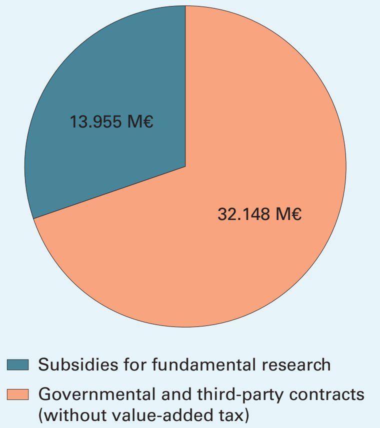
90 engineers

57 technicians

54 highly skilled workers

60 administration and support

2017 Income



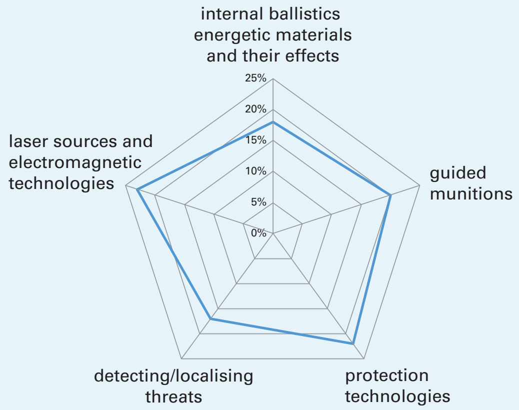
Scientific documents

161 documents with limitative list of recipients

166 publications (conferences, scientific journals, posters)

39 scientific reports and proceedings

Research focus

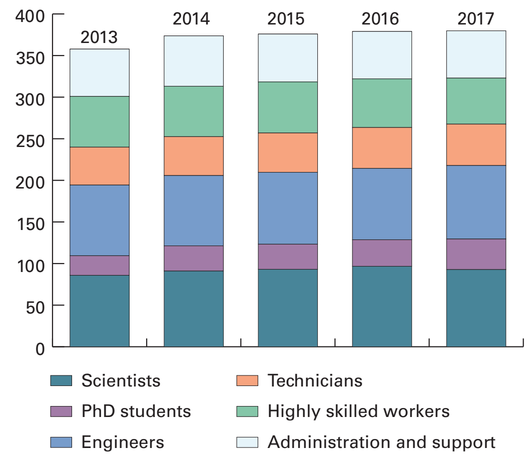


List of selected ISL publications on www.isl.eu

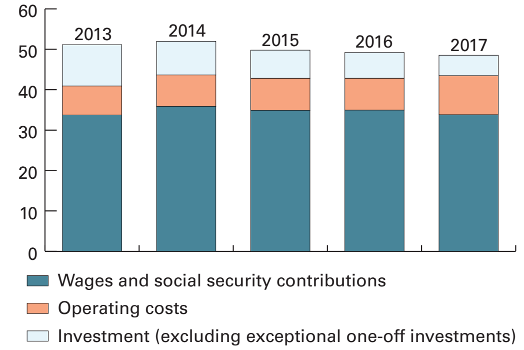
List of patents and licences on www.isl.eu

Evolution since 2013

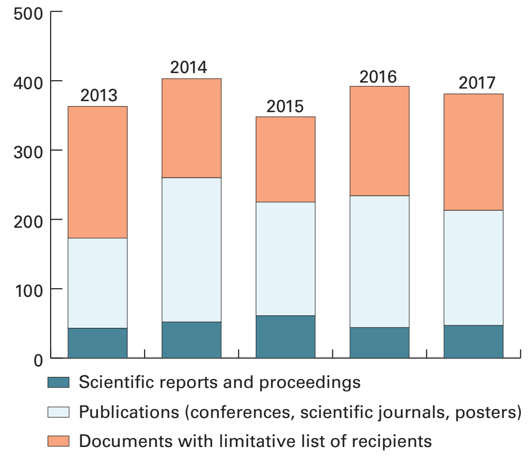
Staff



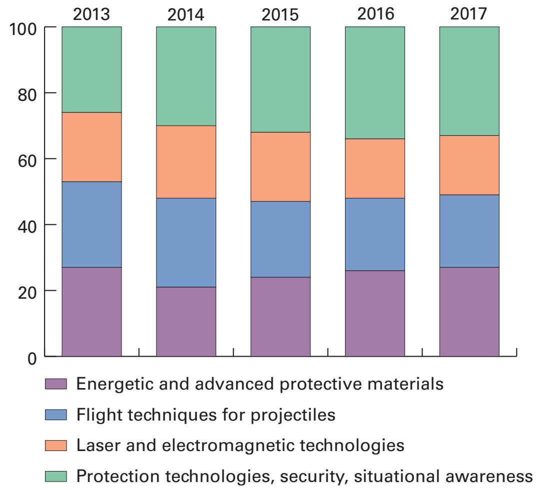
Expenditure



Scientific documents



Research areas



ISL TEAM

Management Team

Christian de VILLEMAGNE
French Director

Thomas CZIRWITZKY
German Director

Yves MEYER
Corporate and Financial Affairs

Jean-Pierre MOEGLIN
Business Development Office

Magdalena KAUFMANN-SPACHTHOLZ
Communication

Sandra LICHTENAUER
Quality, Safety, Environment

Strategic and operational Aspects of Research

Pascale LEHMANN
Acting Head of Scientific Sector

Christophe TAMISIER
Energetic and Advanced Protective Materials

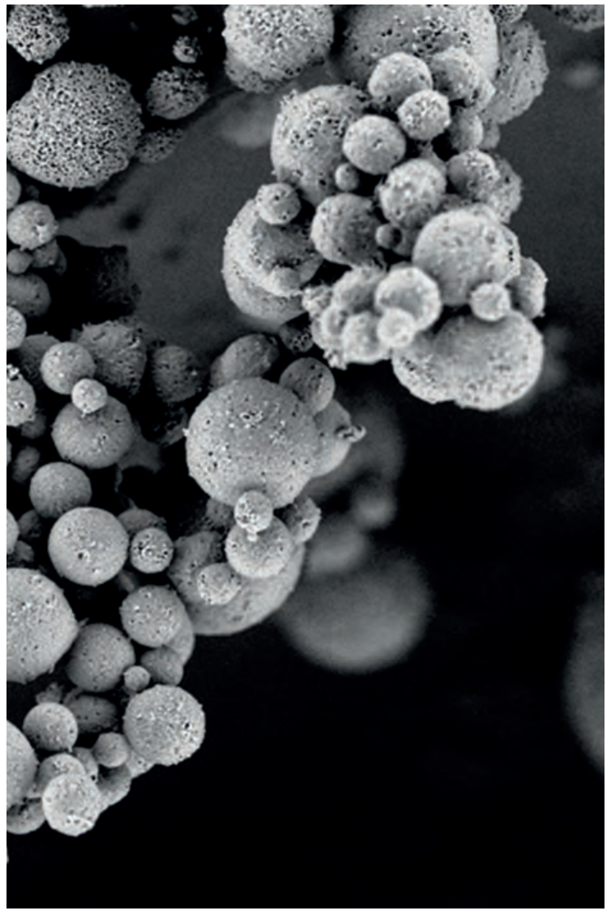
Patrick GNEMMI
Flight Techniques for Projectiles

Markus SCHNEIDER (interim)
Laser and Electromagnetic Technologies

Bernd Michael FISCHER
Protection Technologies, Security, Situational Awareness

Research areas

Energetic and advanced protective materials



While the armed forces get engaged in an ever wider range of missions, soldier protection and weapon efficiency continue to be of primary importance. In the field of protection, new threats have appeared, mainly because of asymmetric conflicts, especially guerrilla and terrorist attacks.

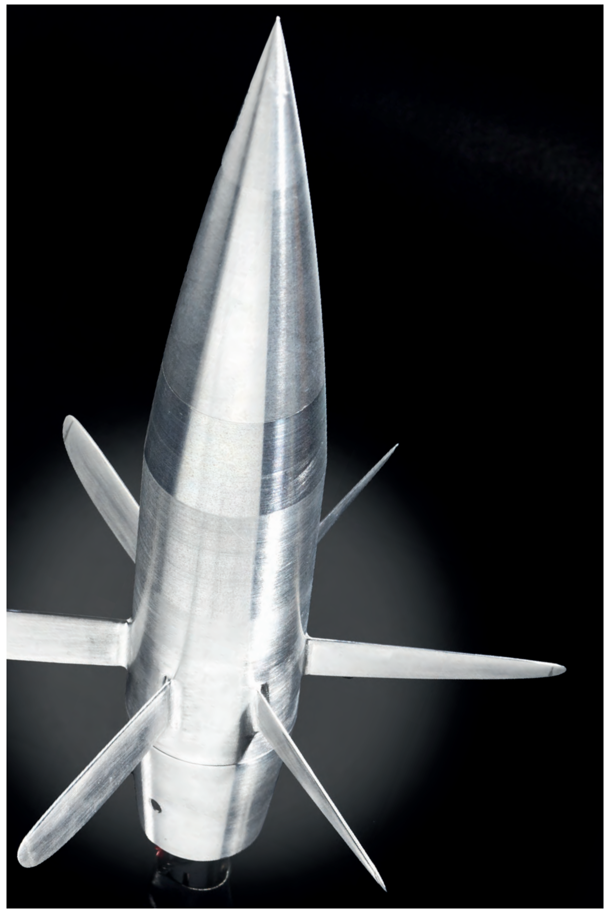
Important issues include protecting against the effects of Improvised Explosive Devices (IEDs) and improving soldier protection. Research activities are ongoing in new materials for ballistic protection (advanced ceramics, lightweight metal composites, fabrics, etc.) and in the ageing behaviour of protection systems. In order to enhance the reliability and the safety of weapon systems, it is necessary to understand and control the reaction phenomena of explosive materials. In this framework, ISL studies for example the relations between microstructure and sensitivity of explosive materials. Work is also carried out on the production and characterisation of energetic nanomaterials as powerful and versatile substitutes to legacy energetic materials. The development and improvement of opto-pyrotechnical igniters and detonators are good examples of ISL's contribution to more reliable, more efficient initiation systems. Interest in ISL's interior ballistic research has increased in France and Germany, as expertise elsewhere has waned out in the aftermath of the fall of the Berlin's wall. Strands of work include: mass reduction, optimal benefit of existing systems (for example: designing systems that may safely operate just beneath the maximum authorised pressure), maintaining or increasing performance regardless of climatic conditions, and insensitive propellant charges.

Beyond these examples, this research area serves comprehensive goals and provides solutions in:

- helping on the one hand to control energetic material sensitivity in order to decrease ammunition vulnerability and on the other hand to develop more efficient ignition systems;
- developing energetic nanomaterials for applications in detonics and interior ballistics, protection and perforation;
- exploring new ways of improving the ballistic properties of materials for protection or perforation (micro or nanostructuration, reinforcement with nano or micro additives, etc.);
- maintaining an enriching expertise in interior ballistics;
- improving weapon efficiency: ignition of propellants (nanothermites or plasma), synthesis of enhanced-performance energetic materials, etc.

This research area also contributes, in a synergetic way, to meeting the challenges of the other ISL research areas.

Flight techniques for projectiles



Western armies tend to move away from saturation attacks in favour of more surgical strikes. ISL's research into guided ammunition focuses on the need for precision-guided, gun-launched ammunitions for ground-to-ground (enhanced precision for existing ammunition, new concepts for improved range and precision, terminally guided ammunition for metric precision, etc.) or ground-to-air (airborne threats including mortars, rockets and ballistic projectiles) applications.

With a view to enabling strategic autonomy, European domestic technologies need to be strengthened in these domains. As recognised by the French-German Common Need paper, ISL is ideally positioned with the necessary skills and facilities to lead research into innovative, independent and competitive solutions and transfer its know-how to sub-assembly manufacturers and system integrators. We must also be able to provide the expertise needed by the state and industry stakeholders for all types of ammunition (guided and unguided, low speed, very high speed). The improvement of existing architectures and development of new ones, of low cost navigation systems based on ITAR-free components (ITAR: International Traffic in Arms Regulations) and of guidance and control solutions are the main challenges ISL scientists face. When compared to missile solutions, just consider the following challenges: guided ammunitions must remain low-cost, while their embedded components must resist acceleration of up to 30,000 g for large calibre ammunition and even more for medium calibre ones!

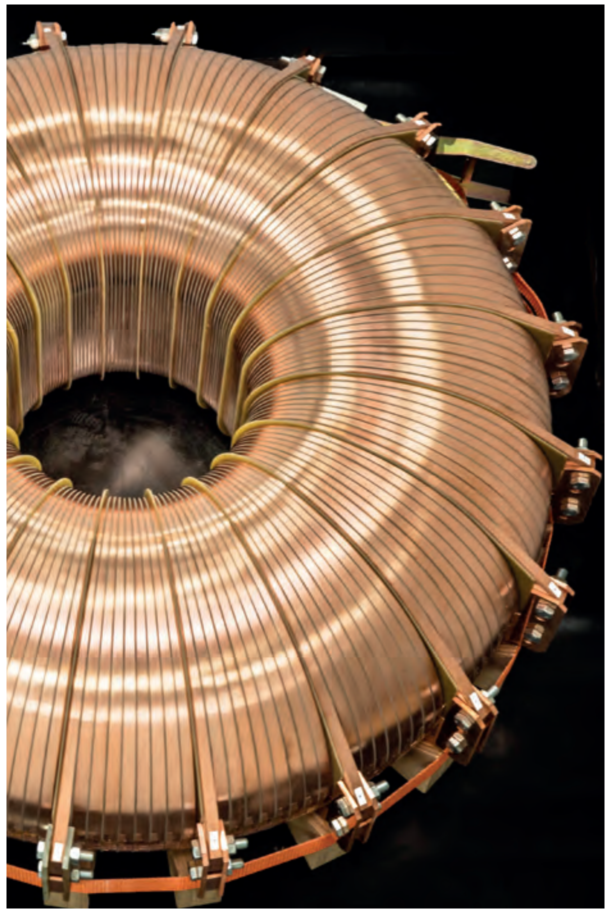
The challenges of this research area are manifold:

- maintaining unique very high-level indoor facilities and measuring tools and unique expertise in exterior ballistics in order to evaluate the efficiency of projectile concepts;
- picking the best architectures for reaching the desired performances: this includes exploring innovative aerodynamic architectures and control devices in order to reach metric precision and ranges of over 100 km; this implies in particular determining the aerodynamic coefficients of all architectures based on wind-tunnel and free-flight test measurements;
- improving the controllability of solutions in order to enhance their efficiency, to reduce collateral damages and to reduce the logistics' footprint; this includes developing low-cost, g-hardened Inertial Measurement Units (IMUs) and IMU-Global Navigation Satellite Systems (IMU-GNSS), embedded in architectures, in order to fully determine their attitude and position.

The know-how in this research area is also key for the electromagnetic launch systems spearheaded by the "electromagnetic technologies" research area.

Research areas

Laser and electromagnetic technologies



Electrically driven weapon and protection systems require specific pulsed power supplies designed to be as compact and efficient as possible. Extensive research is carried out in power-electronic components, in particular power semiconductor devices, in conventional semiconducting switches based on silicon (Si) and in novel semiconducting materials, like silicon carbide (SiC). Current research into energy sources includes:

- the development of unique pulsed power components, notably the manufacturing technology for wide bandgap power semiconductor devices, power supplies for the generation of electromagnetic waves in the context of directed energy weapons,
- their electrical characterisation/evaluation, and the design and testing of switching assemblies based on power semiconductor devices,
- the development of pulsed power generators (MARX, TCLCG, and XRAM) based on semiconductor switching assemblies including aspects of system integration (energy supply chain). These generators supply energy both for railguns and for the generation of electromagnetic waves in the context of directed energy weapons.

Laser research at ISL focuses on three main activities: high-energy laser research for "eye-safe" laser effectors, short-to-mid-wave infrared laser sources in the 2-5 µm wavelength range for countermeasures, and electronic warfare applications.

High-power, mid-infrared lasers are necessary for applications in remote sensing, countermeasures and security, but there is a lack of energetic pulsed laser sources operating directly in the mid-infrared. Infrared light is therefore generated by cascade sources to convert shorter wavelengths into longer wavelengths using optical nonlinearities. ISL minimises the number of sources involved by developing the most efficient, compact and robust laser technologies in the mid-infrared. In the field of jamming lasers, fiber lasers emitting at 2 µm that are efficiently down-converted in an Optical Parametric Oscillator (OPO) are of particular interest. Based on the special single-source fiber laser technology developed at ISL, it allows the generation of full laser power out of a single fiber oscillator by minimising complexity and increasing stability compared with multi-stage amplifier techniques. ISL's work also focuses on highly efficient, high average power OPO and high energy OPO preserving good beam quality to address the needs of jamming and damaging countermeasure scenarios respectively.

Research on innovative electromagnetic effectors includes:

- fundamental investigations on the effect of a magnetic field on shaped charge jets,
- increasing muzzle energy and the development of realistic projectiles for electromagnetic railguns,
- investigations into the multi-shot capability of electromagnetic railguns.

This research area benefits from contributions from ISL's other research areas.

Protection technologies, security, situational awareness

Although this research area combines several different disciplines, they all share one clear objective: to provide the best and most suitable technical capabilities to increase mounted and dismounted soldiers' survivability in a hostile environment. The first step to establish a good level of protection is to anticipate the threat. Work in this sub-area therefore considers both classical threats in a hostile environment, characterised by the presence of energetic materials and ballistic threats, and novel emerging threats, such as drone-borne Improvised Explosive Devices (IEDs) and high energy laser weapons. It also addresses both military operations abroad and homeland security issues.

Different ways of acquiring information that enables a good perception of potential danger and thus an improved situational awareness, are therefore being investigated. Research in this field focuses on: detection of the threat at a safe distance, and analysis and identification of the threats, including snipers, IEDs, Unmanned Air Vehicles (UAVs), and high energy lasers.

Currently, soldiers deal with an almost confusingly large amount of different technical devices for different scenarios, which increases handling complexity and weight. Therefore, the pronounced multidisciplinary character of ISL's research is a clear advantage, as our main aim is to develop innovative interdisciplinary solutions for easier handling that are suitable in different scenarios and for multiple threats.

Beyond threat defeat, which includes destruction, neutralisation or mitigation techniques, and is also investigated at ISL, individual soldier equipment, mobile platforms (land, air, sea) and infrastructures (military field fortifications, critical infrastructures) have to ensure sufficient protection for the crews and individual occupants. For example, ISL develops novel protection systems for individual soldiers with improved functions, such as hearing protection with enhanced communication features.

The diversity, complexity and fast-changing nature of possible threats and the different application fields, require a broad expertise in different scientific domains, which is complemented by strategic collaborations with partner institutions in France and Germany. Towards this aim, ISL teams participate in various national and international expert groups and working groups to ensure that novel technological developments can be easily integrated in larger programs. Furthermore, the clear focus on defence applications allows ISL to provide missing links and thus to complement technical solutions developed mainly by the academic community for the more lucrative civilian market. It is generally acknowledged that for most applications, only multidisciplinary technical solutions can meet the required specifications: this is the avowed objective of ISL!

This research area shares ideas and solutions with ISL's other research areas in a synergetic approach.

ISL ideas serving the future French-German Main Ground Combat System

From long-range detection/identification of incoming threats, to protection of the personnel and onboard high-end equipment, to their destructive power, Main Battle Tanks (MBTs) and their surrogates concentrate many of the challenges that ISL technologies may tackle. However, these masterpieces of land forces equipment have not been a focus for ISL during the past decades. This may well change...

Main Groung Combat System project: from behind the times to new perspectives

After the end of the Cold War, main battle tanks were considered obsolete for years. Some military analysts even predicted that MBTs would disappear from the military landscape of the 21st century, going the way of the cavalry or – given their size – the way of the dinosaur. However, a tank is still an unrivaled solution for mobility, firepower and protection in land operations. This is perfectly summarised by the maxim: "the only thing better than a tank is two tanks".

T-14 Armata, a new reference

The T-14 Armata is a new-generation Russian MBT which was unveiled during the Moscow Victory Day Parade in May 2015. This tank has some outstanding features which are said to exceed the capabilities of all NATO MBTs. The main armament is a 125 mm smoothbore gun which provides higher muzzle velocity and increased penetration capability in combination with new kinetic energy rounds. For long distance targets, the T-14 can fire guided anti-tank missiles at ranges of up to 8 km. Tank survivability is significantly increased by the combination of several features: the turret is unmanned, the three-member crew is protected by an armoured capsule in the chassis and the armour design incorporates a hard-kill active protection system which detects incoming threats and destroys them in flight with specific projectiles. Thanks to its armour design, the tank mass does not exceed 50 metric tons which is a significant advantage in terms of mobility. In short, the T-14 Armata, and the whole family of vehicles based on the same platform have defined new reference capabilities in the (real) world of tanks.

Main battle tank T-14 Armata, Moscow, 9 May 2015.
Photo credit: Vitaly V. Kuzmin

The French-German MGCS project

German Leopard-2 and French Leclerc MBTs were designed and developed in the 1970's and 80's and have been significantly upgraded since then. In 2012, France and Germany decided to launch a joint initiative that may lead to a joint program for designing and developing a new Main Ground Combat System (MGCS) in order to replace their Leclerc and Leopard-2 tanks by 2030-2035. The MGCS is a long-term project comprising five steps: requirements analysis, concepts study, technology development and demonstration, system development and, finally, system production. The first two steps have been completed so far, ISL being particularly active on the second one.

The analysis of the requirements was conducted in 2013-2014 by a joint team of French and German military and technical experts with a basic goal in mind: the MGCS must be able to dominate any high-end hostile land combat system in all situations, including of course a confrontation with Armata MBTs. This analysis resulted in the definition of more than 300 so-called High Level Requirements (HLRs) describing the required or desired levels of performance of the most important capabilities of the future combat system, namely Firepower, Protection, Mobility, SDRI (Surveillance, Detection, Reconnaissance and Identification) and C3I (Command, Control, Communication and Intelligence).

This common list of requirements has then been used as input for two studies of concepts which were carried out from late 2015 to mid-2018 in France and Germany on a national basis under the authority of the French and German Ministries of Defence (MoDs), with strong and frequent interlinkages. The French MoD entrusted our French-German institute with the first study, the German MoD entrusted IABG with the second. A number of MGCS concepts have been created and refined by both teams – from basic ideas to preliminary designs – while the convergence process between the national concepts has been supervised at MoD-level by the French-German Land Systems Roadmap Group (LSRG). The final joint MGCS concept resulting from this approach shall set the perspective for the third step of the MGCS project, as of mid-2018, namely the technology development and demonstration program.

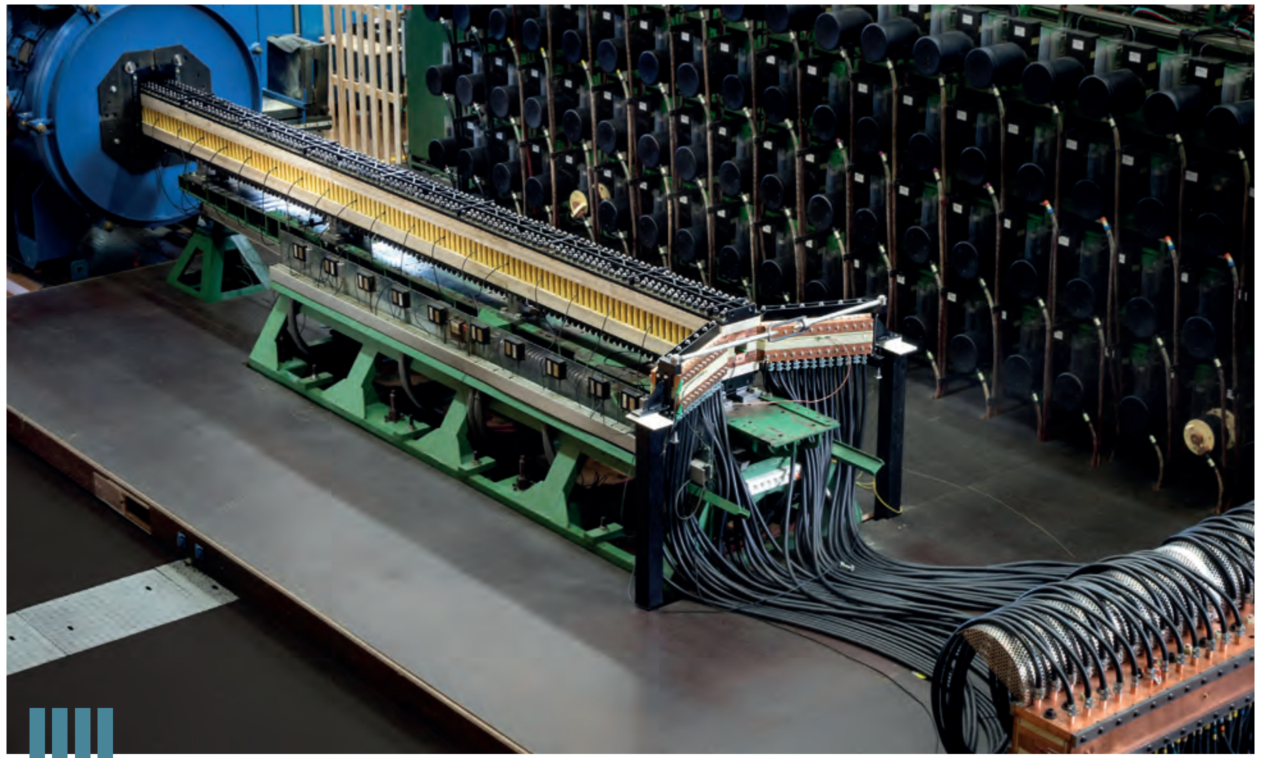
MGCS: system architecture and technology innovations

Regarding the system architecture, the MGCS is first and foremost a team of vehicles. This team may involve manned and Unmanned Ground Vehicles (UGVs) as well as Unmanned Air Vehicles (UAVs). The ground vehicles may be heavy, medium or light platforms with various weapon systems. The word "team" is of prime importance here: compared to a single-platform MBT, the coordination of multiple platforms and weapons can significantly increase the overall system effectiveness, while enhancing personnel protection, a crux for many decision-makers, not least because resilience of Western societies to casualties in their own armed forces declines. Thus, the MGCS will provide increased collaborative combat capability that will require a drastic update of current operations concepts.

Developing the MGCS requires a range of technology innovations, many of which will be contributed by ISL. The following critical technologies have been identified:

- increased-calibre tank gun and ammunition to defeat high-end MBTs at short range;
- hyper velocity missiles to defeat high-end MBTs at medium range;
- gun-launched precision munitions and anti-tank guided missiles to engage all targets at long range, including Non-Light-of-Sight (NLOS) engagements;
- high energy laser to destroy or neutralise UAVs;
- increased survivability: active stealth to reduce vehicles' signatures, reactive armor against kinetic energy rounds, crew citadel located in the chassis, hard and soft kill active protection systems against rockets and missiles;
- automatic long range and 360° SDRI capabilities (incl. virtual reality interfaces) and UAVs for NLOS surveillance;
- enhanced data sharing and processing (incl. artificial intelligence) to provide high-level assistance to operators and automatic fire control system;
- remotely controlled weapon systems (incl. unmanned turret) and vehicles;
- unmanned combat vehicles requiring automatic mobility, SDRI and C3I capabilities;
- artificial intelligence techniques to increase the robot autonomy levels.

Many of those capabilities may benefit from ISL's expertise and innovations. ISL is ready to serve.



Designing unconventional guns

The classical powder-loaded gun has been around for thousands of years, with incremental improvements on propulsive powders, shells or gun tubes. Electric guns have the potential of reaching breakthrough muzzle velocities, are more tolerant to temperature changes and provide a better repeatability of the firings, to the benefit of precision. They may be key enablers for future main ground combat systems and future indirect fire systems.

ISL has focused on two promising technologies: electrothermal-chemical guns and electromagnetic railguns. In a nutshell, electrothermal-chemical guns use electricity to optimise the ignition of existing powder guns whereas railgun technology uses electric energy to launch the projectile.

As many other ambitious innovations in firepower and armour for heavy vehicles, these strands of work have suffered from the "peace dividends" in the aftermath of the end of the Cold War. The Electrothermal-Chemical Gun area of research is now a rich scientific heritage still ready to be revived, while the electromagnetic railgun is briskly gaining momentum after a more slowly period.

ElectroThermal-Chemical (ETC) Guns

Research into ETC gun technology at ISL was motivated by the need to improve direct fire gun systems such as battle tank main armaments. This technology, which had been studied at ISL for years, was too futuristic for an application on the battlefield. With the MGCS project, a focused interest in this technology is growing again. This ISL know-how acquired in the past on the topic allows a potential quick development time. ETC propulsion technology uses electrical energy to both ignite the propellant charge and control the propellant mass generation rate (i.e. the release of the propellant's chemical energy) with a view to improve the performance by using existing conventional guns.

In an ETC gun, the conventional ignition components are replaced with a plasma generator. This generator houses a wire attached between two electrodes. When a high-current, high-voltage pulse is applied, the wire initiates a high-temperature plasma discharge that vents into the surrounding propellant. The electrically conductive plasma transfers energy into the propellant, initiating its combustion much more quickly and repeatably than conventional ignition.

The potential benefits of ETC technology are:

- improved muzzle velocity;
- reduction of ignition delay;
- adjustable peak operating pressure;
- reliable ignition of new, high-energy, high loading density propellants;
- reliable ignition of low-vulnerability propellants;
- maximum performance potential across all temperature ranges (i.e. temperature compensation).

ETC technology therefore offers an improved range and accuracy, two characteristics required for future military engagements. The ISL knowledge-base on ETC propulsion covers the technology areas of plasma properties, plasma generators and plasma-propellant interactions. Efforts have concentrated on developing capabilities in ETC gun firing at 20 mm, 60 mm and 120 mm calibre, for the experimental evaluation of concepts and, to a lesser extent, computer model development and validation.

For the optimal design of plasma generators, time resolved spectroscopy and high-speed camera technique were used to characterise the plasma produced. Several concepts of plasma generators were developed and investigated. ISL has notably focused on plasma-jet generators (Fig. 1). During the interior ballistics process, the plasma produced interacts with the propellant. In this way, the burning behaviour of a wide variety of propellants was determined in closed vessels. Moreover, ETC gun firings at 20 mm and 60 mm calibre, allowed us to establish empirical relationships between ignition delay and plasma energy. ISL studies also dealt with the integrability of the electric energy storage needed for a plasma-ignited large-calibre gun. The values of the energies, which depend on the gun calibre, are much lower than the energy levels assumed in the past. Table 1 summarises the detailed performance parameters. The total electrical energy required ranges of between 2 kJ and 120 kJ/shot, with a charging voltage of 5 kV to 10 kV.

Calibre [mm]	120	155
Muzzle velocity [m/s]	2000	1200

Table 1: Performance of ETC guns of various calibres

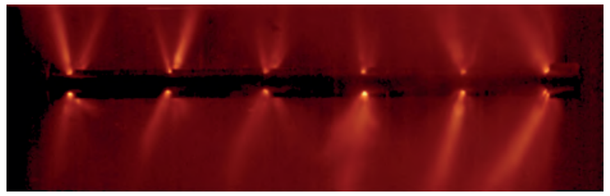


Fig. 1: Electrothermal-chemical plasma-jet igniter working in an open-air test

Electromagnetic railgun

The electromagnetic railgun uses electric energy to accelerate projectiles. While the muzzle velocity v_0 in powder guns is limited to approximately 1800 m/s, railguns can reach a muzzle velocity v_0 well above 2500 m/s. Consequently, projectiles may be launched at distances of up to 400 kms. Developing a railgun implies that all system features have to be taken into consideration, from the supply of primary energy that has to be converted into kinetic energy using a transfer chain, to the design of guided projectiles. A compact and weight-optimised power supply is very important in this case. Today, laboratories all over the world are using commercially available capacitive energy storage devices. ISL is working on alternative storage technologies, for example inductive storage units with ten times higher energy density, in comparative terms (Fig. 2). ISL has achieved extremely important results with a view to implementing an extended-range gun. For instance, we demonstrated that railgun efficiency levels (ratio of kinetic energy to used electric energy) for extended range shots with velocities in excess of 2500 m/s can exceed a gain of 65%. This is a world record in interior ballistics and this value is double the efficiency of powder guns (ratio of kinetic energy to chemical energy of propellant). Many issues remain to be solved and are now on the agenda: interior ballistic questions (for example material wear), electromagnetic compatibility with other nearby pieces of equipment, transitional ballistic, external ballistic, terminal ballistic aspects of projectiles launched by a railgun, etc. Subject to investment priorities, the next significant leap forward will be an operational demonstrator on ISL's shooting range.

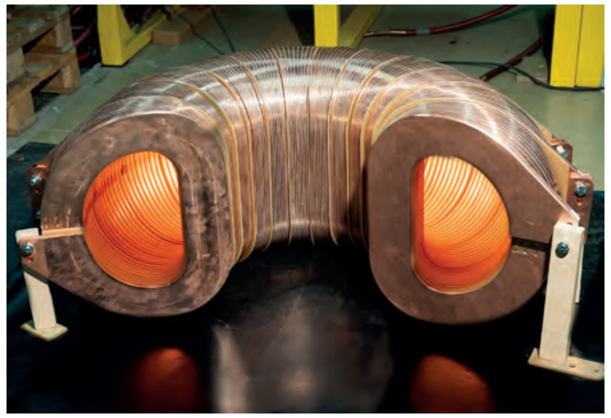


Fig. 2: Inductive storage device developed at ISL. The toroidal coil can store 1 MJ and is designed to power railguns

Protecting with and against laser light

Directional InfraRed CounterMeasures - DIRCM

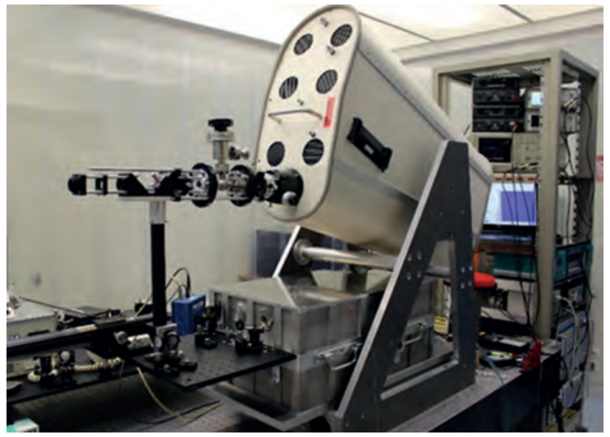
For applications in remote sensing, countermeasures and security, high power mid-infrared lasers are requested. Due to a lack of powerful or energetic pulsed laser sources operating directly in the mid-infrared, it is common to cascade sources to convert shorter wavelengths into longer wavelengths using optical nonlinearities. Developing efficient, compact and robust laser technologies in the short-wave to mid-wave infrared allows for minimising the number of sources involved. The research on short-to-mid-wave infrared laser sources addresses two main goals: achievement of beyond-state-of-the-art highly versatile laser sources in this wavelength range, which is of specific military importance, and providing high-level expertise for the national electronic warfare communities, including knowledge on sources and components as well as participation in field trials and measurement campaigns with current state-of-the-art ruggedised lasers.

In 2017, an upgrade of an optical parametric oscillator based on an image-rotation cavity setup using a Galilean telescope allowed for simultaneous divergence compensation, optimisation of the optical-to-optical conversion efficiency, and high beam quality of high-pulse-energy mid-infrared beams. This confirms the high potential of such a cavity which was implemented in a laser prototype used for field tests performed in summer 2017 in close collaboration with the German MoD.

Besides, several improvements of the already existing powerful mid-infrared sources were addressed to surpass their previous performance. The implementation of in-house fibered components enabled the increase of the pump average output power generated together with an optimisation of the optical-to-optical efficiency. Those achievements consolidate the route for an all fibered ruggedised source and pushed the previous mid-infrared average power record. This preliminary test experiment proved that the 2 steps scheme based on fiber laser pumping crystal-based non-linear converters is promising.

A beam shaping design has been implemented in an existing laser prototype allowing for accurate long-distance field trials and optimum beam quality according to needs revealed during previous field tests.

The progress achieved in the development of short-to-mid-wave infrared laser sources for airborne platforms may also result in promising applications increasing the survivability of ground platforms in the battlefield.

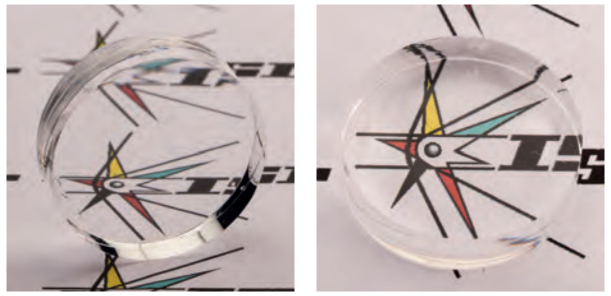


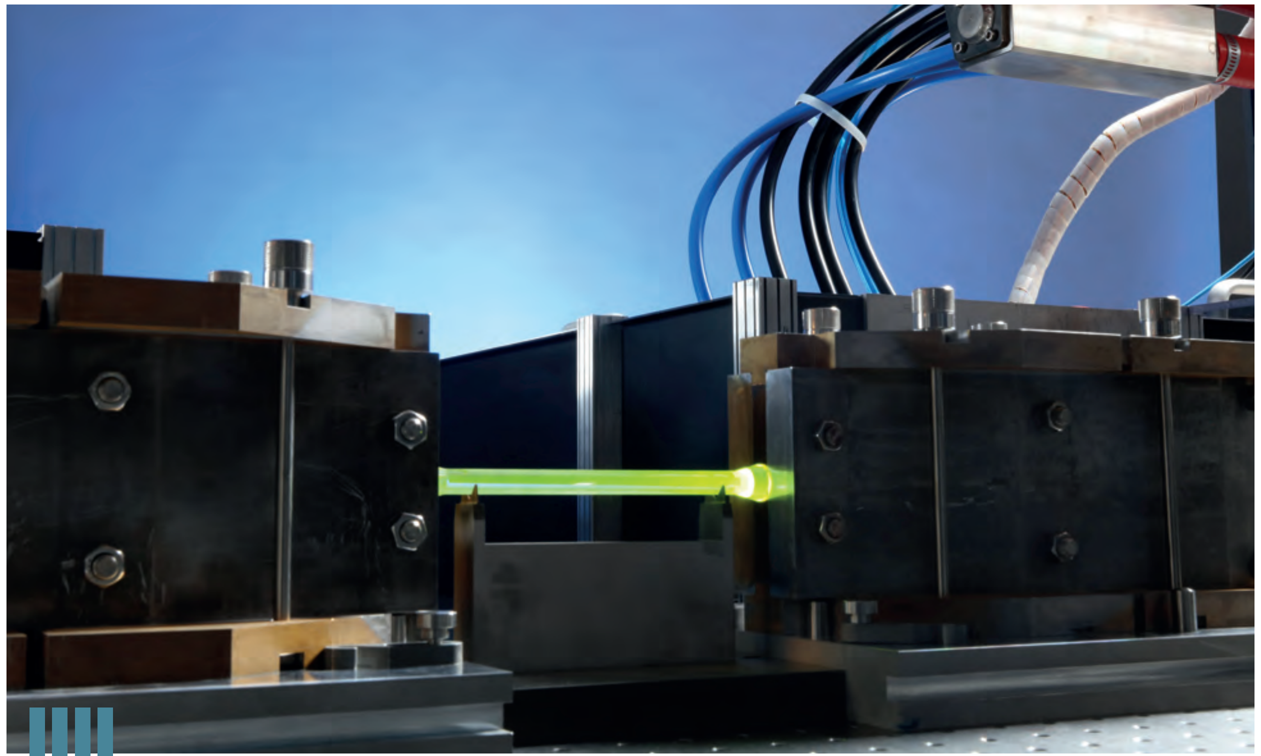
Optical limitation

Optical limiting studies conducted within the timeframe of this report attempted to design innovative nonlinear optical polymer-based guest-host filters for the protection against incident laser radiations ranging from visible to ShortWave InfraRed (SWIR) wavelengths. Generally speaking, the research have been performed on 2 types of host materials, PolyMethylMetacrylate (PMMA) on the one hand and polylactide on the other hand. PMMA is the most usual organic glass, it exhibits excellent properties such as small chromatic dispersion, high linear transmittance in the VIS, NIR and the SWIR part of the spectrum. Polylactide polymeric systems are known to exhibit high nonlinear performance. In addition they are biodegradable and biocompliant in agreement with the green chemistry commitments. Their use as optical limiting components had never been reported yet.

Different solid-state systems like Detonation NanoDiamond/PolyMethylMetacrylate (DND/PMMA) or polylactide/dyes have been synthesised and characterised. Although in recent years the DND/PMMA system has proven its worth, the polylactide/dyes one gains prominence thanks to its fully innovative character. The chemical synthesis of PMMA has been successfully improved. The transmission of the filters has increased by 10% when compared to the first generation filters. ISL demonstrated that, using the ring opening polymerisation technique, polylactide/dyes optical limiting filters could be produced. The added value of this new concept is that the nonlinear active principle (i.e. the dye) can be directly bound to the polymer chain since it is used as the reaction initiator.

The nonlinear transmittance was assessed in the visible and near infrared spectral bands. The DND/PMMA system has proven its efficiency in the Near InfraRed (NIR) since it presents a low activation threshold and a nonlinear attenuation as high as Optical Density OD = 2.5 when the incident laser radiation equals 10^4 J/cm². In other words, transmitted laser radiations leaving the optical limiter would be fixed at a level of 12 µJ independently of the incident laser energy in compliance with the ED50 laser protection standard. The use of strongly nonlinear active dyes in the second type of optical limiters based on polylactides confirmed our expectations in terms of nonlinear attenuation. Indeed, "giant" limiting levels have been reached in the NIR, ranging from OD = 4 to OD = 5. Accordingly, transmitted laser radiations would be limited at a level of 1 µJ independently of the incident laser energy. In the latter case, the very ambitious MPE level (ED50÷10) is fullfilled.





Countering threats with light: the MELIAS laser source

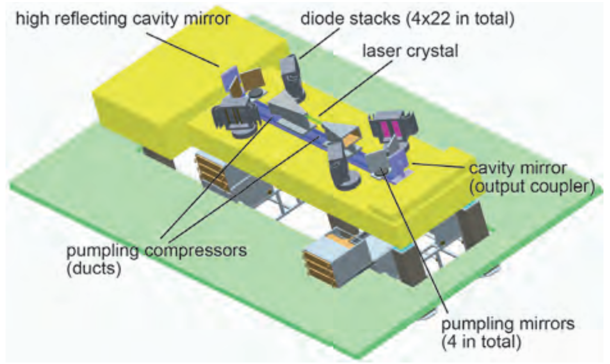
High Energy Lasers (HEL) provide a game-changing technology to counter asymmetric and disruptive threats, while facing increasingly sophisticated traditional challenges. Laser technology offers major advantages in military applications over kinetic weapons due to its high precision and instantaneous on-target effects, precise and scalable impacts, avoidance of collateral damage caused by conventional ammunition, small logistic footprint and minimum costs per shot.

Thanks to the considerable progress achieved over the past years in solid-state lasers and other related technologies, the design and manufacture of laser weapons for maritime or ground platforms will be possible in the future. In this context, technical aspects such as the generation of high laser power with good beam quality are not the only features that have to be taken into account to offer long distance focusing. Because laser weapons could often be used in the presence of civilians, safety aspects must also be taken into consideration. The coherence and low divergence angle of laser light, aided by focusing from the lens of an eye, can cause laser radiation to be concentrated into an extremely small spot on the retina. Although people may not feel pain or notice immediate damage to their eyesight, permanent blind spots or blindness may occur. Even if such a weapon would not have been designed to blind people, the issue would certainly be emotion-filled, as an international ban on blinding weapons has been widely ratified: such collateral damages would probably be as devastating for the country using laser weapons as a suspected use of chemical warfare. The term "eye safety" is therefore of particular importance. Here, the term "eye safety" means that light at a wavelength of > 1.4 µm does not penetrate the eye and will therefore not be focused onto the retina.

According to standing orders on operational safety, the maximum permissible exposure of the eye to light of this wavelength range can be several orders of magnitude higher than that of light within the so-called "non-eye-safe" wavelengths, which may cause permanent eye damage even at low power levels. Moreover, a low-power beam in the invisible wavelength range would not cause a defensive reaction (palpebral reflex) in individuals. With respect to that, safety distances at the important wavelengths of 1 µm and 1.6 µm differ by a factor of six. Therefore, the necessary protection requirements and the risk of collateral damage are much smaller when using lasers at a wavelength of 1.6 µm.

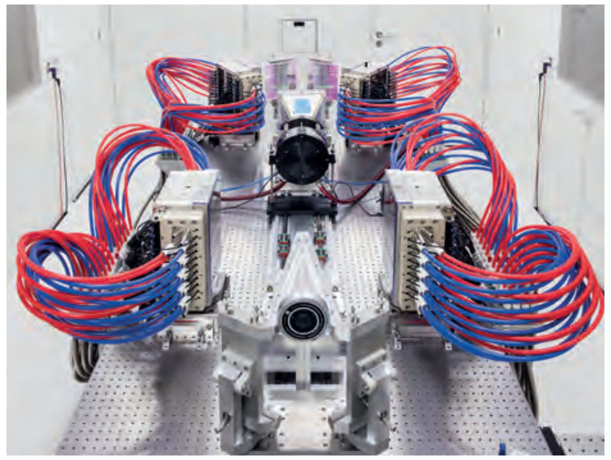
Medium Energy Laser In the "Eye-SAfe" Spectral Domain - MELIAS

Within the scope of the MELIAS project, ISL is studying a promising laser technology emitting in the "eye-safe" wavelength region called the erbium heat-capacity laser. This laser type can be characterised by its compact design, simple and robust technology and a scaling law which, in principle, allows the generation of laser power far beyond 100 kW at small overall volumes. The unique feature of this laser is its operating scheme: a laser medium (either crystal or ceramics) is used for one shot (lasting about 3 to 5 seconds) without any cooling, to the benefit of the laser beam quality. It is then replaced by a new, cold medium. Several shots, even without cooling of the media when they are not used, may be made by using the revolver technology designed at ISL. Alternatively, if an adopted cooling system for the revolver is added, the laser can operate in repetitive, continuous mode. Cooling requirements and thus weight and volume can be optimised depending on the threat-scenario.
MELIAS I and MELIAS II, two smaller laboratory prototypes of this type of laser, were set up as proof of concept and to show the scalability of this technology. The next step, MELIAS II+, is currently under construction. While MELIAS II delivered up to 4.65 kW for several hundred milliseconds, the aim for MELIAS II+ is to reach 30 kW peak power for several seconds. The principle optical setup is shown in the following figure.



The pump light is provided by 4 diode blocks, each of them filled with 22 diode stacks, fed into the laser crystal by means of four mirrors and two pump light compressors (ducts). All these optical elements have been designed and already implemented on an optical table. The transmission of the pump system has been evaluated to be 95%.

In the last year, the cooling system and the power supply chain have been integrated and tested. In parallel, a command and control system, including hardware and software safety functions, has been developed, set up and tested.



The overall installation of the new MELIAS II+ system includes the cooling system of the diodes and the power supply system. The laser head itself (depicted above) is integrated in a clean room environment. ISL will finalise the laser system set-up in 2018 and conduct the experimental evaluation in the first half of 2019.

Pioneering disruptive bricks for future guided projectiles

Future guided ammunition need not only superior aerodynamic architectures, disruptive aerodynamic actuators and creative guidance and control loops, they also require innovative gun-hardened means of communication, low cost inertial measurement units for the navigation and pyrotechnical actuators. This article reveals a few facets of ISL's technological bricks designed and already available for future guided projectiles.

Antennas

There is a growing need for antenna functionalities, including bi-directional communications with ground stations or deployed units like UAVs, with a high data rate and an increased range, as well as GNSS (Global Navigation Satellite Systems, including GPS, Galileo,…) -operations in multiple frequency bands. It should be possible to reconfigure these antennas during the flight, particularly the radiation patterns, to allow the beam to be dynamically steered towards the direction of the transmitter/receiver, in order to improve the communication range or the data rate, or as a feint to jammers. Antennas also require anti-jamming functions based on spatial filtering.

Recent works have shown the viability of miniaturised metasurface-inspired antennas, which can be integrated into projectiles and withstand the high accelerations during firing. Metasurfaces are materials with subwavelength-scaled patterns. Current activities initially focus on the design of miniaturised GNSS antennas for the L1, E1 and G1 bands; the design should then be extended to dual-band operations by also addressing the L2, E5 and E6 bands.

Digital antenna baseband processing is currently under investigation instead of using existing beam-steering units based on microwave components.

Low cost navigation units

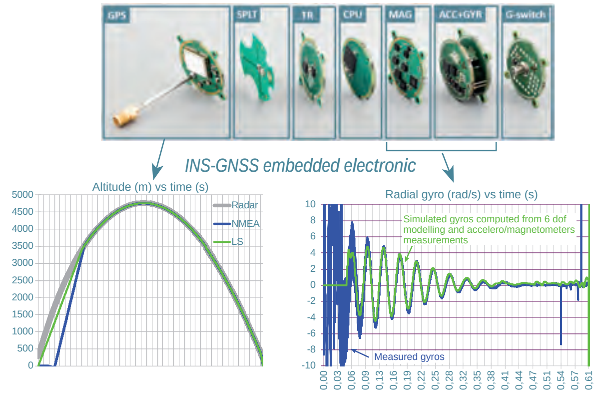
The use of magnetometers in navigation units for guided ammunition is very promising because of their ability to assess the projectile's attitude (pitch, yaw and roll) with respect to a direct external reference – the geomagnetic field –, while the use of classical Inertial Measurement Unit (IMU) algorithms, especially when using rate gyroscopes, leads to a continuous drift increase due to the integration process, possible saturation and uncertain initial conditions. The magnetometer technology able to compute the projectile roll angle in real time has been validated in flight with an accuracy of less than 2° at a roll rate of 800 Hz.

The objective of this research project is to develop a gun-hardened IMU based on ITAR-free low-cost off-the-shelf components and, in particular, on magnetometers adapted to various types of guided ammunition. These activities involve the design of on-board electronics, which include sensors, real-time computing units and Radio Frequency (RF) telecommunication systems. They also involve the development of dedicated navigation algorithms taking into account the modelling of the sensor behaviour under the given firing conditions and integrating a simplified 6 DoF (Degree of Freedom) ballistic model of the projectile.

Regarding hardware, studies focus on the identification and the g-hardening tests of various sensors (magnetometers, accelerometers, gyroscopes and GNSS receivers) compatible with ammunition applications. Sensors and associated calibration processes are modelled to assess the sensor correct responses under high dynamic stresses and in a harsh projectile environment.

Instrumented projectiles are fired at ISL's free-flight outdoor testing range or, if longer ranges are needed, at German and French national proving grounds, in order to validate the algorithms and the behaviour of the tested sensors. 155 mm projectiles with embedded civilian Global Positioning System (GPS) receivers were fired at DGA/TT Bourges in October 2016. Raw and National Marine Electronics Association (NMEA) data provided by the GPS were transmitted to the ground station using the ISL telemetry system coupled to a GNSS monopole antenna. NMEA is a standard data format supported by all GPS manufacturers and used by all customers. Raw data have been post-processed by ISL and compared to NMEA data and to radar data: all results match from the moment when satellites are recognised by the on-board GPS, proving the possibility to develop specific GNSS algorithms for projectiles.

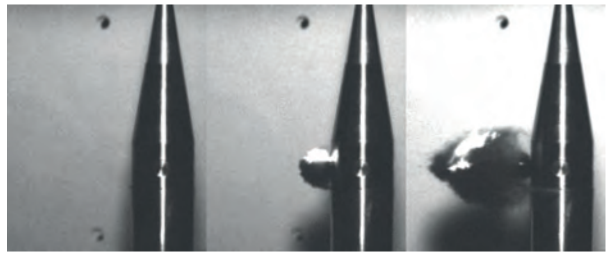
ISL has also demonstrated that projectile's incidence and rotation rate can be estimated using solely magnetometers and accelerometers. The magnetometer and accelerometer measurements have been post-processed in order to validate them through a comparison with the measurements provided by the embedded rate gyroscopes. Different

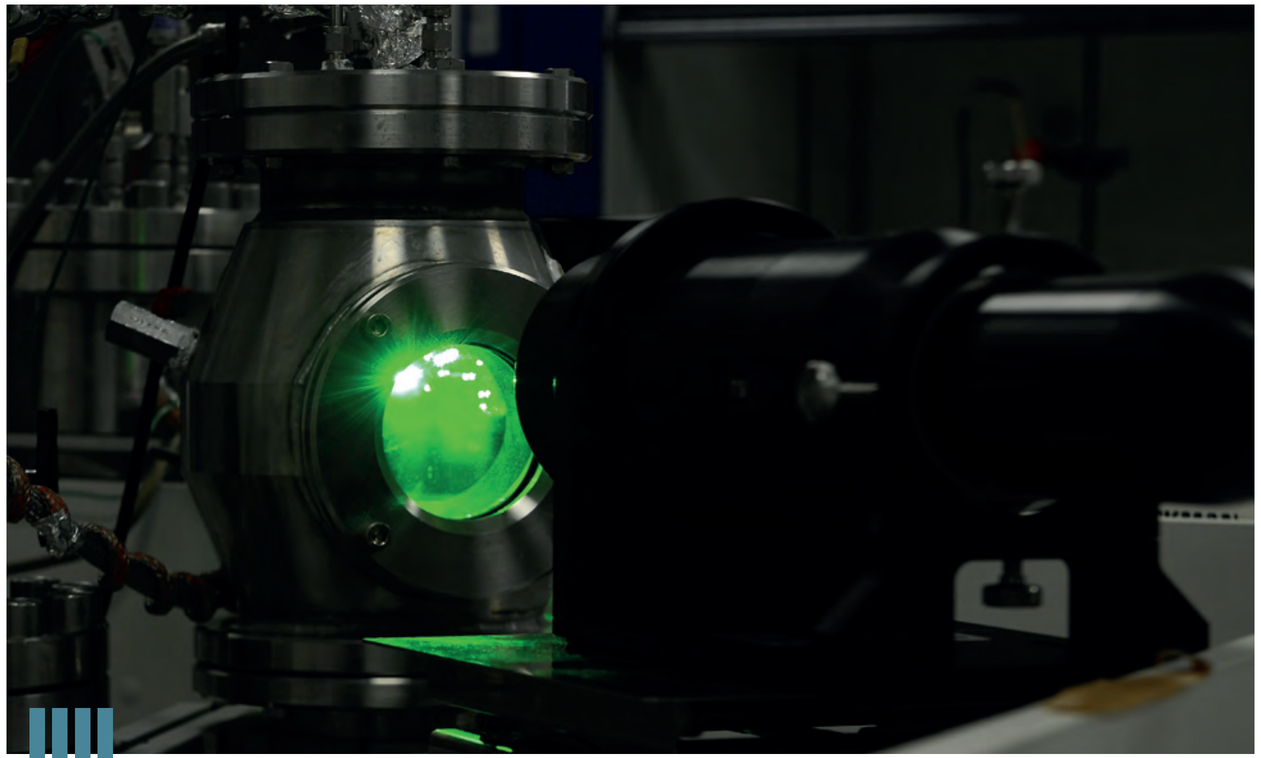


integration methods for coupling the GNSS with inertial sensors and magnetometers are also investigated.

Pyrotechnical thruster

ISL has designed and developed a complete pyrotechnical system comprising an electronic initiation device, a detonator and an impulse thruster for correcting the trajectory of spin-stabilized mid-calibre projectiles. The device is sufficiently compact to be integrated into projectiles of less than 40 mm calibre, robust enough to sustain harsh acceleration, fully safe as it uses only secondary high explosive, even for the detonator designed by ISL, and reliable. It uses the detonation of a small amount of secondary explosive to propel a lid perpendicularly to the trajectory. The system can generate high impulse levels over a very short delivery time and with a very low dispersion (±6 μs), meeting the synchronisation needs with the roll position of projectiles at high spin frequencies. Free flight tests with modified 35-mm-calibre projectiles equipped with the impulse thruster system have shown that 3 N·s impulses can deflect the projectile from its ballistic trajectory in a reproducible manner with an average deviation angle of 4.9 mrad. Future work will focus on the impulse thruster system combined with a navigation module based on the magnetometer technology able to compute projectile roll angle in real time. The objective is now clearly to demonstrate its ability to precisely control the direction of the projectile deflection.



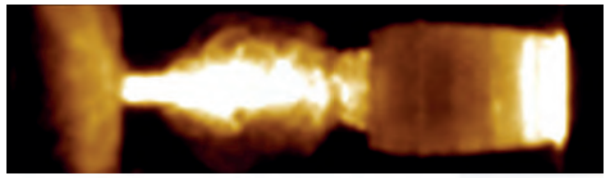


Leveraging the infinitely small world of energetic nanomaterials

ISL is now a global leader in research on submicron and nano-sized energetic materials for future high-performance applications and systems. Different types of applications are envisaged. The first one is the development of high energy ammunitions, with high penetration capacity, for small and large calibre weapons. The objective is to perforate the world's most resistant amours. A second cutting-edge application of energetic nanomaterials is the development of "green" detonating substances, which will be used in detonators to replace lead-based primary explosives. Finally, "green" nanothermites can be used to ignite propulsive powders and enhance their performance. These advances were made possible by the Spray Flash Evaporation process (SFE), which is used to prepare large amounts of explosive nanopowders. This unique process has been developed at ISL over the past few years. Energetic materials prepared by SFE have an unrivalled degree of homogeneity and meet the specific requirements of a variety of applications. The SFE process actually provides the elementary bricks of energetic matter, which are necessary to design the energetic systems of tomorrow.

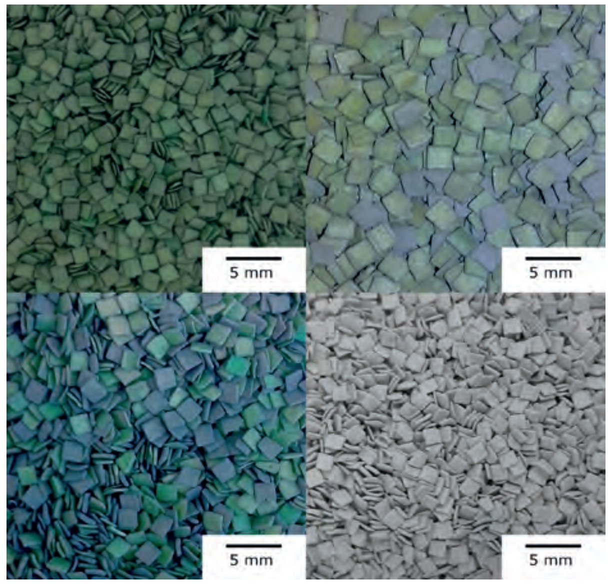
NSTEX for green detonators

NanoStructured Thermites and EXplosives (NSTEX), which are a new family of energetic materials, were developed at ISL. These compositions are prepared by mixing a nanothermite with an explosive nanopowder prepared using the SFE process. NSTEX were integrated in "green" detonator prototypes to replace primary explosives which traditionally contain heavy metals. These detonators are far less hazardous from a toxicological point of view, not only for the people who manufacture them, but also for their end-users. NSTEX technology will replace lead azide, the use of which will probably be prohibited by a European regulation (REACH). NSTEX perform better than lead azide and are also far less dangerous to handle because they do not contain primary explosives.



New propulsion systems for projectiles

NSTEX compositions pave the way for the development of new concepts that increase the terminal effects of some systems, such as kinetic penetrators. The detonation velocity of a NSTEX can be adjusted between 500 and 6000 m/s, by playing on the ratio of its components and on its porosity. The fact that the detonation velocity can be adjusted is a real global breakthrough. A particularly promising application of this effect could be the acceleration of a projectile just before it hits its target with the impulsion produced by the low detonation velocity of a NSTEX charge. The fact that the detonation velocity can be adjusted at a level which is below the sound velocity within the material the projectile is made of, means it is possible to give an impulsion without damaging the projectile before its impact on target. Nanothermites are also used at ISL for igniting and modifying the combustion of propulsive powders and are used in weapon barrels. The coating of propulsive powder grains with planar or tubular morphologies can be used to control the combustion velocity and adjust the pressurisation law in weapon barrels.



New properties with conventional explosives

The research carried out at ISL on the preparation and the properties of submicron or nano-sized explosive powders has shown that critical diameter decreases with the size of particles (the critical diameter is the minimal diameter of a tube containing energetic materials, that allows the propagation of a detonation). For instance, hexogen with micron-sized particles has a critical detonation diameter of about four millimetres, while in a submicron-sized powder state (< 500 nm), this explosive has a detonation diameter of below 300 microns. This effect has been used at ISL to increase penetration in targets of small calibre projectiles.

The preparation of explosive cocrystals in the form of submicron and nano-sized particles, has led to materials with lower sensitivities, which nonetheless detonate very quickly when the projectile in which they are placed hits a target. The outstanding properties of explosive nano-powders show the considerable impact that these materials will have in a near future in this domain and confirm that the orientation of research at ISL on this topic over the past decade was right. Several important scientific breakthroughs in the domain of energetic materials were made possible by the development of the Spray Flash Evaporation process. Current research on SFE deals with the intimate understanding of the mechanisms of this process and aims at further widening its possibilities. Research also focuses on scaling up the SFE process for industry-scale production. The SFE process is protected by five international patents, which puts ISL, and incidentally the DGA and the BAAINBw, in a global leadership position in this field.

Detecting threats on the battlefield with acoustic sensors

Acoustic systems are based on passive detectors and are used as a surveillance technique to spot enemy activities by the noise emitted by their weapons, vehicles or other equipment such as UAVs. They are used for self-protection by ground vehicles and to allow the crew to know if their vehicle is targeted by hostile fire. Another application is a low-cost gunfire locator that detects and locates artillery gunfire.

An acoustic detector is an arrangement of microphones with a wide aperture detection range (360°) used to detect, classify and locate the origin of a shot (small, medium and large calibre weapons, anti-tank rockets, mortars, explosions, etc.) or to detect and track small UAVs, airplanes or ground vehicles. This technique supplements a radar or optronic system, filling some local detection gaps observed in shadow zones (a shot is heard even if the shooter is behind a wall, a tree, etc.), using locally deployed low-cost acoustic sensors.

The applications primarily concern hostile fire detection. A small detector may be used in a stand-alone configuration or in a network of detectors deployed on the battlefield or mounted on vehicles. An acoustic system can be used alone or coupled with other detection technologies (optical, radar, etc.). Sensors' data are fused and processed by algorithms based on noise propagation laws. A system like this allows crew members inside a vehicle to know if they are being fired at by small calibre weapons, where the shooter is, and allows them to react. The system may also provide an enhanced auditory reconstruction of battlefield sounds (audible representation of threats and of the environment) to improve the crew's situational awareness. It has already been deployed on the battlefield with experimentally observed detection distances of between 300 m and 1,200 m, depending on the enemy weapon calibre.

The detection of artillery gunfire is also of significant importance. In order to survey a large zone at long range and detect mortars and large calibre artillery guns, a network of detectors have to be deployed on 4 to 10 positions. Each detector uses a microphone antenna to perceive the departure of a shot. The system may operate automatically for detection as an advanced post (AP) or coupled with a counter-battery radar for an early warning.

Figure 1 shows the acoustic signal and its spectrogram at medium range. The vertical lines on the spectrogram correspond to high-energy impulsive events. The first one corresponds to the Mach wave of the projectile, the second one to the muzzle wave (the time of this event is the time of departure of the projectile). A first low-frequency and small-amplitude signal corresponds to an acoustic/seismic coupling wave propagating at the firing position. As the waves in the air and in the soil are not travelling at the same speed, the difference in the time of arrival between the two events may provide a distance estimation.

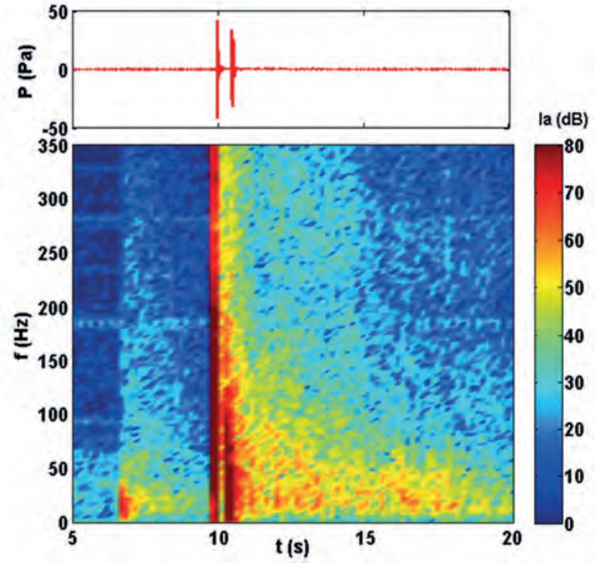


Fig. 1: Spectrogram of an acoustic signal (155 mm artillery gun)

Detection and tracking of UAVs is also addressed by ISL. In the OASyS² project, technology bricks are developed for countering UAV systems. Detection, identification and neutralisation is investigated at a fundamental laboratory level as well as in field trials. A distributed acoustical sensor network is used in parallel with a combination of optical sensing channels for the identification. By fusion of passive vision and active laser gated viewing, ISL has demonstrated an optical sensing close to natural human perception and an increase of the object-to-background contrast.

The first acoustic antenna prototype was deployed during a field trial organised in Todendorf, Germany and then optimised in 2017 at ISL's proving ground. Real-time detection was achieved. Depending on the type of drone, the typical detection range varied from 100 m for stealth UAVs to 300 m for commercial drones. The acoustic array estimates the azimuth and the elevation of the detected event in real time (Fig. 2). With inputs from several arrays, a triangulation may be performed. The latter may feed optical trackers for both refined trajectory and optical identification. The tracking is obtained by the acquisition and filtering of the successive positions.

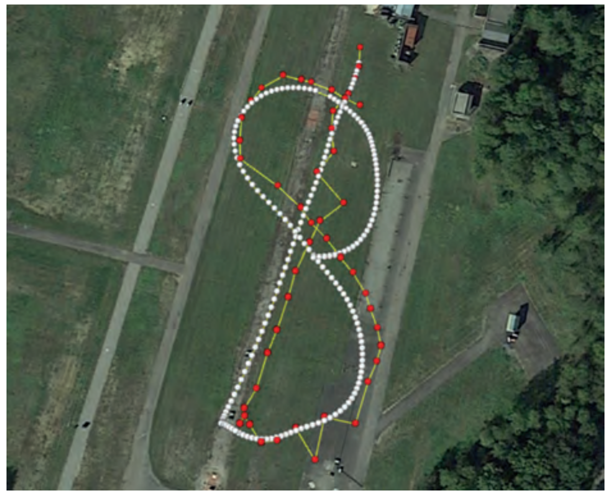


Fig. 2: Tracking of a small UAV using three acoustic arrays ("8 shape trajectory). White points: ground real data, red points: estimated position

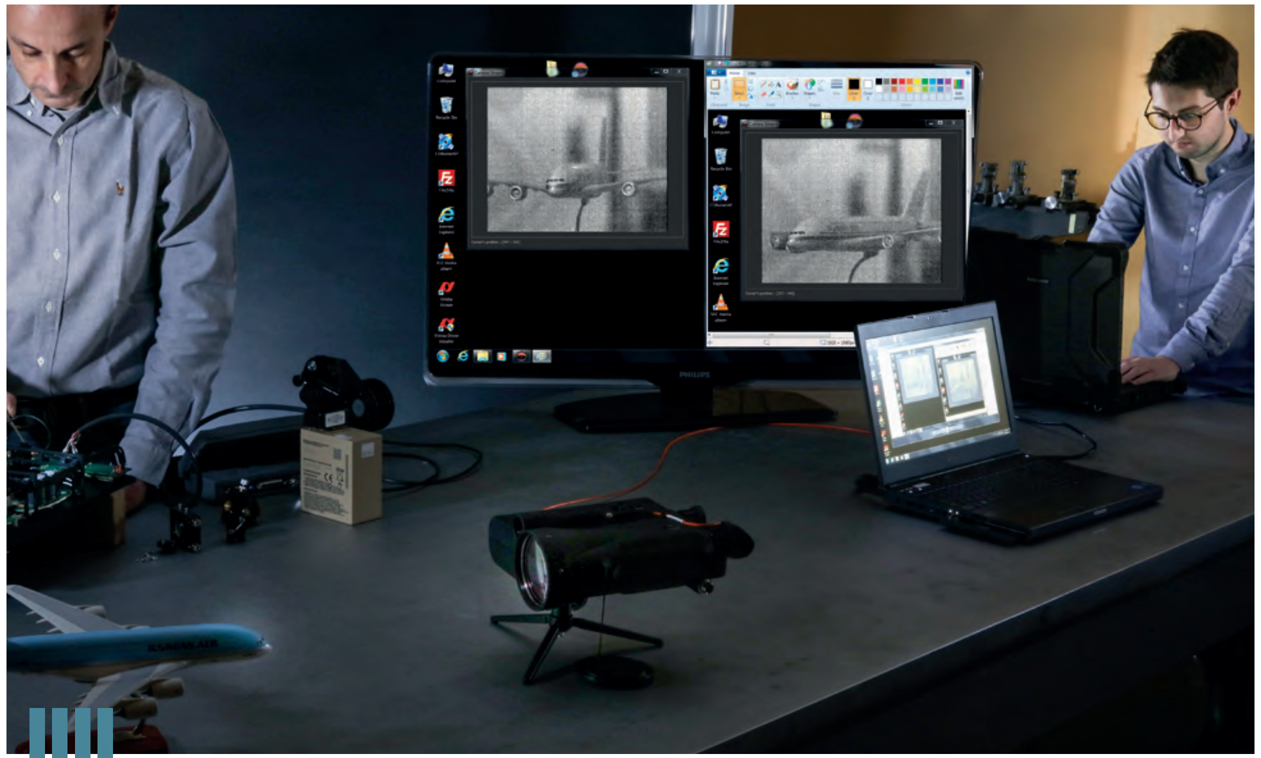
Detection in urban environments is also a goal. Most of the acoustic detection systems developed in recent years are well suited to free-field surveillance. Because of the buildings, highly urbanised environments exhibit more complex propagation effects and require adapted signal processing techniques.

Two approaches have been considered to locate an impulse acoustic source in an urban environment. Both require at least a coarse modelling of the environment, which is easily achievable using existing reconnaissance data :

- time matching: the source position is estimated by comparing the time-of-arrival measured by the microphones to the direct simulations,
- time reversal: the objective is to perform simulation of backward propagation of the measured signals to retro-focus the waves on the location in space and time corresponding to the source.

For the future, the integration of acoustic detection/localisation capabilities in the soldier hearing protection equipment is also under investigation to improve soldiers' natural situational awareness capacities.

In parallel, new-generation acoustic detectors using differential antennas and MEMS microphones are being studied with academic partners to provide the benefits of a more compact array and multi-threat detection. They are also orders of magnitude less expensive than comparable industry solutions.



Lighting a discreet flashlight: active imaging

Laser Gated Viewing (LGV) is an imaging technique using its own laser illumination. This technique permits day/night viewing capabilities and is particularly adapted to vision through turbid media such as rain, fog, mist, smoke or turbid water. It uses "range gating" or "time gating" techniques to eliminate the backscattering effects during the propagation of the illuminating light through diffuse environments. The elimination of the backscattering effects leads to a significant increase in the vision range. The operational benefits for surveillance purposes in land, sea or aerial military operations are obvious, as long as the illumination remains inconspicuous, a feature encompassing different strategies, depending on the intended purposes and operational scenarios.

Two main spectral wavebands are of interest for this technology. The Near InfraRed (NIR) offers the more mature technology concerning the lasers and the sensors and commercial LGV systems are available off-the-shelf. At this wavelength, ISL was able to build a system with a range capability above 20 km and a very narrow field of view with a remarkable low speckle. Another promising waveband is the ShortWave InfraRed (SWIR) and more precisely the so-called "eye safe" spectral band ranging from 1.4 µm to 1.8 µm, undetected by widely available sensors (as – for example – those of smartphones and the likes). Several development programs, where ISL acts as one of the major players in Europe, are currently considering these promising wavelengths. These systems have TRL levels ranging from 4-5, which means that their maturity is close to fulfill the military requirements.

These two wavebands are of interest on both MGCS and CIFS platforms for the visualisation of several kinds of threats and targets.

By using adapted focal lengths and illumination powers, the LGV technology covers the whole spectrum of the SDRI (Surveillance, Detection, Reconnaissance and Identification) capability from short range to more than 20 km. Moreover, the use of a dedicated and stealthy illumination source allows the detection of sniper's pointed optics based on the so-called "cat's eye effect", without the risk of being detected by the enemies. Finally, the synchronisation between the laser pulse emission and the gated receiver allows time-of-flight discrimination and 3D imaging and offers a remarkable penetration capacity when obscurants are used on the battlefield.

The gating of the receiver allows different visualisation capacities which can lead to significant

Example of LGV images: long gate (a), short gate (b) and 3D perception (c)

operational advantages. As illustrated, it is possible to select the representation of the scene from long to short depth and even silhouetting. The 3D perception can give the spatial position of the different objects and can work as a telemeter for each pixel of the image.

The performance in range of LGV systems depends on the technologies available in the different wavebands. LGV systems in the NIR are roughly four times more efficient than in the SWIR because of the current sensitivities of today's sensors. In order to increase the performances of the sensors and the laser sources, and therefore the operational capabilities of these systems, ISL is involved in different French and German studies. The upcoming results of these studies will offer our forces systems with increased performances and small SWaP (Size, Weight and Power), while using wavelengths ensuring a perfect stealth and the advantage to offer ITAR-free systems.

In this perspective, ISL recently proposed a new SWIR hand-held active imaging goggle for short-range surveillance applications. This goggle will be a useful eye-safe device for surveillance and imaging under all weather conditions. In the military domain, it can be used for night vision, intelligence, detection, recognition and identification of persons, while in civilian environments, it could be used for surveillance in the context of drug traffic, urban violence or counter-terrorism.

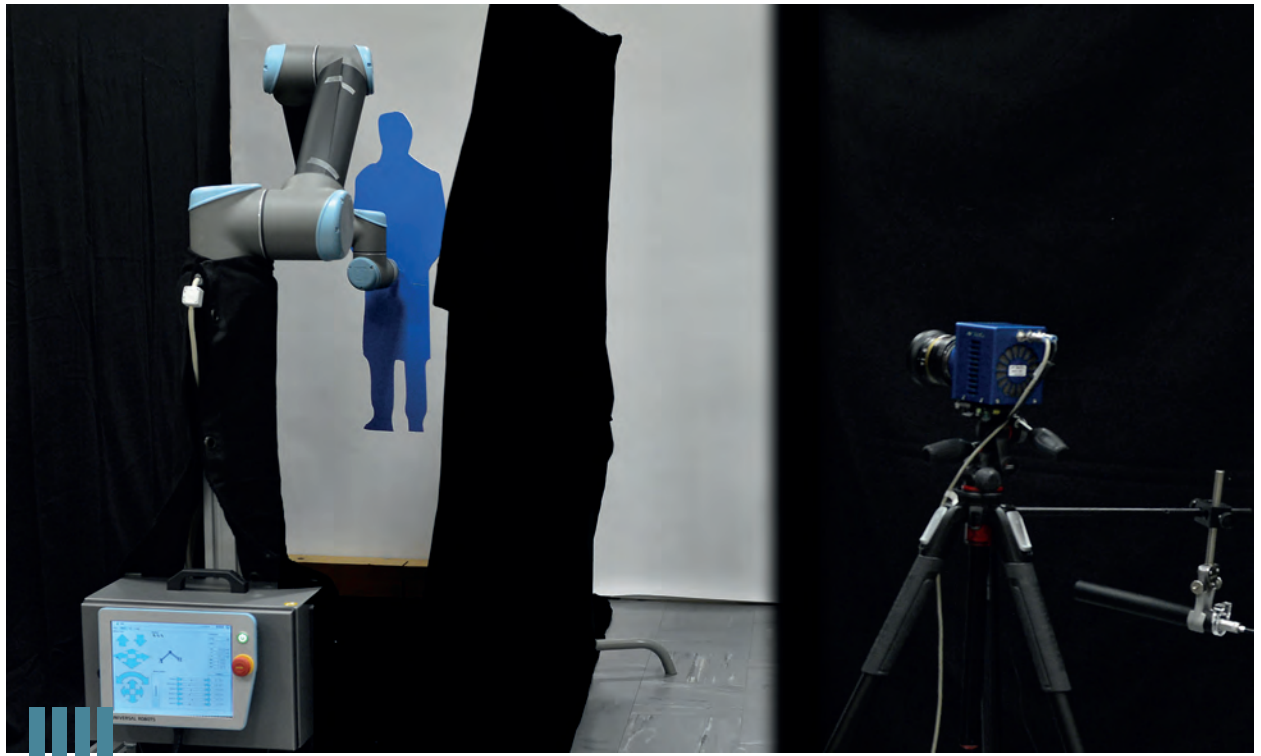
Even though at 1.5 µm most of the scenes appear as they do in the visible spectrum, it is well known that human skin looks black, due to the high absorption of water. But civilian and military applications often require facial identification as a legal proof in case of illicit behaviour, and images at 1.5 µm cannot be used for face recognition.

In order to overcome this drawback, ISL has implemented in its "RETINight" goggle a bi-wavelength (1.064 µm/1.570 µm) pulsed laser associated with a SWIR camera: at 1.064 µm, the skin appears with the same reflectance as in the visible spectrum. The laser is an active Q-switched YAG laser. A small part of the pump is used to emit approximately 15 mJ of 1.064 µm, the remaining part is OPO-shifted to provide about 15 mJ of 1.570 µm. The sensor is a SWIR high dynamic range camera (logarithmic response) synchronised with the laser pulses. The system gives a real-time SWIR video of the scene and, if necessary, the user can take a snapshot at the second wavelength for facial recognition.

In order to ensure eye-safety at this second wavelength, we use image processing algorithms on the SWIR video to estimate the distance of the illuminated persons in the scene. If someone is considered to be too close, the possibility of using the second wavelength is blocked.

New ISL bi-wavelength range-gated night vision goggle: "RETINight" goggle

Example of a human face image at 1.5 µm and 1.06 µm

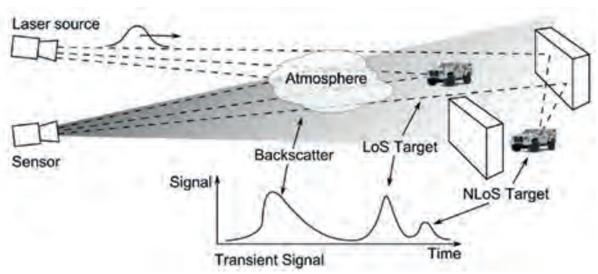


Seeing around the corner

Conventional imaging systems, such as laser gated viewing systems, rely on line of sight intensity imaging with a direct view on the scene even if the targets are very far away. When illuminating a scenery, the photons bounce on the targeted object but also on different surfaces and particles other then the targeted object: they are diffusely reflected or scattered many times. Typically, only ballistic photons, that are photons which are reflected once on the target, are required for high resolution imaging. While reflected multiple time, direct imaging information is lost. Thus, multiple reflected photons have an illicit impact on the image quality and can be temporally filtered by gated viewing. Nevertheless, these photons carry essential information about the target surfaces on which they were reflected, even if these surfaces are outside the sensor's field of view. This information can be revealed by a computational imaging approach by recording of transient information of the photon time of flight and analysis with strong computational algorithms.

Non-Line-of-Sight (NLoS) imaging aims at the reconstruction of target surfaces which are hidden from the direct line of sight, in order to enable sensing around corners. With this computational imaging approach any reflecting surfaces (wall, floor, ceiling, etc.) can be used as a diffuse mirror or a relay surface which redirects the light onto the hidden space. The principle of this technique is thus to illuminate a diffuse reflecting surface with a pulsed laser and to collect all multiple echoes with time discrimination in order to reconstruct hidden objects. Until now, this technology has been a topic for fundamental research and has a very low Technical Readiness Level (TRL), but current studies demonstrated that it is already possible to detect if an object is moving in a hidden area. In contrast to through-the-wall RADAR imaging systems which are operated in close distance to the wall to be penetrated, non-line-of-sight optical imaging systems have the capability to sample a remote scene; even space applications are under discussion. Further, these optical systems can be setup in a more compact volume and promise to reach higher three dimensional resolution due to shorter wavelengths. As such, this technology may prove quite useful for MGCS platforms used in urban environments.

The sensing process of NLoS imaging is illustrated on the figure below. A laser pulse is propagating through the scene and is partly scattered by the atmosphere. Then, the laser bounces off different surfaces several times and the sensor unit records photons which are reflected or scattered in the direction of the sensor aperture. Photons which are reflected (or scattered) at different ranges arrive on the sensor at different times. Thus, a transient or time resolved sensing of these photons can help distinguish photons by their different times of flight. The timing accuracy is determined by the effective temporal bandwidth of the system. The latter is impacted by the bandwidth and timing jitter of the sensor, the laser source and other components involved in the recording process.

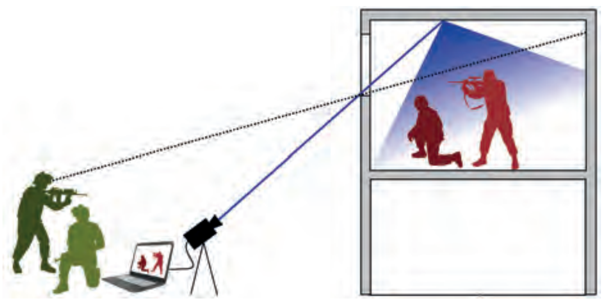


Transient imaging can be used for non-line-of-sight sensing

The location of hidden objects can be reconstructed using a back-projection algorithm which works similar to the famous Radon-transform in Computer Tomography (CT), which is well known in medical imaging. This algorithm uses the temporal information from different sensing configurations to triangulate the origin of reflection signatures. A rough localisation of a single point can be obtained easily, but higher resolution and more complex surface structures demand high computation loads. Here, further developments call upon massive parallel processing of data.

Through clever optimisations of the algorithms and specific developments, ISL has demonstrated that it is possible to detect and track movements (with 6 degree of freedom) around a corner at small ranges, in real time. However, increasing the performance of such laboratory experiments requires very high speed sensor able to record very low intensities with high temporal bandwidth: single photon detection is a key factor for the performances of such technology. Geiger mode avalanche photodiode array are the main used sensors. But the TRL level reached for this type of system remains quite modest for the time being. ISL is focusing on the application of ShortWave InfraRed wavelengths (SWIR) which are not visible and hard to detect with low-cost, off-the-shelf detector technology and can be operated very discretely (in camouflage).

Coming technological developments and research on new algorithms will be crucial for the increase of performance of such systems, which will very quickly find many applications for defence and security forces. Our institute remains at the forefront of these innovations.



Non-line of sight imaging could be used in urban environment to identify alien forces in hideouts

From detecting changes to image-based navigation

Over the past few years, ISL has made significant efforts to assist the detection of improvised explosive devices in foreign military operations. In this context, it has proposed an onboard vehicle system to help detect traces of improvised explosive devices using a computer vision device that displays changes occurring between two successive passages of a convoy on the same route. The merits of this system and its robustness, as well as the resulting operational added value have been demonstrated in a DGA contract – "Study and development of image processing algorithms for the detection of scene variations for the fight against improvised explosive devices" – and through evaluations at the WTD52 military technical center. Furthermore, feasibility trials of UAVs with embedded change detection systems have also been successfully carried out for both the DGA Techniques Terrestres and the WTD91 military technical centers.

The use of Global Navigation Satellite System (GNSS), like GPS or Galileo, was originally considered a compelling solution for the geolocation of the images acquired by the onboard camera of the vehicle traveling along the route under surveillance. However, in this case it proved inadequate, because its spatial resolution was insufficient for the application under consideration. Furthermore, the use of a GNSS is often unreliable since this device is vulnerable to poor reception conditions and jamming. The first image-based localisation algorithms were therefore studied to counter the GNSS weaknesses of our vision-based change detection system. Moreover, where road-clearance military convoys are concerned, it is obvious that the front vehicle operating the change detection system is particularly exposed to the threat of Improvised Explosive Devices (IEDs). In order to protect the front vehicle operators, the idea of using a Remotely Operated Vehicle (ROV) is admittedly not new. But what about an autonomous vehicle that would rely on a change detection system enhanced by a vision-based navigation module? It would offer significant operational added-value!

Besides road-clearance operations, our funding ministries are also interested in an autonomous Multifunctional Utility Logistics and Equipement Unmanned Ground Vehicle (MULE UGV) designed to support the infantry in daily tasks like carrying equipment or caring for a wounded soldier. Desirable features include the ability to precisely follow a defined itinerary forwards or backwards, and deal with unexpected temporary detours, for example in the case of obstacle avoidance. These features are of course also necessary in both UGV- and UAV-based autonomous patrol robots.

All of these considerations have led to propose an image-based navigation solution. This was originally intended to support ground military operations and meet the previously identified operational needs, but can also be used in future aerial unmanned vehicle (UAV) applications.

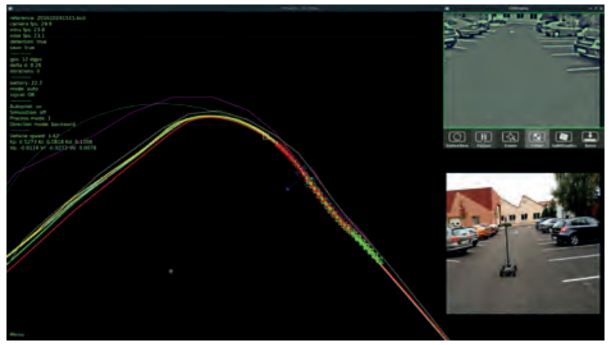
ISL has addressed the question of following trajectories defined by image databases of the route, since this is useful for both the autonomous steering of road-clearance military convoys and the guidance of mule UGVs. The simplest way to produce an image database of a trajectory is to operate the UGV remotely on an itinerary and to record a video of the route using its onboard camera. However, working with other global video/image resources (e.g. Google Earth/Street/Map) could also be possible in the future. The images taken along the route and the GNSS coordinates (mainly used optionally for alignments on a map) associated with the position of the successive shots are saved in a database defining the entire route. The UGV's trajectory during this initial phase then becomes the reference for further journeys along the same route. Once a reference database exists, the image-based navigation system we are studying generates the control information (wheel steering angle) allowing the UGV to follow the reference itinerary as defined by its image database. Several internal operating modes, which are transparent to the user, dovetail with one another to offer the best compromise between robustness and accuracy whatever the conditions the UGV is in.

The best route accuracy (roughly estimated to be at decimeter level) can be achieved when the navigation system is able to evaluate, at each processing stage and over a long period, the position and angle of the current camera view compared with that of the closest image in the database. This makes it possible to realign visual-odometry tracks which differ slightly, by balancing the differences using the relative positions of the current and reference camera views. Ultimately, this leads to a self-contained drift-free navigation system. The trajectory tracking function can also be reversed to return to the starting point, maintaining the orientation of the camera relative to the reference track. The system can therefore return to its starting point under the same conditions of use.

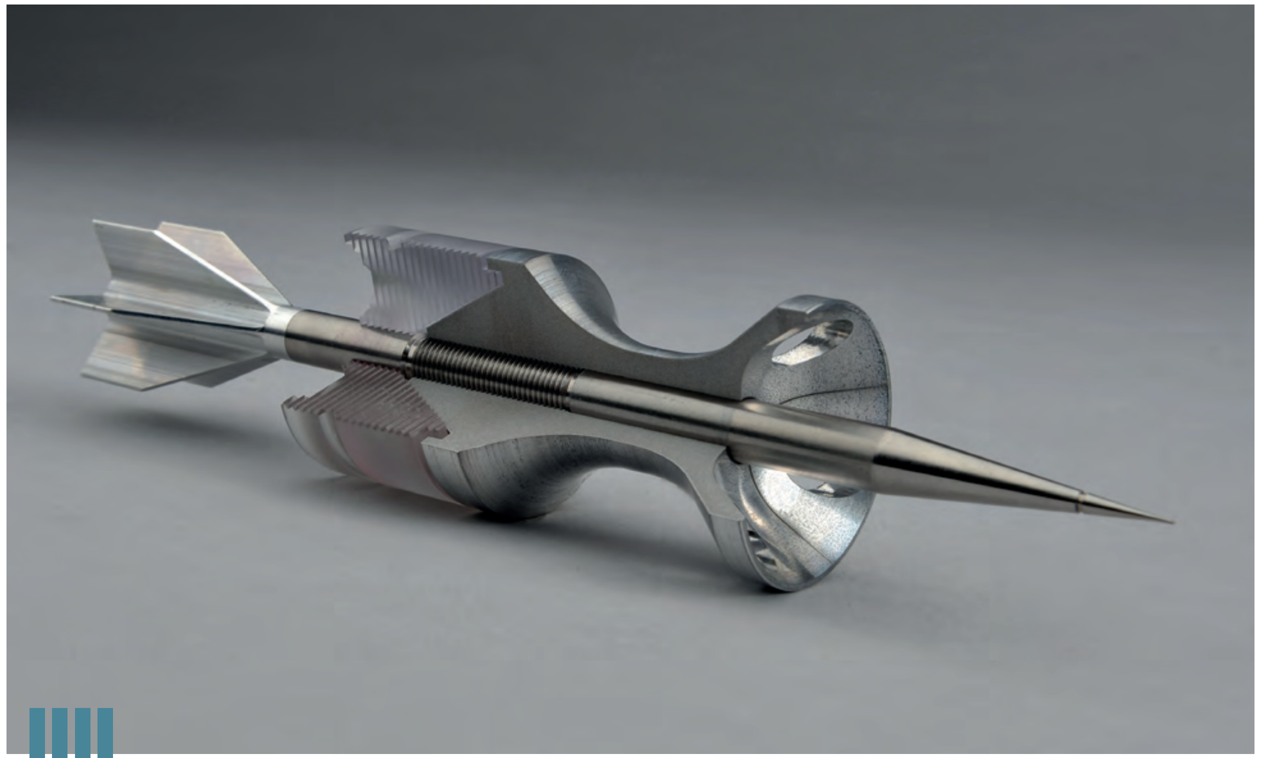
If the UGV deviates too much from its reference trajectory and the viewpoint of the onboard camera no longer makes it possible to align its current view with an image from the reference database, the navigation system relies on pure visual-odometry information and continues to use the image information to estimate its trajectory as accurately as possible while permanently attempting to retrieve an image corresponding to the current camera view from the reference database. This mode is the one that makes it possible to avoid an obstacle and return along the reference trajectory once avoided.

This approach has been tested on the ISL 1:5 STAMINA-UGV at up to 30 kph and on the autonomous vehicle platform of our academic partners at UHA at up to 45 kph. In both experiments, the accuracy in the trajectory tracking task was roughly at a decimeter scale. The STAMINA-UGV hardware architecture has been designed, with the appropriate payload and security level in mind, for use on an upcoming ISL STAMINA-UAV platform. Thus our future applications of the STAMINA concept will take into account UGV and UAV platforms for advanced collaborative image-based navigation motion.

The STAMINA software environment autonomously steering an autonomous vehicle platform at the "Cité de l'Automobile" circuit in Mulhouse



The STAMINA software environment autonomously steering the STAMINA-UGV at ISL



Protecting heavy armoured vehicles

Protection against shaped charge jets

Shaped charge warheads are a frequent and severe threat for light and heavy armoured vehicles. Whilst the general principle of shaped charges is known, many different designs of shaped charge warheads exist. Depending on the required level of protection and the type of warhead, the protective solution may incorporate explosively- or electro-magnetically-driven active systems with fragment and/or blast effects against the warhead. Passive, reactive or active protection elements acting with sophisticated material combinations are effectively used against the shaped charge jet itself.

At ISL, these solutions are investigated with high-speed imaging and other physical measurement techniques to visualise and analyse interaction between the shaped charge and the protective solution.

Major efforts have been made, especially in relation to the interaction between shaped charge jets and passive bulging armour elements and reactive armour elements, to identify optimised material and design solutions. These activities are carried out in close coordination with industrial partners, which provide state-of-the-art protection systems. The experimental techniques used offer an understanding of the physical mechanisms during the interaction between the shaped charge jet and the armour system. Ongoing activities aim to obtain deep insights into physical phenomena during interaction between shaped charge jets and passive and reactive armour, and the effect of active protective systems on warheads.

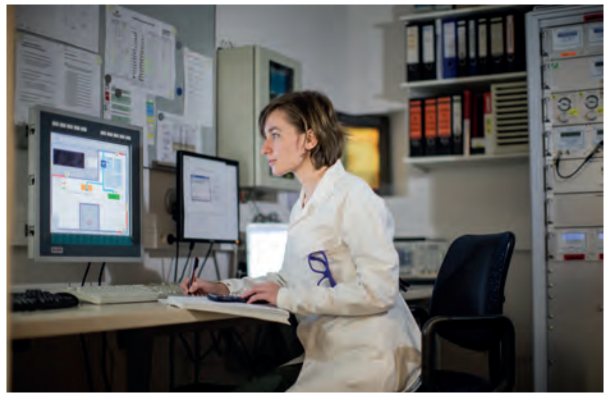
Shaped charge jet disturbed by bulging armour plates

Protection against long-rod penetrators

Long-rod penetrators are a threat and an increasing danger to the armed forces of NATO countries. Medium-calibre machine guns launch long-rod penetrators at a high frequency, and big-calibre guns launch long and slender heavy metal penetrators with high penetration capability.

ISL has carried out research in the field of protection against various designs of long-rod penetrators. A simulant for the STANAG Level 6 penetrator was developed in the medium-calibre range to enable ISL to investigate different protection strategies against this type of threat. These activities are carried out working closely with research teams focusing on protection against shaped charge jets, as similar solutions are investigated in order to provide mass-effective multi-purpose armours.

Numerical models describing the failure mechanisms of target materials were developed and successfully verified to obtain further insight into the mechanisms necessary to defeat heavy metal long-rods. This work will be continued and extended on projectile materials to do numerical design and investigate armour solutions.



Numerical simulation of a long-rod projectile perforating layered armour

These results and outcomes are used to investigate the effect of the penetrator's geometry in order to predict the performance of large calibre long-rod penetrators fired from the main guns of heavy battle tanks.

Protection against Improvised Explosive Devices (IEDs)

In recent decades, research on the blast protection of mobile platforms has exclusively focused on buried mines with moderate masses (~10 kg NEQ TNT) detonated under the belly of the targets. These mine threats have been successfully coped with by reinforcing the stiffness of the targets' main structure and by optimising the geometry of the hull in order to deflect the blast.

Blast test in an underbelly threat scenario with home-made explosives

Current and emerging blast threats generated with Improvised Explosive Devices merely loaded with homemade explosives have dramatically increased threat levels, for both deeply-buried and side-blast operational scenarios.

The survivability of mobile platforms against such high level blast threats cannot be dealt with exclusively by reinforcing the structural resistance of the main hull, merely because of mass constraints. Therefore, new add-on blast protection architectures are being investigated in order to provide two distinct physical mechanisms interacting with the incoming blast wave: disturbing the blast profile with shock diffraction on dedicated geometries and/or absorbing/damping the energy with a deformable material prior to transferring to the main hull.

Both numerical and experimental investigations are conducted to understand and describe the physics of energy dissipation/retardation mechanisms in order to mitigate the load transferred to the vehicles' main hull.

Using highly instrumented blast test-rigs operated on the ISL explosive test range, the research team can embed and evaluate a wide range of innovative multi-phase sacrificial protection architectures.

Explosive threat devices are designed and manufactured in ISL's own pyrotechnic lab, allowing a large spectrum of explosive compositions to be covered, from commercial (military, civilian) to various home-made explosives.

Events and Awards

Ambassador visits ISL

The German Ambassador in Paris, Dr. Nikolaus Meyer-Landruth, visited ISL on January 31, 2017, together with his Defence and Armament Attaché. Representatives of the local and regional political and military authorities of the three neighbouring countries (France, Germany and Switzerland) attended a festive dinner on top of the railgun laboratory to discuss the possibilities for exchanges and collaboration. The gathering ended with an impressive shooting demonstration at the railgun facility.

Capability Chief visits ISL

On July 27, 2017, General BEAUDOUIN, former director of STAT (technical division of the French Army) and now French Army Capability Chief discovered ISL. He has been heralding ISL competences and innovations ever since: ISL is proud of having gained such a distinguished supporter!

ISL welcomes a Nobel Prize winner

On April 28, 2017, Jean-Pierre Sauvage, the 2016 Nobel Prize winner in Chemistry, gave a conference entitled "From chemical topology to molecular machines". He was followed by Pierre Braunstein, with a conference on the topic of "Hybrid ligands: complex metals, catalysts and precursors of nanomaterials". Dr. Jean-Pierre Sauvage and Dr. Pierre Braunstein are both members of the French Academy of Sciences and Professors Emeriti of the University of Strasbourg. We are particularly thankful to them for their one-off conferences, which could not have been possible without ISL's outstanding scientific reputation.

GICAT and BDSV meet at ISL

On April 5 and 6, 2017, ISL has organised a common meeting of the steering boards of the French Land and Security Industries association and of the German Security and Defence Industries association, GICAT and BDSV respectively, to discuss future cooperation. Georg Wilhelm Adamowitsch and Andreas von Büren, respectively Managing Director and Deputy Managing Director of BDSV, General Jean-Marc Duquesne and Emmanuel Chiva, respectively Managing Director and Chairman of the GICAT R&T committee, were given an extensive overview of the diversity and quality of the research carried out by ISL.

Sharing know-how at ISL's international workshops

State representatives and industrial experts from France and Germany, as well as international cooperation partners have met on April 4, 2017, to discuss the different aspects of material ageing in protective structures. This workshop was organised for the first time. It was an initiative of ISL scientists, under the patronage of DGA and BAAINBw. This first edition covered wide-ranging issues in this field, from ageing effects in personal protection devices and vehicle protection to possible techniques, allowing the detection of these effects. It focused on special issues regarding the experimental quantification of ageing effects in:

- polymers and composites,
- adhesives,
- transparent armour,
- metals/welds,
- blast and terminal ballistic performance in aged structures,
- destructive/non-destructive testing techniques.

The unexpectedly huge success of this first meeting on a new topic has prompted the organisation of a follow-up workshop in Mai 2018.

2017 Workshop on Active Imaging

active IMAGING

The sixth Workshop on Active Imaging, an ISL initiative, took place on November 15 and 16, 2017.
Active-imaging systems, i.e. systems that employ an illumination source, are becoming more and more prevalent. Recent advances in component technology, coupled with increased processing capability, have caused a surge in the development and implementation of laser-based imaging systems for diverse military or civilian applications:

- novel component technologies for illumination and sensor aspects,
- demonstrations and applications of active-imaging systems,
- advanced techniques like 3D imaging, compressed sensing.

In 2017, special focus was given to novel advanced imaging concepts such as non-line-of-sight imaging and imaging with multi-scattered photons.

Zernow Award bestowed to ISL at the International Symposium on Ballistics

ISL received the Louis and Edith Zernow Award at the International Symposium on Ballistics which took place on September 11-15, 2017, in Long Beach (California). This award is given to the authors of the paper presenting the best scientific results in ballistics. It is the most prestigious accolade given at the symposium and was awarded to ISL for the fourth time since its creation in 1992.
The award-winning paper is entitled "Aerodynamic characterisation of a new concept of long range projectiles from free flight data" (Marie Albisser, Simona Dobre, Cédric Decrocq, Fayçal Saada, Bastien Martinez and Patrick Gnemmi).

ISL at SOFINS, the Special Forces Fair

From March 28 to 30, 2017, ISL exhibited the latest results of research dedicated to special forces at the SOFINS fair near Bordeaux. This event served as the occasion for special forces to discover some of the most recent prototypes developed by ISL with industrial partners:

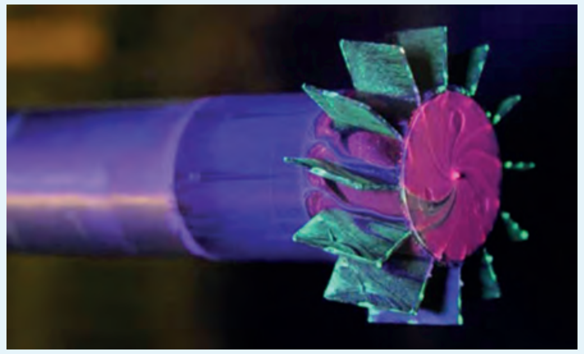
- BANG: a new-generation hearing protection device with a talk-through function, which ensures enhanced communication capability;
- B-SAVED: a highly secured, intelligent, autonomous visual event sensor equipped with two cameras offering foveal and panoramic visions;
- SMARTCAM: an intelligent camera capable of recognising the detected event and reacting accordingly;
- I-WARN: an electronic camouflaged sentinel for active zone surveillance.

Innovation Trophy

At SOFINS 2017, ISL received the "Best Special Forces - Expert Centre Collaboration" award.

2017 CMOI-FLUVISU Awards

ISL received two awards at the International Symposium on Flow Visualisation. Stephan Weidner was awarded first distinction for his contribution "Visualisation by fluorescence at Mach 2 on the back of a 40-mm-calibre projectile". The second distinction went to Myriam Bastide for her research on "Visualisation of the blast effects by Differential Interferometry".



ISL in the media

Articles are regularly published about ISL research in non-scientific magazines. The German magazine "Wehrtechnik" notably published one-page articles about different scientific topics throughout the year. The Bundeswehr media, for example the Military Scientific Research Report and Y cover also diverse themes like the detection of ultrafine explosive traces or the electromagnetic railgun. ISL also appeared on French TV evening news (see opposite page) and has been regularly present in the local press (l'Alsace, DNA, Badische Zeitung etc.).

ISL contributes to BAAINBw's vocational retraining

Due to the dearth of candidates for vacancies in the technical department of German armament services, BAAINBw has created in 2009 a specific Bachelor's degree in Mechanical and Electrotechnical Engineering, Computer Science and Aeronautics. ISL helps to develop the technical skills of these students. Since 2011 the number of graduates has risen from 2 to 40.

DGA Innovation Forum – French TV evening news feature the electric railgun

The DGA Innovation Forum is organised every year by DGA, at the prestigious École polytechnique, to showcase the most recent research topics and success stories in the field of armament research and innovation. Servicemen, industrial, academic and state entities as well as national media are invited to attend a two- day specialist seminar. Presenters are invited on a selective basis. ISL presented a functioning mini electric railgun mounted on a truck model, delivering realistic shots on demand. The leading French TV channel TF1 featured the innovation in its Sunday evening news programme, the most watched TV daily news.

6th Budding Science Colloquium at ISL

The 6th Budding Science Colloquium held on June 21–22, 2017, at ISL, is an annual event that serves as the principal forum for discussions, exchanges and presentations by the PhD students of ISL in the Institute's different research topics: energetic and advanced protective materials, flight techniques for projectiles, laser and electromagnetic technologies and protection technologies, security, situational awareness.
The Budding Science Colloquium aims at stimulating and promoting young scientists preparing a PhD thesis at ISL. During the colloquium, PhD students and other scientists share and exchange a wealth of knowledge through oral and poster presentations, fostering ISL's renowned transversality.

UNISTRA – UHA – ISL Workshop

The University of Strasbourg (UNISTRA), the University of Upper Alsace (UHA) and ISL are fostering active scientific cooperation and exchanges of students as part of an integrated partnership. The representatives meet once a year to assess past initiatives and plan future ones. The 2017 workshop took place on September 26-27, 2017.

Excellence in Apprenticeship

ISL regularly takes specific actions to recruit qualified French and German staff as well as European scientists, engineers and highly qualified technical and administrative staff. These actions are undertaken at academic job fairs but also locally, for example at the Saint-Louis Recruiting Day.
Salomé Foisset an Thomas Pinoit, two trainees in Optoelectronics were awarded first and third prize respectively in the "Meilleurs Apprentis de France" competition which rewards France's best apprentices in their specific fields.

The ISL Scientific Symposium

From March 13 to 14, 2018, the ISL Scientific Symposium brought together scientific and national defence experts. These yearly meetings focus on ISL's main research topics:

- energetic and advanced protective materials: detonics, interior ballistics, energetic materials and nanomaterials, advanced materials for protection;
- flight techniques for projectiles: guided ammunitionsystem aspects, aeroballistics, guidance navigation and control, miniaturised on-board electronics;
- laser and electromagnetic technologies: laser sources, electromagnetic acceleration, pulsed-power technology;
- protection technologies, security, situational awareness: light ballistic armour, protection against IEDs, threat characterisation, acoustic and blast protection, advanced visionics – active imaging, laser-matter interaction.

Academic Excellence

Thesis defended in 2017-2018

Contribution to the understanding and modelling of the injury mechanisms on the thorax related to the exposure to a shock wave
Johanna BOUTILLIER
Supervisor: Pascal MAGNAN (ISL)
Directors: Rémy WILLINGER (ICUBE University of Strasbourg), Caroline DECK (ICUBE University of Strasbourg)
January 16, 2017

Nanostructuring study of multi-component energetic materials to be used for propellants with reduced sensitivities
Axel LE BRIZE
Supervisor / Director: Denis SPITZER (ISL, Unistra)
February 13, 2017

Development of magnesium based composites for lightweighting applications and ballistic protection in the field of transport
Mathieu MONDET
Supervisors: Élodie BARRAUD, Sébastien LEMONNIER (ISL)
Directors: Thierry GROSDIDIER (LEM3 University of Lorraine), Nathalie ALLAIN (LEM3 University of Lorraine)
April 11, 2017

Development of Al/B_4C composites for ballistic protection
Hippolyte QUEUDET
Supervisors: Sébastien LEMONNIER, Élodie BARRAUD (ISL)
Directors: Éric GAFFET (IJL Nancy), Nathalie ALLAIN (LEM3 University of Lorraine)
May 18, 2017

Objective prediction of the effect of tactical communication and protective systems on sound localization performance
Thomas JOUBAUD
Supervisor: Véronique ZIMPFER (ISL)
Director: Alexandre GARCIA (CNAM)
September 15, 2017

Initiation en détonation d'explosif secondaire par des nanothermites
Cédric MARTIN
Supervisor / Director: Marc COMET (ISL, Unistra)
September 19, 2017

Contribution à la modélisation, l'identification et la commande d'un hélicoptère miniature
Emmanuel ROUSSEL
Supervisor: Vincent GASSMANN (ISL)
Director: Edouard LAROCHE (University of Strasbourg)
October 12, 2017

Experimental and numerical study of the mechanical behavior of metal/polymer multilayer composite for ballistic protection
Charles FRANCART
Supervisor: Yaël DEMARTY (ISL)
Director: Nadia BAHLOULI, Saïd AHZI (University of Strasbourg)
October 13, 2017

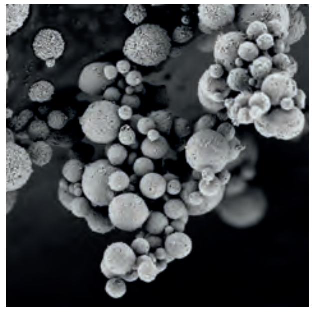
Élaboration d'assemblages multicouches polymère/métal par frittage Spark Plasma Sintering (SPS)
Jean-Charles SEBILEAU
Supervisors: Sébastien LEMONNIER, Élodie BARRAUD (ISL)
Directors: Adèle CARRADO (IPCMS), Michel NARDIN, Marie-France VALLAT (IS2M)
February 07, 2018

Habilitation to direct Research

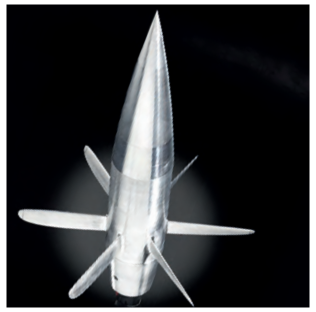
Antennas and microwave circuits for projectiles and flying systems. Applications for telemetry, bi-directional communications and GNSS in harsh environments
Loïc BERNARD
June 26, 2017

One minute silence in memory of the victims of a terrorist act in March 2018

Cover page captures



SEM image of synthesised and spray-dried YAG ceramic powder



New concept of long-range guided ammunition

Storage coil of an XRAM generator for the electrical power supply of railguns

BANG - New generation earplugs

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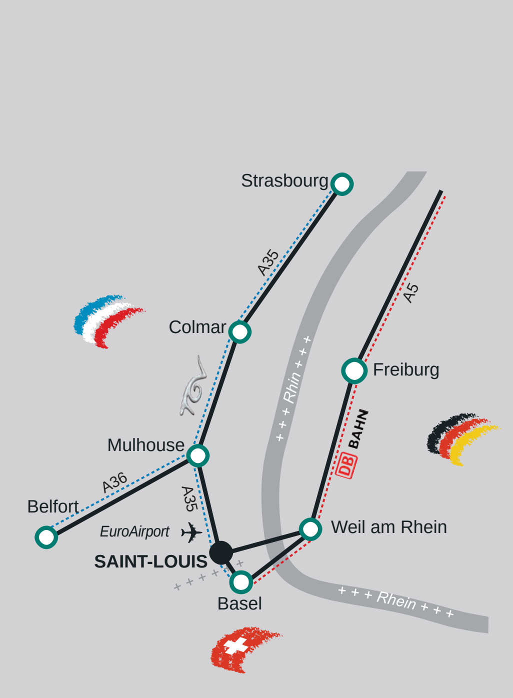

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