Georgia Tech Lorraine

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UNITE MIXTE INTERNATIONALE GEORGIA TECH-CNRS, UMI2958

2018-2022 RESEARCH PROGRAM

UMI 2958

Founding Members

Associate Members

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Executive summary

The UMI was created with an agreement between Georgia Tech and CNRS for the years 2006 to 2009. Extensive efforts were made during this first period to build laboratory facilities, to purchase and to install state-of-the-art equipment, to hire researchers and PhD students and to initiate research programs in secure networks and smart materials.

In the second agreement than spanned 2010-2013 the UMI extended its research program to secure networks with the creation of the “Smart Home” with CentraleSupelec. It extended its research activity in the UMI GT/Atlanta site. It substantially increased its external grants through public research programs at national, European and international levels as well as increased contracts with industrials. It achieved high visibility through its research publications and conference presentations. It actively contributed to the creation of the Lafayette Institute—a platform for technology transfer.

In the third contract of 2014-2017, we have achieved many things in our research projects and have made major contributions to local, national and international research programs. We have continued to improve our physical research facilities, and have established significant alliances with academic and industrial partners. We have played a leadership role in building a bridge for faculty researchers and student exchanges between France and Atlanta. We have also played a leading role in the creation of the Institut Lafayette, a platform for technology transfer and innovation in the area of optoelectronic devices.

Abdallah Ougazzaden led the three first contracts successfully. The next agreement of the UMI will see a change in leadership. Jean Paul Salvestrini, Professor at Georgia Tech Lorraine will succeed him. Their common vision for the next 5 years, 2018-2022, is that UMI will:

- <u>Focus on research areas with recognized expertise and leadership in</u>:
    - Nonlinear dynamics in photonics and terahertz science and technology
    - Materials and nanostructures for photonics and electronics, materials by design and advanced manufacturing, and multi-scale non-destructive evaluation of materials
    - Network information systems, robotics for environmental assessment and monitoring, and system design and integration.
- <u>Leverage opportunities arising from</u>:
    - **Institut Lafayette**, a platform for innovation and technology transfer in optoelectronics combining both high-level applied research and commercialization services,
    - **ISITE Lorraine Université d’Excellence**, which aims to develop a leading global engineering university, with a strong emphasis on technological research and education through research. LUE will provide, over a long period, an annual flow of several million euros dedicated to the development of the academic site as a European and international reference on Global Engineering. Georgia Tech Lorraine is one of the eight partners of this program.
    - **CEA TECH**, which is the CEA’s (the French Atomic Energy and Alternative Energy Commission) technology research unit. CEA Tech has opened a branch office in the Grand Est region, located in Metz, next to Georgia Tech Lorraine. The regional offices are intended to play a key role in France’s strategy to boost industrial competitiveness through high added value and enhanced product quality. Their mission is to develop local research programs that round out existing programs and that meet the unique needs of locally-anchored industries
    - **LIA Atlas Morocco**, **(2017-2021)**, “Associated Trans-Mediterranean Laboratories for Applications in Solar Energy,” is a formal structured international laboratory collaboration created by CNRS, Georgia Tech, and Moroccan education (MESRSFC) and research (CNRST) entities for international collaborations. Partners are the UMI, Université Mohammed V, and the Université Internationale de Rabat. This agreement has a plan for collaborative research in renewable energy. This lab will allow for scientific synergies in photovoltaics, energy efficiency, and provides resources for the exchange of students and researchers, and a platform for building joint projects funded by companies and by public sources.

- Open Lab PSA Peugeot Citroën France and Morocco was created in January 2015 with an agreement between PSA, Georgia Tech, Institut Lafayette, and 7 other universities on the subject of sustainable mobility for Africa. This laboratory provides an additional link between the UMI and PSA, and the opportunity to collaborate with Moroccan researchers in the sustainability area.

- Reinforce strategic areas:
    - Grow UMI presence in Atlanta, notably as described with the growth of the UMI Atlanta Mirror Lab in project C1, “Network Information Systems”.
    - Partnership with European research centers. The UMI will continue to strengthen its European network.
    - Education through research. Approximately 700 students pass through GTL per year, and this is planned to increase to 1000 per year by 2020. The majority of these students are Atlanta-based undergraduate students. In the 2013-2017 UMI agreement, over 50 undergrad students have participated in UMI research projects. We plan to increase student participation in research to 120 in the 2018-2022 period, while formally adopting site-appropriate versions of leading Georgia Tech experiential learning programs such as Invention Lab, Ti:Ger, VIP, etc.
- Build critical size:
    - Hire more researchers and engineers. The UMI will do its utmost to create permanent researcher positions through CNRS, Georgia Tech, or other UMI partners. We will also seek to increase the number of researchers and engineers paid for by research contracts.

The evolution compared to the previous contract in each research area is summarized below.

Nonlinear optics: enabling photonic technology

Project A (Nonlinear optics) will continue to have a strong emphasis in nonlinear dynamics. During the 2014-2017 term, a state-of-the art laboratory for the analysis of multi-GHz optical nonlinear dynamics has been built and several applications of these dynamics have been investigated. During the 2018-2022 term, we plan to leverage the potential of the acquired equipment and know-how to unfold the origins of dynamical behaviors in diode lasers of various kinds. Deep understanding of the dynamics will help us develop cutting-edge applications in the field of photonic information processing. The expertise of Prof. Damien Rontani, Dr. Yanne Chembo, and Prof. M. Bloch will help us achieve our goals.

Looking forward to 2018-2022, changes have been made to the previous Project A-2, led by Paul Voss, will be discontinued to allow Prof. Voss to devote almost all of his research time to subprojects B-1 and B-2, where he has been involved in the design and modeling of semiconductor devices for Project B-1 and B-2. This change will lend additional scientific strength to Project B, and is consistent with opportunities in semiconductor fabrication made available by the start of Institut Lafayette.

Disruptive technologies in materials, characterizations and device applications

Development of synergies between experiments and simulations for accurate prediction of microstructure evolution and development of data-driven models will be the major objectives in project B2 “Material by Design and Advanced Manufacturing”. Mohammed Cherkaoui and Laurent Capolungo are responsible for most of the achievements in former project B2 “Material by Design” have left Georgia Tech and the UMI. At this time Etienne Patoor is the only ME permanent faculty working on this topic. His accomplishment in analysis and modeling of the martensitic phase transformation at different lengthscale and his strong relations with partner laboratory LEM3 and also with FEMTO-ST are very important for the new research program.

In addition, the hiring of new permanent faculty in ME is a priority. The Woodruff School of Mechanical Engineering has open a faculty position for GTL, several candidates have been interviewed, the process is now coming close to its conclusion and a new faculty having strong background in the development of data-driven models is supposed to join GTL in 2017.

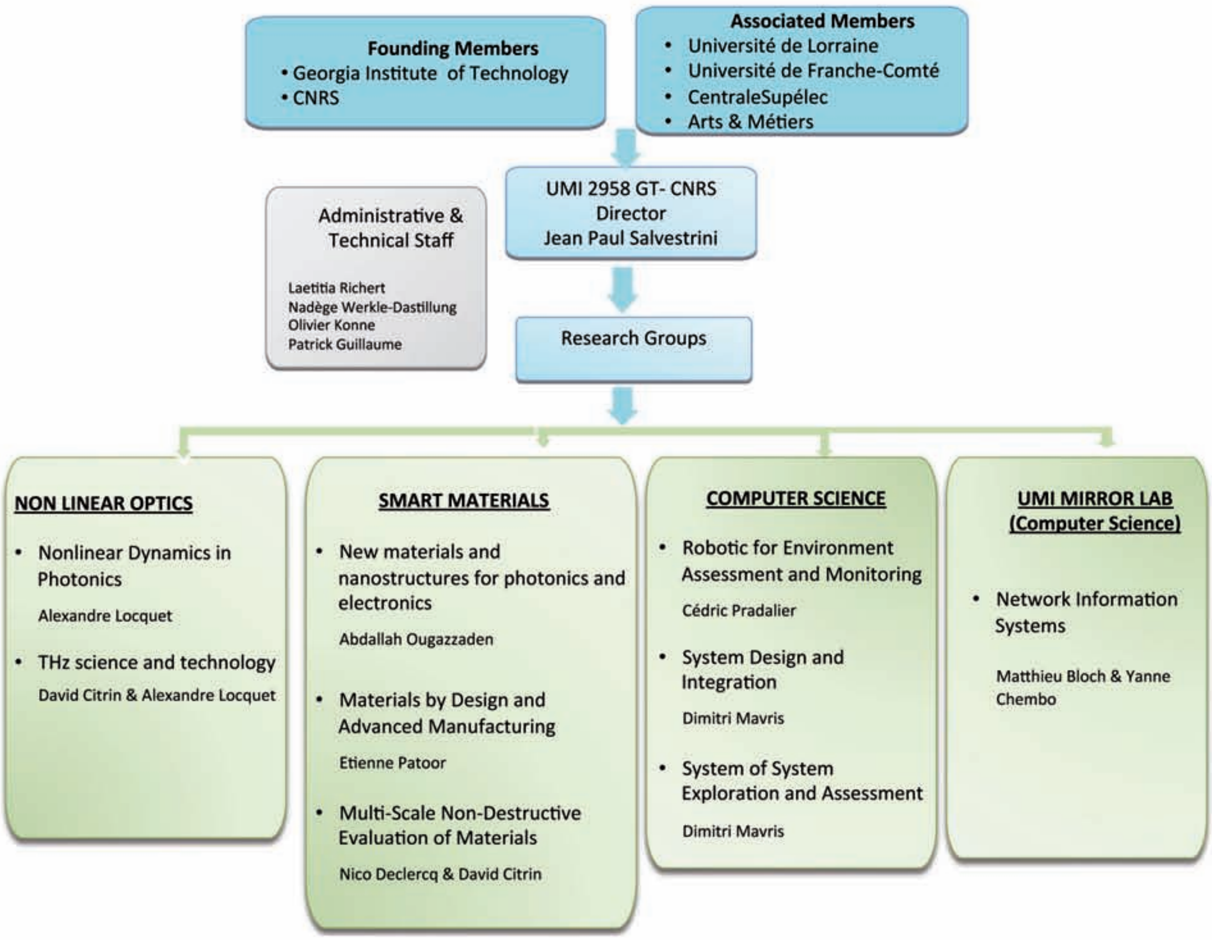
Emerging areas in computer sciences

The computer-related activities within the UMI are expected to continue to expand in the direction of secure networks and robotics for natural environments. Research on cognitive systems, mostly from CentraleSupelec faculties, will join a new team at Loria with a strong focus on cognitive sciences and bio-inspired solutions. By integrating GeorgiaTech researchers from the Aerospace System Design Lab, the computational activities will expand in the direction of computer-aided integration and design for complex systems and systems of systems.

The Aerospace Systems Design Lab (ASDL), within GeorgiaTech Aerospace department, is a research laboratory that focuses on complex system design and analysis. ASDL has been the leading group for conceptual system design and integration, including systems of systems design, for the past 25 years, with European industry partners such as Airbus, Dassault System or Safran. ASDL at GTL will build itself to become a multi-disciplinary, conceptual design research facility that is home to academic faculty, research faculty and post-docs, graduate students, and undergraduate students. Dr. Dimitri Mavris, Regents professor in the Aerospace Engineering department at Georgia Tech's Atlanta campus, will serve as the lead of the research laboratory. One or two Atlanta research faculty members will be present at GTL every semester and the ASDL staff in Atlanta will support the ASDL integration at GTL.

The nature of the research conducted by ASDL at GTL will be mostly computational; therefore, even though it originates from the aerospace department in Atlanta, this activity will initially be considered below the Computer Science umbrella and take advantage of existing computational resources within the UMI.

Organizational chart



UMI staff

- **List of UMI Permanent Members**
- ***Researchers***

Yves Berthelot,

- Professor of Mechanical Engineering, President & Director of GTL
- Research Areas: acoustic characterizations, sensors
- Publications and awards: Over 100 publications, Gold medal of American Society of Mechanical engineering, Lindsay award of the acoustical Society American, NSF Presidential Young Investigator award

Michel Barret,

- Professor of Statistical Signal Processing at CentraleSupélec, Responsible of the Major "Interactive Systems and Robotics"
- Research Areas: Data Compression, Statistical Analysis of Data, Stability of N-D Recursive Filters
- Publications and awards: 2 books, over 35 publications

Matthieu Bloch,

- Assistant Professor of Electrical and Computer Engineering
- Research Areas: Information Theory, Coding Theory, Wireless Communications, physical-layer security
- Recipient of the 2011 IEEE Communications Society and Information Theory Society Joint Paper Award
- Author of Physical-Layer Security: from information to security engineering, Cambridge University Press

Yanne Chembo,

- Research Scientist at CNRS (CR)
- Research Areas: exploration of nonlinear, quantum and stochastic phenomena in optoelectronics, microwave photonics, and laser physics
- Publications and awards: over 100 publications, 2 book chapters, Juan de la Cierva fellowship 2008, ERC laureate StG 2011 & PoC 2013, NASA Inventions and Contributions Board Award 2013; NASA Tech Brief 2016

David Citrin,

- Professor of Electrical and Computer Engineering,
- Research Areas: Nonlinear optical properties of semiconductor materials, devices, Terahertz spectroscopy and imaging, Nonlinear Dynamics, High-speed electronic, photonic, optoelectronic devices, Quantum computing, Photovoltaics.
- Publications and awards: Over 150 Publications, Presidential Early Career Award for Scientists and Engineers (PECASE), Friedrich Bessel Prize (Alexander von Humboldt Stiftung)

Nico Declercq,

- Associate Professor of Mechanical Engineering
- Research Areas: Ultrasonic Microscopy, Acousto-Optics, Physical Acoustics
- Publications and awards: 72 journal publications, over 155 congress presentations, president of the 2015 International Congress on Ultrasonics, European Union Promodoc Ambassador, International Commission for Acoustics Early Career Award in 2007, International Dennis Gabor Award in 2006, Sigma Xi Young Faculty Award in 2006

Alexandre Locquet,

- IR CNRS, Adjunct Professor of Georgia Tech's School of ECE
- Research Areas: nonlinear dynamics, semiconductor laser dynamics, physical-layer security, terahertz imaging
- Publications and awards: 110 publications, 40 journal publications, 1 book chapter

Steve W. McLaughlin,

- Professor of Electrical and Computer Engineering, Vice Provost for the International Initiatives
- Research Areas: Communication & information theory, Quantum key distribution
- Publications and awards: more than 200 publications, 26 patents, President IEEE Information theory society, NSF Presidential Early Career award (PECASE)

Abdallah Ougazzaden,
- Professor of Electrical and Computer Engineering, Director of the UMI Georgia Tech-CNRS
- Research Areas: Materials growth, Optoelectronics devices
- Publications and awards: over 340 publications, 22 Patents, CNET/France Telecom Award, Peugeot PSA Award, Denning Global engagement award

Etienne Patoor
- Professor of Mechanical Engineering
- Research areas: Mechanics of Materials
- Publications and awards: over 200 publications, 2 patents, 2 books

Cédric Pradalier,
- Associate Professor of Computer Science
- Research Areas: Field Robotics, Environment Monitoring
- Publications and awards: over 90 publications, 10 journal publication, 1 book chapter
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Jean Paul Salvestrini,
- Professor of Electrical and Computer Engineering, Georgia Tech Lorraine
- Research Areas: Material characterization, Optoelectronic devices
- Publications and awards: over 100 journal and conference publications, 8 patents, Recipient of the 2005 Lorraine Region Award of the Best Researcher

Suresh Sundaram,
- Research Instructor in School of Electrical and Computer Engineering, Georgia Tech Lorraine
- Research Areas: Semiconductor Physics, MOCVD growth of III-nitrides, Optoelectronic devices

Publications: over 45 journal and conference publications.

Paul Voss,
- Associate Professor of Electrical and Computer Engineering, Georgia Institute of Technology
- Research Areas: Quantum Communications, Nonlinear Optics, Design & Simulation of Nitride Semiconductor Devices
- Publications and awards: more than 160 journal publications and conference presentations, NASA graduate student researcher fellowship, Demetrius T. Paris Professorship Recipient

Stephane Vialle,
- Professor of Computer Science, CentraleSupélec
- Research Areas: Parallel and Distributed Computing
- Publications and awards: over 50 publications, 5 journal publications, 3 patents

- ***Technicians and administrative staff***

Patrick Guillaume

- Technician - CNRS
  Vacuum technology
  Mechanics

Olivier Konne

- Technician – CNRS
  Electronics
  Lab software

Laetitia Richert

- Administrative staff - CNRS
  Contract support
  Finance management

Nadège Werklé-dastillung

- Administrative staff – CNRS
  Human ressource

List of UMI associated Members

- Nonlinear optics

○ Damien Rontani (LMOPS, EC CentraleSupélec)

○ Germano Montemezzani(LMOPS, PR UL)

○ Nicolas Marsal (LMOPS, EC CentraleSupélec)

- Smart Materials

○ Thierry Aubert (LMOPS, EC CentraleSupélec)

○ Alain Maillard (LMOPS, PR UL)

○ Bertrand Boussert (GTL, PR)

○ Surya Kalidindi (GIT, PR)

○ Stéphane Berbenni (LEM3, DR),

○ Mostafa Daya (LEM3, PR UL),

○ Lazlo Toth (LEM3, PR UL)

○ Fodil Meraghni (LEM3, PR Arts & Métiers)

○ Jean Sébastien Lecomte (LEM3, IR CNRS)

○ Vincent Laude (FEMTO-ST, DR)

○ Abdelkhrim Khelif (FEMTO-ST, DR)

- Computer Science

○ Mario Marchetti (LMOPS, CR CEREMA)

○ Dimitri Mavris (GIT, PR)

○ Turab Zaidi (GTL, PR)

○ Katherine G. Schwartz (GIT, Research Engineer)

○ Jimmy Tai (GIT, Research Engineer)

○ Simon Briceno (GIT, Research Engineer)

○ Elena Garcia (GIT, Research Engineer)

○ Olivia Pinon Fisher (GIT, Research Engineer)

AE: School of Aerospace Engineering
AI: Assistant Ingénieur
CR: Chargé de Recherche
EC: Enseignant Chercheur
ECE: School of Electrical and Computer Engineering ENSAM: Ecole nationale Supérieure d'Arts et Métiers
Femto-St: Franche-Comté Electronique Mécanique Thermique et Optique- Sciences et technologies
GT: Georgia Institute of Technology
IJL: Institut Jean Lamour
IR: Ingénieur de Recherche
LEM3: Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux
LMOPS: Laboratoire Matériaux Optiques, Photonique et Systèmes
ME: School of Mechanical Engineering
TCN: Technicien
UFC: University of Franche Comté
UL: University of Lorraine

Involved researchers

By scientific topic - Overview										
	Permanent members				**Associate members**					**TOTAL**
Topic	**GT**	**GTL**	**CNRS**	**Centrale Supélec**	**GTL**	**GT**	**FEMTO-ST**	**LEM3**	**LMOPS**	
A	1	-	1	-	-	-	-	-	3	**5**
B	1	6	-	-	1	1	2	5	2	**18**
C	2	1	1	2	1	6	-	-	1	**14**
TOTAL	**4**	**7**	**2**	**2**	**2**	**7**	**2**	**5**	**6**	**37**
	15				**22**					

By institution			
	Permanent members	**Associate members**	**Total**
GT-GTL	11	9	**20**
CNRS	2	4	**6**
CentraleSupélec:	2	3	**5**
UL	-	5	**5**
Arts & Métiers		1	**1**
UFC	-	-	**-**
Total	**15**	**22**	**37**

By lab			
	Permanent members	**Associate members**	**Total**
LMOPS (CS/UL)	-	6	**6 (3/3)**
FEMTO-ST (UFC/CNRS)	-	2	**2 (0/2)**
LEM3 (UL/A&M/CNRS)	-	5	**5 (2/1/2)**
ASDL (GIT)	-	7	**7**
Other (GTL)	-	2	**2**
Total	**-**	**22**	**22**

UMI scientific program

A – Nonlinear Optics

A – 1 Nonlinear Dynamics in Photonics

Strategy

Engineering has been traditionally dominated by linear systems mainly because of their simplicity and predictability. Awareness is growing that nonlinear systems and their associated nonlinearity underlies a plethora of physical, biological, and social phenomena and is useful in building systems that provide superior flexibility compared to purely linear systems. Indeed, nonlinear systems can perform more complex operations than linear ones; this means that they are able to implement at the hardware level many of the operations that are typically devoted to offline post-processing in linear systems.

Photonic devices are especially interesting for the study of nonlinear dynamical phenomenon, both because of their inherent speed, which makes them prone to higher frequency applications than what electronic systems can achieve and because of their flexibility, which makes it possible to make fundamental investigations of their sub-ns dynamics.
Our work in chaos-based communications is focused on the various intersections between dynamics, materials and devices, nanotechnology, and nonlinearity

In particular, we use external-cavity lasers (ECLs) as a test bench for many conjectures in nonlinear dynamics. These use an external cavity to provide time-delayed optical feedback into the laser diode (LD), and lead to a variety of dynamical behaviors depending on the operating and device parameters. Due to the peculiarities of the delayed feedback, an infinite-dimensional dynamical system results in which hundreds of attractors or attractor ruins can co-exist in the same region of phase space, a phenomenon known as generalized multistability and leading to a wealth of dynamical regimes of varying complexity. ECLs typically serve as a prototype for high-speed (sub-nanosecond) chaos in high-dimensional time-delayed dynamical systems. Their highly complex dynamics further makes them attractive for applications such as secure communications, high-speed random-number generation, and neuromorphic computing.

Despite interest in ECLs, experiment has suffered, from a lack of detailed and systematic experimental knowledge of the dynamical regimes that can be accessed by a continuous tuning of the operating parameters and a clear assessment of the most promising applications.

Over the course of the previous term (2013-2017), we have developed a state-of-the art experimental facility to study the sub-ns dynamics of diode lasers. In particular, we are able to resolve systematically the bifurcation mechanisms that lead to the various dynamical regimes used in applications. In addition, we have studied experimentally several applications of these dynamical regimes. In particular, chaotic regime have been exploited for in high-speed random bit generation, for securing communications, and for compressive sensing; the periodic regime has been exploited in the study of an optoelectronic oscillator and in reservoir computing, while the sensitivity of a CW laser to feedback has allowed to get rid of the photodiode in a CD/DVD reader.

Topics

In the next term, we propose to investigate the following topics:

- ***Experimental nonlinear dynamics of high-dimensional photonic systems***

Despite considerable work in the field of ECLs, several aspects of the real, experimental, dynamics, still need to be explained. In particular, we have noted significant discrepancy[1,2] between the widely-used Lang and Kobayashi model for ECL dynamical behavior. We will work on developing a model that reproduces the experimentally observed behavior. This will require the full unlocking of the dynamical behavior of an ECL through the simultaneous observations of its optical intensity, phase, and carrier density as bifurcations points are passed through. We will also work on confirming experimentally the minimum set of independent laser and operating parameters that are needed to obtain a given

[1] N. Li, B. Kim, A. Locquet, D. Choi, W. Pan, and D. S. Citrin, "Statistics of the optical intensity of a chaotic external-cavity DFB laser," Opt. Lett., vol. 39, 5949–5952, Oct. 2014.
[2] B. Kim, A. Locquet, D. Choi, and D. S. Citrin, "Experimental route to chaos of an external-cavity semiconductor laser," Phys. Rev. A, vol. 91, no. 6, 061802, Jun. 2015

dynamical behavior. Accurate understanding of the dynamical behavior and of its origin is expected to contribute to a better mastery of the applications of ECLs.

- ***Quantum and nonlinear photonics***

There is currently a trend towards the implementation of compact or integrated photonic systems able to generate quantum states of light at room temperature. We aim in this project to explore the quantum phenomena in whispering gallery mode resonators with Kerr, Raman or Brillouin nonlinearities, with applications in microwave photonics, optical communications, and aerospace engineering.

- ***Nanophotonics***

Integrated nanophotonics aims at incorporating on a chip various miniaturized light-guiding and processing devices in a fashion analogous to the remarkable degree of integration that occurs over the past forty years in electronics. Thus, a photonic integrated circuit can be thought of as the photonic analogy to the (electronic) integrated circuit. Applications of photonic integrated circuits include sensor systems and ultrahigh-speed communications, to name just two.

This project aims at developing tools and integrated-nanophotonic technologies for with a focus on structures to guide and process light for photonic integrated circuits. A particular interest is structures based on photonic crystals and nanoplasmonics as these approaches permit an extremely high degree of miniaturization and integration.

- ***Neuromorphic computing***

Interest has grown recently in developing realizations of brain-inspired computers. Abstract realizations of brain-inspired computing have been pursued for potential energy efficiency, as well as, computing power that could be improved by several orders of magnitude when compared to current digital computers. In the previous term, we have investigated the fundamental properties that allow an ECL to behave like a reservoir computer and used to this knowledge to determine optimum operating points[3]. In the future, we will investigate to what extent more complex architectures can provide improvement of the RC efficiency. In particular, we will investigate the possibility of multi-tasking and bring in some concepts from the field of deep learning, to help the RC self-determine the features of interest in the data it has to process.

- ***Sensing***

The use of the laser diode itself as a substitute for the photodetector in a CD/DVD reader illustrates the potential of lasers subjected to external optical feedback to serve as detectors[4]. We will further explore the potential of laser diodes to act as simple and effective sensors, in particular in the context of biofilms.

- ***Optoelectonic oscillators and frequency combs***

We have successfully demonstrated a multi-GHz tunable optoelectronic oscillator[5] that does not make use of a fast photodetector. Despite the interest of this device, its stability still needs improvement. We will work on this aspect in the future term. In addition, some periodic regimes of the optoelectronic oscillator, a passive mode locking phenomenon is observed that leads to generation of optical frequency combs, which are useful in many applications including WDM. We will investigate the potential of an ECL to be a compact source of optical frequency combs.

- ***Physical-layer security***

Multi-GHz chaotic optical signals generated by ECLs are good sources of entropy to use for the generation of random bits are at high rates that are needed in cryptographic applications and in some kinds of intensive numerical simulations (e.g. Monte-Carlo). We plan to investigate to what extent a chaotic ECL can be considered as a *true* source of random numbers, to determine efficient randomness extractors and to determine the achievable bit rates.

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[3] M.J. Wishon, A. Locquet, C.Y. Chang, D. Choi, and D.S. Citrin, "Evaluating Fundamental Properties of a Photonic Reservoir Computer", submitted to Nature Comm (2017), (Under Review)

[4] M.J. Wishon, A. Locquet, G. Mourozeau, D. Choi, Sreejith KR, A.A. Sahai, and D.S. Citrin, "Reading bits on a CD-ROM without a photodiode", submitted to IET Opto, (2017), (Under Review).

[5] Tunable X-band optoelectronic oscillators based on external-cavity semiconductor lasers, C. Y. Chang, M. J. Wishon, D. Choi, A. Locquet, K. Merghem, A. Martinez, F. Lelarget, A. Ramdane, D. S. Citrin. *IEEE J. Quant. Electron*. (under review).

- ***Compressive sensing***

Compressive sensing (CS) is a technique to sample a sparse signal below the Nyquist-Shannon limit, yet still enabling its reconstruction. As such, CS permits an extremely parsimonious way to store and transmit large and important classes of signals and images that would be far more data intensive should they be sampled following the prescription of the Nyquist-Shannon theorem. We have used the optical signals generated from a chaotic ECL to construct the sensing matrix that is employed to compress a sparse signal. The chaotic time series produced having their relevant dynamics on the 100 ps timescale, our results open the way to ultrahigh-speed compression of sparse signals[6]. In the future term, we will work on a fully real-time experimental implementation of the compressive sensing approach we have proposed.

Involved peoples

Coordinator: Alexandre Locquet
Permanent members: David Citrin, Alexandre Locquet, Matthieu Bloch, Yanne Chembo
Associate members: Damien Rontani (LMOPS), Nicolas Marsal (LMOPS)

A – 2 THz science and technology

Strategy

Terahertz (THz) techniques are of great interest for subsurface investigation of a range of dielectric (nonconducting) materials, including coated materials, ceramics, glasses, polymers, composites, wood, paper, textiles and biomedical materials, to name a few. In addition, near-surface investigation of conducting materials is also possible. This includes coatings (e.g., paint, polymer, oil, oxide) on metals as well as changes in the reflection coefficient of conducting materials due to near-surface defect formation (e.g., metals, carbon-fibre composites).

THz approaches in some contexts may provide advantages over or used in conjunction with alternative approaches, such as x-ray imaging or tomography and ultrasonic imaging. X-ray techniques are useful to provide nano- and larger-scale information, but are associated with significant health risks. They also may be ineffective in dealing with materials and structures in which the contrast is associated with small-atomic-number elements or with various materials with close atomic numbers. Ultrasonic imaging may also provide poor contrast in cases where there is little acoustical impedance mismatch between materials or where the materials are scattering or absorbing at the high frequencies needed to obtain high spatial resolution. In addition, most ultrasonic implementations are quite narrowband.

Our THz laboratory is centered on a Teraview Spectra 3000 that provides picosecond THz pulses at a ~100 MHz repletion rate. These short pulses provide a spectral bandwidth from ~100 GHz to 4 THz. By monitoring position-dependent changes in the reflected or transmitted THz signal, we can build up an image of the material utilizing various contrast mechanisms. For example, in the time domain in a stratified medium, due to the Fresnel coefficient associated with refractive-index variations between the layers, the detected signal will be composed of various time-delayed echoes that are detected and then disentangled to identify layer thicknesses and refractive indices. Using advanced signal-processing techniques, we can obtain in some cases layer-thickness estimates down to ~20 mm. Such thicknesses are well below the expected resolution based on the available bandwidth; however, in cases where we have physical knowledge of the system (of the layers and their order), we can write down a mathematical model of the THz impulse response function of the system and in essence fill in portions of the transfer function in the frequency domain where we have poor (or even no) data, leading to our ability to characterize such thin layers. In fact, one of our laboratory's specific strength is our state-of-the-art ability to extract as much information as possible from our detected signals, whereas many competing laboratories settle for the raw detected signal in which bandwidth and other limitation prohibit the direct extraction of such fine-scaled information. In addition, in the future term, we will look into alternative sources and detectors that could further improve the imaging capability.

The sequel of this section discusses anticipated areas of concentration with regard to our effort in THz imaging for nondestructive testing.

[6] D. Rontani, D. Choi, C.Y. Chang, A. Locquet, and D. S. Citrin, "Compressive Sensing with Optical Chaos", Sci. Rep. 6, 35206 (2016).

Topics

- ***Nondestructive testing of materials and structures***

We have already begun work on THz reflective imaging of polymer-coated steel in collaboration with Arcelor Mittal. THz imaging was shown by us to be effective in identifying various defects in a sample subjected to surface scratching and accelerated aging[7,8,9,10]. While the steel substrate is conductive, and thus highly reflective, the coating and corrosion is transmissive to THz radiation. Thus, by analyzing the time-domain reflected signals (Fig. 1) using THz frequency-wavelet deconvolution in conjunction with de-noising techniques, we were able to identify sub-coating corrosion and delamination of the coating from the steel substrate. Such information is of great importance, as THz techniques may provide information on sub-coating failure before such failure becomes visually evident. In some cases early remediation may halt further degradation. Applications include automotive, aerospace, and civil engineering.

In preliminary work we have adapted autoregressive deconvolution techniques to characterize coating thicknesses on steel down to tens of microns in thickness—translated to the frequency domain, out to about 80 THz. Such thicknesses are far thinner than one might expect possible due to the bandwidth (100 GHz to 3 THz) of our apparatus. This apparent paradox is resolved by understanding that using our knowledge of the layer structure in the sample (but not the layer thicknesses), we can construct a model for the expected reflected THz signal. Autoregressive deconvolution uses that model and extends the detected signal out to frequencies outside the instrument bandwidth using our model. As such, this technique can be classified as providing super-resolution depth imaging.

Our objectives are:

(1) Resolve optically thin multilayer coatings on metals with THz reflective imaging and deconvolution including measuring refractive indices of the various layers.

(2) Investigate uniformity and failure modes in such coatings, such as delamination, blistering, and sub-coating corrosion.

(3) 3D quantitative imaging of the polymer-coated steel with THz reflective imaging.

We will pursue our efforts using autoregressive deconvolution but for optically thin multilayer coatings, as are increasingly used in the automotive industry. Layer optical thicknesses are determined by time delays between peaks in the deconvolved impulse response function while refractive indices can be extracted from the relative amplitude of the various peaks. Combining this information gives the physical thicknesses of layer.

Obtaining such super-resolution information in a multilayer system again requires some knowledge of the system, but we expect that directly applying the THz autoregressive deconvolution technique will be too demanding for the approach. We have therefore recently obtained a flexible stage enabling angular control with goniometer capability to also include angle dependent measurements. Our estimates indicate that such rich data will provide super-resolution depth characterization in optically thin multilayer samples.

In addition to multilayer painted steel, the technique will be of use for a range of applications. Polymer-coated steel frequently ~10 mm incorporates primer and/or oxide layers to suppress corrosion and to enhance coating adhesion to the substrate. In addition, we have been conducting discussions with an airline that has interest in characterizing thermal-barrier coatings on turbine blades. Such coatings are often multilayer coatings involving various ceramics (or nominally the same ceramic with microstructure structure varying with depth) and metal-ceramics. We aim to apply these techniques to these structures. Other materials of interest include coated carbon-fiber composites and coated carbon-

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[7] J. Dong, A. Locquet, D. S. Citrin,"Terahertz Quantitative Nondestructive Evaluation of Failure Modes in Polymer-Coated Steel", IEEE Journal of Selected Topics in Quantum Electronics 23(4), 8044207 (2017).

[8] J. Dong, X. Wu, A. Locquet, D. S. Citrin,"Terahertz Super-resolution Stratigraphic Characterization of Multi-layered structures using sparse deconvolution", to appear in IEEE transactions on Terahertz Science and Technology (2017).

[9] J. Dong, A. Locquet, D. S. Citrin, "Terahertz Reflective Imaging of Damage Mechanisms in the Coating on Metal Substrate", IRMMW-THZ 2016, Copenhagen, Denmark (2016).

[10] J. Dong, A. Locquet, D. S. Citrin, "3D Quantitative Damage Characterization in the Coating of a Metal Substrate with Terahertz Waves", QNDE 2016, Atlanta, GA, USA (2016)

nanotube composites and materials for marine applications.

- ***Machine learning for nondestructive testing of materials and structures***

This project discusses plans to realize reservoir computers (RC) based on external-cavity semiconductor lasers (ECSL) for a number of applications. RCs are a neuromorphically inspired computing approach that relies on a network of nonlinear nodes with random couplings. Unlike the better-known neural nets, RCs rely on the transient response of the system. One of the drawbacks of conventional neural nets is the lengthy training process; RCs frequently exhibit dramatically shorter training for similar tasks. That is because training of a neural net requires the neural net to change over time with training, while for the RC, training is a purely mathematical process.

RCs are a type of deep-learning approach. Broadly speaking, deep learning refers to neuromorphic computers in a net-like topology with an input layer, and output layer, and many layers (thus the deep) in between.

While RCs as initially conceptualized consist of a random network of nonlinear nodes, it has been shown that an ECSL with a long feedback loop is equivalent to certain classes of RCs. We have recently carried out work quantitatively analyzing performance based on a realized ECSL-based RC and have demonstrated state-of-the-art optimized spoken digit recognition[11] .

Pattern recognition (often in the context of speech) is a common application of ECSL-based RCs. That is, ECSL-based RCs naturally handle time series (one-dimensional input since they have one input node). More generally, pattern recognition in multidimensional data sets (THz images are three dimensional: a two-dimensional array of pixels, and the third dimension is the time delay in the detected signal at each pixel) is also of interest. Various approaches exist to turn multidimensional data into one dimensional data, ranging from concatenating rows/columns to taking various projections or slices (motivated by tomography). Other approaches for ECSL-based RC include machines built from more than one optically coupled ECSL.

The objectives are:

(1) Identify defects in images from various nondestructive testing (NDT) modalities using our ECSL-based RC.

(2) Focusing the approach on THz imaging of damage in fibre composites.

Machine learning is of great interest across the board in automating various NDT techniques. We have acquired a set of x-ray images of weld joints from an airline NDT facility. The metal part in question is built up using welding as wear occurs, but following welding, it is necessary to ensure that there are no micro-cracks or pores present. Two-dimensional x-ray imaging is typically carried out and a human operator is needed to identify potential flaws. The facility has committed to providing a large image archive to us for RC training.

The initial approach will be to concatenate rows/columns of pixels to obtain one-dimensional data streams. Defects if present will thus be associated with correlations at the row/column length and will thus be part of the defect-identification process. The RC will be trained on a set of selected images containing or not containing a limited type of defect for our first attempts. Later work will exploit images containing various types of defects.

The advantage of working with these x-ray images—beyond the clear interest in automating defect identification for this application—is to acquire experience for defect identification in fibre composites and other materials in our x-ray images. These are three-dimensional datasets, as pointed out above, and thus will present a significantly more involved task. To assist in our work, we also plan to work with Prof Pradalier to devise appropriate image processing approaches to precondition our datasets to facilitate efficient RC-based defect identification.

- ***THz imaging of cultural heritage***

Terahertz (THz) techniques have proven to be an attractive technique for the subsurface exploration of cultural heritage, including paintings on canvas, paintings on wood, metal artifacts, ceramics, stone, wood, paper, parchment, vellum, and textiles. THz imaging is nondestructive and noncontact, and presents no known health risks. While THz imaging has been

[11] M.J. Wishon, A. Locquet, C.Y. Chang, D. Choi, and D.S. Citrin, "Optimized photonic reservoir computer," Nature Commun., submitted

applied to a wide range of cultural artifacts, we focus here on paintings on various supports.

While there are various techniques to produce a painting (such as with a pallet knife), the majority of techniques involve the successive application of multiple layers of paint. For example, a gesso layer might be applied to regularize the support (perhaps a wood panel), followed by an overall dark ground, with successive applications of lighter colors for the face, torso, drapery, and finishing with the hands and facial features. Various washes and varnish might finally be applied over the entire painting or specific areas. These paint layers may be as thin as tens of microns or as thick as several millimeters depending on type of paint, application technique, and style. It is not well explored, but various coatings of paint produce interfaces with dielectric discontinuity, and thus Fresnel coefficients that result in echo-like signals when subjected to an ultrafast THz pulse. With a knowledge of the refractive index of the paint, time delays between the echoes provide information on the thickness of various applications of paint. Time-domain THz imaging, therefore, can provide important information on the process by which paintings were produced, can reveal underdrawings, revisions, and restorations.

The objectives are:

(1) Apply advanced signal processing approaches for super-resolution stratigraphic analysis of paintings with thin layers (~20-100 um) typical for pre-20th century paintings on canvas and wood panels.

(2) Use THz imaging in conjunction with multispectral imaging and other techniques to provide a picture of cultural artifacts greater than the sum of its parts.

(3) Maintain an activity related to other types of cultural artifacts, including but not limited to fresco, ceramics, manuscripts, marquetry, cloissoné, enamels.

References [12,13,14] provide a case study of the application of THz imaging in conjunction with multispectral imaging to provide detailed information about the build-up of paint in a mid-20th century oil painting on paperboard. In addition, THz techniques specifically provide stratigraphic information (the alternative is to take microscope sections—a destructive technique) as well as have revealed inclusions tentatively identified as oil or biological material in the paperboard support.

We are currently working on three paintings on load from Musée de La Cour d'Or (Metz), including at 17th century oil on canvas, a 19th century oil on canvas and a 12th century tempura on wood panel. Our results are most extensive for the first two paintings. Preliminary results reveal the stratigraphic structure of the paintings showing up to five applications of paint. In particular, the 17th century painting shows a region in the background with an anomalous number paint applications, we have tentatively identified as a restoration. We have carried out multispectral imaging with Profilocolore srl (Italy) and are working on correlating and analysing the images.

We plan to start by using these paintings as test cases for our more advanced signal-processing techniques, including autoregressive deconvolution. While some of the paint layers are barely resolved in our past analysis, autoregressive deconvolution has been adapted by us specifically for characterizing optically thin layers in multilayered structures.

The 12th century wood-panel painting also provides a demanding test for our signal-processing approaches. Not only are the paint layers thin—they are in some cases heavily abraded and overall closer to washes—but the surface morphology of the wood panel is uneven and further roughened by exposure to fluctuations in temperature and humidity and past infestation by insects. We also plan to use the angle-control/goniometer stage to assist in adjusting the imaging geometry to optimize signals (ensure a specular geometry at all positions on the surface).

[12] J. Dong, J. Bianca Jackson, M. Melis, D.Giovannacci, G. C. Walker, A. Locquet, J.W. Bowen, and D. S. Citrin, "Terahertz Frequency-Wavelet Domain Deconvolution for Stratigraphic and Subsurface Investigation of Art Painting", Optics Express 24, 26972 (2016).

[13] J. Bianca Jackson, M. Melis, J. Dong, D. Giovannacci, G. Walker, A. Locquet, J. Bowen, D. S. Citrin, "Comparative Study of Mid-20th C. Art Using THz and X-ray Imaging", IRMMW-THZ 2016, Copenhagen, Denmark (2016).

[14] M. Melis, J. Dong, J. Bianca Jackson, D. Giovannacci, D. S. Citrin, A. Locquet, J. Bowen, V. Detalle, and G. Rizza, "Non-invasive and innovative analysis of an Ausonio Tanda Painting Using Multiple Band-Multiple Technology Approach in the Bands of THz, NIR, Visible, UV, and X-Ray", 5th EOS Topical Meeting on THz Science, Pecs, Hungary (2016).

The research plans above involve specific objects; however, by working on these we plan to devise methodologies that are hardly available in this sphere, and then to apply them to more significant objects in the future.

Involved peoples

Coordinators: David Citrin and Alexandre Locquet
Permanent members: David Citrin, Alexandre Locquet
Associate members: Germano Montemezzani (LMOPS), Nicolas Marsal (LMOPS)

B – Smart Materials

B – 1 New materials and nanostructures for photonics and electronics

Strategy

The most recent and significant developments in optoelectronics and electronics are mostly related to advances in the crystal growth of semiconductor heterostructures. The outcomes of these breakthroughs have been successfully demonstrated and have yielded understanding of the subjects beyond quantum phenomena. Furthermore, they have given rise to tremendous industrial growth and replaced several conventional systems.

GaN related alloys have been recognized as among the most promising materials for optical and electronic devices in the short-wavelength region because of their wide and direct bandgaps, enabling strong optical direct transition.

The wide direct bandgap III-N based alloy system has excellent properties for device applications. It is the only III-V material system covering light emission below the green wavelength (520 nm) and the only one covering the solar blind wavelength (240 nm<λ<280 nm). This material is suitable not only for light emitting source but also for high-temperature electronic applications. III-nitrides also have the requisite structural chemical and thermal stability necessary for high temperature and harsh environment applications. They have high electron saturated drift velocity ($3x10^7$ cm/s for GaN) and high breakdown fields (~3 MV/cm for GaN) that can be exploited in high power, high speed and high voltage electronic devices such as transistors or thyristors.

The research and development of gallium nitride (GaN) have reached a stage where several devices (e.g. LEDs, diodes) have been commercialized. Several other devices are on the verge of commercialization. After the major breakthroughs and successful commercialization of GaN based LEDs, the development of other devices based on these materials has followed an accelerated course, prime examples of which being deep UV sources and detectors, high power electronic (inverters, rectifiers...), sensors and harvesting energy.
This project aims to develop new materials and structures for new generation of photonic and electronic devices and more specifically deep UV

sources and detectors, sensors and harvesting energy. The area of application covers in particularly the particularly the energy, environment and biomedical.

Topics

- ***New materials based on boron semiconductor***

Boron nitride (BN) and its alloys have emerged as an important multifunctional material system. From one hand, the boron incorporation in GaN allows the tuning of the electrical resistivity of $B_xGa_{1-x}N$ by orders of magnitude with less than 1 % of B. It can be thus used to compensate for the residual doping. The boron incorporation in AlN allows also to strongly modify the refractive index, which is useful for the realization of thin Bragg mirror in the UV range for instance. We will continue the exploration of these new alloys.

On the other hand, boron nitride has emerged as an important multifunctional material system, which may find applications in both optoelectronics in the yet to be explored deep ultraviolet (UV-C) region (100 - 290 nm), as well as in microelectronics as novel high speed and high power transistors for high temperature and harsh environments.

Analogous and complementary to graphene, the two dimensional (2D) atomic layers of h-BN are very interesting from the perspectives of both basic science and application. It is to be noticed that thin h-BN layer can be used as sacrificial layers for the lift-off and transfer of III-N based structures on host substrates. Furthermore, low dimensional BN systems are biocompatible, easily functionalized, and exhibit rich, reliable and superior physical properties in comparison with carbon nanotubes (CNTs).

In spite of its great potential, the BN system is the least investigated among the III-Nitrides. Moreover, progress has been slower than the desired because the growth of high crystalline quality BN and its alloys with high crystalline quality have proved challenging to date.

This research proposal focuses on the growth of BN and its alloys with other semiconductors using a state-of-the-art Metal Organic Vapor Phase Epitaxy (MOVPE) facility. Fundamental properties of this unexplored BN system will be investigated further and exploited for next generation electronic and photonic devices.

- ***Simulation of devices with new III-N materials and nanostructures***

This project seeks to put in place a chain of numerical simulation tools to facilitate scientific understanding, improve the quality of devices, and to multiply external scientific and economic impact in the area of III-N devices with new materials and nanostructures.

This project will incorporate the materials parameter results from UMI topic B-3, which deals with growth of nanostructures and simulation of materials properties into device simulations.

This project will help create a virtuous circle of simulation, design, and experiments for the development of excellent device performance. For this project, the UMI is well positioned with respect to laboratory equipment.

A computing cluster and several high power workstations were added in Nov. 2015 with ample computational power for performing this work and a range of commercial and in-house software ranging from the atomic, nano, and micro scales is in use.

- ***Deep UV emitting sources***

Recent progress in highly sensitive optical transducers has led to the development of optical sensors of chemicals and bio-molecules, with applications in diverse fields including clinical diagnosis, bio-molecular engineering, drug design, environmental control, and the food industry.

Along with visible and IR spectroscopy, UV spectroscopy is among many techniques used for such chemical and biochemical sensing and can routinely qualitatively determine the presence of elements and organic compounds. However, the primary limitation of current UV optical sensors is the existing sources of UV light, which lack of robustness, compactness, energy-efficiency, and are expensive. Replacement of the wide-spectrum deuterium-halogen or filtered narrow-band mercury discharge lamps, which are currently the most widely used UV light sources, would be extremely attractive.

The objectives of this project is to address this need by developing boron based semiconductors, and using their unique properties to develop efficient vertical cavity surface-emitting lasers (VCSELs) operating in the deep ultraviolet (UV) (<300 nm).

- ***Gas sensors based on wide bandgap semiconductors.***

There is a critical need to develop novel, more sensitive and reliable technologies for biological detection. Already, the conducting 2DEG channel of AlGaN/GaN, which is very close to the surface, was found to be extremely sensitive to adsorption of analytes. AlGaN/GaN HEMT sensors have been used for detecting gases by the modification of the surface (with proper functionalization) in the gate region of the HEMT.

This electrical detection technique is simple, fast, and convenient. The detecting signal from the gate is amplified through the drain-source current and enabling greatly increased performance in sensor applications. Still there are some critical issues with these AlGaN/GaN HEMT devices: high temperature packaging and surface functionalization layers. Both these issues will be addressed in the frame of a new ANR project (CLEANING) started in November 2015.

This project is under the framework of the OpenLab that we created in 2011 with the company Peugeot PSA one of the main car maker in France. The goal is to develop gas sensors for NO, NO_2, and NH_3 and to develop and test a prototype for use in diesel engine anti-pollution systems.

- ***Neutron detection***

To overcome the problems faced by ^{3}He tubes and proportional counter type devices, several solid-state neutron detectors were developed recently. The ^{10}B isotope has a capture cross-section of 3840 b for thermal neutrons (with 0.025 eV energy), which are several orders of magnitude larger than those of most isotopes. When a ^{10}B atom captures a neutron, it undergoes nuclear reaction creating alpha and Li particles losing their energy within the host material itself, generating electron hole pairs which can be collected as signals.

Depending on the host material the neutron conversion may be indirect or direct. The indirect conversion process has number of process complexity and tradeoffs, which can be avoided by the development of semiconducting ^{10}B containing material. This will result in neutron conversion and electron-hole collection within one material. h-BN is an excellent candidate for this purpose.

This project is under the framework of a Ganex Labex project and in the frame of an international ANR project (application in 2017) with the Nagoya University (Prof. H. Amano).

- ***InGaN nanopyramids-based LEDs and photovoltaïcs***

Demand for photovoltaics are rapidly increasing as the need for renewable, environmentally friendly sources of energy grows more acute. A high-efficiency, low-cost, environmentally friendly solution can eventually be found in the $In_{1-x}Ga_xN$ materials system, which possess a bandgap between 0.7 eV and 3.4 eV that can be tuned by varying the gallium content. Thus InGaN multi-junction devices are predicted to be able to achieve an efficiency of >70%.

To date, single-junction devices have been grown on sapphire. This project seeks to produce demonstrations of InGaN nano-pyramids for photovoltaic or LED array devices on inexpensive substrates and to measure and understand their fundamental physical properties.

The key innovation in this work will be the use of the selective area growth at the nanoscale (NSAG) that will greatly reduce dislocation density and thus allow for the growth of high quality InGaN on different substrates such as sapphire and silicon. This project is under the framework of a CEATECH project.

- ***Power electronics***

Recent progress in GaN based power electronic devices has been remarkable. While lateral GaN devices (up to 600V) have entered into the medium power conversion market, vertical GaN devices are getting more research attention to provide solutions for the high power market.

We will work in this direction. For that, we will use selective area growth (SAG) to grow highly doped drain and source micron size GaN regions. This should help decreasing the contact resistance of the ohmic contacts. SAG of GaN p++ will also be explored for lateral normally-off HEMT operation.

We will also explore the growth of HEMT structure on 2D h-BN for the lift-off and report on silicon wafer.

Involved peoples

Coordinator: Abadallah Ougazzaden
Permanent members: Abdallah Ougazzaden, Jean Paul Salvestrini, Paul Voss, Suresh Sundaram

Associate members: Thierry Aubert (LMOPS), Alain Maillard (LMOPS), Bertrand Boussert (GTL)

B – 2 Materials by Design and Advanced Manufacturing

Strategy

Our objective is to develop cutting edge research activities in strategic technological areas including Smart Materials and to promote local, national and international collaborations and also partnership with industry. Two primary focus of interest build on the existing core strengths existing at Georgia Tech Lorraine are considered:

- Lightweight automotive components,
- Nanoselective area growth in optoelectronic semiconductors.

Existing core strengths lay on the areas of multiscale modelling, materials design, epitaxial growth of advanced thin films for energy applications, multiscale characterization, and data sciences.

Topics

- ***Lightweight automotive components.***

This project aims to address the critical gaps existing between the available knowledge in material science and mechanical engineering and the design of innovative value products for automotive enterprises. Its objectives are to build an integrated approach from ab-initio to forming simulation exploiting

- multiscale modeling
- innovative high throughput experimental strategies
- Accomplishing data-driven highly efficient scale-bridging
- systems approach for managing uncertainty
- Bringing together expertise using e-collaborations

This project linking Structure / Property-Processing Relationships in Materials will help to leverage existing strong relationships at Georgia Tech Lorraine with industry partners in the automotive sector and will contributes in the "Materials and Processes Open Lab" that was established in 2011 on Georgia Tech Lorraine's campus by the French car manufacturer PSA-Peugeot Citroen.

Special attention will be given to phase transformation for the design of high performance composite materials taking advantage of the high intrinsic strength presented by nanowires (up to 40 GPa with an 8% elastic strain). To overcome the strength limitation due to the occurrence of early delamination cracks between ultra-high strength reinforcement and matrix having standard strength property, the use of coated particles having an intermediate adaptive layer will be investigated and shape memory alloys are good candidates for this layer.

Development of in deep analysis to understand and model mechanisms acting at this scale will be considered through multiscale analysis of the martensitic transformation by nano-indentation and development of new advanced materials like High Entropy Alloys using a material by design approach. Macro indentation analysis will be also developed for material characterization of functionally graded materials produced by additive manufacturing.

Development of synergies between experiments and simulations for accurate prediction of microstructure evolution and development of data-driven models will be major objectives in this project. Hiring of new faculties having strong background in these fields will be a priority.

- ***Nanoselective area growth in optoelectronic semiconductors.***

This project will benefit from the strong expertise hold by the UMI in the field of epitaxial growth of advanced thin films for energy applications and from the existence of the Lafayette Institute. Lattice mismatch and induced crystal defects are very detrimental for the performance and the reliability of such advanced thin film. As for high performance composite an elastic strain engineering approach will be considered to overcome these problems and allows the development of innovative products.

The thermoelastic martensitic phase transformation is again a good candidate for the development of solutions based on lattice strain matching concept. The large reversible deformation exhibits by shape memory alloys may induce an elastic strain field avoiding lattice mismatch and defect generation. In addition, recent publications have shown that elastic strain engineering may also be used for turning physical properties of materials such as electronic (bandgap change [15] [16]), optical, magnetic and photonic by controlling the elastic strain field. This could open the development of a large range of products for the Lafayette Institute. Close collaboration between, material science, optoelectronics and mechanical engineering is necessary to achieve such development and Georgia Tech Lorraine is the right place for that.

Since the seminal paper by Novoselov and Geim in 2004[17], two-dimensional materials receive an ever growing attention due to their true potential for advanced technological application[18]. Exciting challenges, like continuing downscaling of digital electronic devices in accordance with Moore's law and the development or extremely low energy electronic components that can be powered by energy harvested from the environment, become now almost close to hand. The most highly studied two-dimensional material is graphene. But handicaps of gapless graphene-based electronic devices have recently motivated research efforts towards the study of 2D semiconductors presenting an intrinsic bandgap. Two-dimensional crystal of transition-metal dichalcogenides (TMDs), are now a primary focus of many researchers[19].

The UMI has developed its own custom NEGF solver that takes into account electronic, optical and phonon contributions to electron transport in this kind of nanostructure. that the electronic band structure of these materials is strongly affected by interlayer coupling. Heterostructure resulting from a combination of TMD materials with other 2D materials like graphene or h-BN enable flexible engineering of electronic and phonon properties [20]. That is now called straintronics appear to promise a wide range of applications.

Topological defects such as dislocations and grain boundaries, altering mechanical properties, pose great challenges for atomistic and molecular dynamics simulation and it is of first importance to develop thermodynamics based continuum models to capture the behavior of two dimensional systems.

Uniaxial, biaxial, localized, first investigations show the stress state is an important player, but these preliminary results are obtained on small samples (flakes) and with loading conditions (micro-beam bending) far from those available in scalable electronic or optoelectronic devices. Close collaboration between electrical and mechanical engineering is required to tackle this problem and in fact a significant amount of scientific papers about this topic are co-authored by scientists belonging to these departments.

The UMI is well positioned with respect to laboratory equipment. A computing cluster and several high power workstations were added in Nov. 2015 with ample computational power for performing this work. Georgia Tech Lorraine, which hosts the CNRS-Georgia Tech UMI and the Institute Lafayette appears to be the right place to do it.

Involved peoples

Coordinator: Etienne Patoor
Permanent members: Etienne Patoor, Paul Voss
Associate members: Stéphane Berbenni (LEM3), Surya Kalidindi (GIT), Lazlo Toth (LEM3), Mostafa Dahia (LEM3), Jean Sébastien Lecomte (LEM3)

B – 3 Multi-Scale Non-Destructive Evaluation of Materials

Strategy

In our modern economy, new materials and new use of materials are constantly under development. It is very important during the development, fabrication and use of these materials to be equipped with the necessary tools for nondestructive inspection. In order to cover the whole range of new materials and applications it is crucial that these techniques are developed for each scale of magnitude and

[15] Optoelectronic crystal of artificial atoms in strain-textured molybdenum disulphide, Hong Li et al., Nature Communication, June 2015, DOI: 10.1038/ncomms8381

[16] Elastic Deformation in 2D van der Waals Heterostructures and their Impact on Optoelectronic Properties: Prediction from a multiscale Computational Approach, Hermant Kumar et al., Nature Scientific reports, June 2015, DOI: 10.1038/srep10872

[17] Novoselov, K. S.; et al., Electric Field Effect in Atomically Thin Carbon Films. Science (Washington, DC, U. S.) 2004, 306, 666–669.

[18] Strain engineering the magnetic states of vacancy-doped monolayer $MoSe_2$, Journal of Alloys and Compounds 635 (2015) 307-313.

[19] Ganesh R. Bhimanapati et al., Recent Advances in Two-Dimensional Materials beyond Graphene, ASC Nano, VOL. 9, NO. 12, 11509–11539 (2015),

[20] Bin Ouyang, Zetian Mi, and Jun Song, Bandgap Transition of 2H Transition Metal Dichalcogenides: Predictive Tuning via Inherent Interface Coupling and Strain, J. Phys. Chem. C (2016), 120, 8927–8935.

range of interest, from the micron level up to the centimeter scale for sensitivity and the meter range scale.

At the UMI different techniques are being used or studied for this purpose, such as ultrasound, TeraHertz (THz), Atomic Force Microscope (AFM) and a Scanning Electron Microscope (SEM), ellipsometry, and X-ray diffraction. Our interests and plans for the next 5 years range from investigation of new semi-conductor materials, investigation of damage in new fibre reinforced composites to large structures such as ships. For these reasons, it is natural for all researchers involved to collaborate with UMI teams at GT Lorraine developing new materials and investigating robotics, but also with other teams working on development of new composites and phenomena of interest in non-destructive evaluation of materials such as for instance nonlinear acoustic effects.

The UMI will position itself as a structure capable of nondestructive evaluation of materials in a vast range of scales. Our strengths are mainly based on our qualifications and good reputation in this field. Some of the techniques are developed and are used in other research, while for instance Ultrasonics is in constant development and has been highlighted recently when GTL organized the 2015 International Congress on Ultrasonics. Also Terahertz research at GTL is gaining reputation due to ongoing developments in applications of the technique. Our weakness is mainly our small number of researchers as compared to other well-known laboratories in the world.

We can clearly see an excellent opportunity in the interdisciplinarity of this project while maintaining the identity of each research field involved in this project. Indeed, while searching for grants to further develop collaborative research, it is perfectly possible to continue to build further on topics within each field separately. Having different research fields so closely located together within GT Lorraine and having such great contacts between the different teams forms an excellent opportunity to collaborate at each level in this multi-scale project.

Threats and risks exist in the case of a lack of funding. Indeed great plans for collaboration exist, but if no grants to hire researchers such as PhD students or post-docs are found the collaboration could be severely hindered and we will have to count on survival strategies for the teams individually.

Our strategy is to continue to develop research within our own research fields while seeking research grants for interdisciplinary research projects of common interest to multiple teams involved, as well as of interest to calls for proposals and to the industry.

Topics

- ***Ultrasonics / Acoustics***

Ultrasound, investigated by the team of Nico Declercq at GT Lorraine, is actually high frequency acoustics and is, at least at amplitudes considered within the UMI, totally nondestructive and exploits and explores mechanical properties of structures, materials, joints, etc. For example, in order to be used as structural parts in next generation cars, a complete characterization of the mechanical behavior and the damage evolution through the whole lifetime of composites must be achieved.

This will be further investigated in collaboration with the team of Fodil Meraghni at ENSAM within the open lab framework with PSA. Research on the use of guided waves for defect detection in metallic plates will be undertaken in collaboration with Arcelor Mital. In the context of non-destructive testing of materials and detection of damage, it is also very important to investigate nonlinear acoustic effects. These investigations have recently commenced and in collaboration with the team of El Mostafa Daya at LEM3. In the near future grant proposals will be submitted in collaboration with the robotics team of Cedric Pradalier at GT Lorraine to develop ultrasonic NDE techniques positioned on a robot with the purpose of the investigation of large structures.

In addition, the ultrasonic team will also focus on materials characterization at the micron and sub-micron level using an acoustic microscope in the framework of collaborative efforts between the ultrasonics team and the team of Abdallah Ougazzaden at GT Lorraine.

- ***Terahertz***

Terahertz is a research topic of the team of David Citrin and Alexandre Locquet. Within the proposed multi-scale NDE research project the collaborative efforts involving THz will mostly be focusing on areas where THz is complimentary to other more established evaluation techniques, such as ultrasound. Indeed, there are materials, such as glass fiber composites where the use of ultrasound is difficult and the use of THz works better than in carbon fibre composites for instance. Also the mapping of paint coatings on metallic parts may in some cases be better with THz than with ultrasound because for coatings one must typically rely on guided wave techniques in ultrasonics which is somewhat harder to interpret in-situ than C-scans using THz waves.

- ***Raman Spectroscopy***

A research group of 4 people from LMOPS laboratory, led by P. Bourson, specialist in Raman spectroscopy and developing both fundamentals studies and Raman optical sensors should be soon involved in common research project with UMI, particularly on material analysis and possible Raman spectroscopy coupling with other characterization techniques, such as ultrasonics or THz.

- ***Robotics***

Robotics is the research topic of the team of Cedric Pradalier. As mentioned in the Ultrasonics section, research projects are sought to investigate large (civil) structures based on ultrasonics equipment mounted on a robot. The goal is to fabricate light-weight autonomous robotic vehicles that will map damage located inside metallic materials used in huge structures such as ships. For this purpose, techniques will be developed to generate ultrasonic waves and to detect and analyze ultrasonic waves based on lightweight existing parts that will be selected and assembled for our purpose.

Involved peoples

Coordinators: N. Declercq
Permanent members: N. Declercq, D. Citrin, A. Locquet, C. Pradalier
Associate members: Germano Montemezzani (LMOPS), Vincent Laude (FEMTO-ST), Abdelkrim Khelif (FEMTO-ST), Mostafa Daya (LEM3), Fodil Meraghni (LEM3).

C – Computer Science

C1 – Network Information Systems

Strategy

The research program that will be developed at the Atlanta mirror site of the UMI will focus on the various applications of nonlinear photonic systems in three distinct but complementary areas: quantum optics, microwave photonics for aerospace engineering, and optical telecommunications. This program will be developed in collaboration with the group of Prof. Matthieu Bloch at GeorgiaTech, and in interaction with the other members of the Georgia Electronic Design Center (GEDC). Research in optoelectronics will also be led in collaboration with Profs. Citrin and Locquet, and will ensure thematic continuity between the Metz and Atlanta sites.

We aim to establish the mirror site as a privileged platform for scientific research and exchanges. Our program of scientific animation for this site will be developed on base of the three points outlined hereafter.

Human resources on the Atlanta site:
Our short-term objective is that there should be at any time at least one postdoctoral researcher and one PhD student in the Atlanta site. As far as postdoctoral fellows are concerned, we aim to establish the UMI as an excellence research center that can enable the young PhD graduates from INSIS research institutes to gain a postdoctoral experience in the US. As far as PhD students are concerned, our objective is to systematically enroll them in a double-PhD program between a French university associated to the UMI and Georgia Tech. This double PhD program, which is quite unique in France, will allow us to attract the best Master students and to strengthen the partnership between Georgia Tech and CNRS through the UMI site of Atlanta.

Scientific partnerships in the Atlanta site:
We aim to strengthen the collaborations between the INSIS research institutes and Georgia Tech through the Atlanta mirror site. In particular, we aim to consolidate the position of the mirror site as a bridge between the INSIS centers and Georgia Tech, beyond the UMI. An important aspect that will contribute to achieve this goal will be the establishment of a program of short visits (from few days to few months) for

researchers, postdoctoral fellows or doctoral students coming from France to the mirror site. These visitors will have the opportunity to collaborate not only with the UMI staff based in Atlanta, but also with the other scientists in Georgia Tech.

Franco-american research projects:
Another key objective of the project in the Atlanta mirror site will be to develop joint activities with Georgia Tech research groups on new topics, namely microwave photonics and optical communications. There is already an expression of interest which will be strengthened within the framework of the participation to joint grant calls, including whenever possible other French and/or American partners.

Topics

- ***Quantum photonics for communication systems***

Kerr-nonlinear whispering-gallery mode resonators host two types of quantum phenomena depending on if they are pumped below or above threshold. When the resonators are pumped below threshold, it generates pairs of entangled photons (also referred to as twin photons) in adjacent modes. These photons lead to the formation of a hyper-parametric fluorescence spectrum. The specific advantage of ultra-high Q resonators is that they permit to obtain important an important flux of such twin photons (> 10^3 s^{-1}) with very small pump powers (< µW). These twin photons are fundamental ingredients for many protocols in quantum information systems. When the resonator is pumped above threshold, the system outputs the so-called Kerr combs, which are characterized by a strong quantum correlation between symmetric modes (signal and idler), thereby leading to the phenomenon of squeezing. Concretely, amplitude noise can become smaller than the quantum limit (shot noise) if one accepts to increase the noise on the phase quadrature (Heisenberg principle). This phenomenology find its principal application in optical metrology.

The objectives of our research program are essentially to develop the best resonators possible for these quantum information applications. Using ultra-high Q whispering gallery mode resonators will guarantee a very long intra-cavity photon lifetime (> 1µs), and therefore, will significantly increase the probability of interaction amongst them. We here wish to develop two distinct research strategies, namely using crystalline resonators ($Q \sim 10^9$ at telecom wavelengths) on the one hand, and using integrated resonators ($Q \sim 10^6$) on the other. In the first case, the objective is to reach record performance levels (twin photon generation at a rate of 10^6/s; squeezing of the order of 10 dB below the quantum noise level).

The second objective is chipscale miniaturization, allowing us to propose constitutive parts of room temperature quantum processors for quantum information systems.

- ***Information theory for quantum communications***

With the purpose of strengthen existing collaborations, we will explore certain theoretical aspects of quantum communications. This theoretical research line will complement the more experimental aspects and will permit to strengthen the synergy with the group of Prof. Matthieu Bloch, while preserving the specificity of the UMI research program.

A particularly promising research topic is the exploration of undetectable quantum communications for which it is possible to provide, under certain hypothesis, the impossibility of detection using any statistical test. This activity will also allow make the connection with the research lead at the UMI on secure communications.

- ***Optical fiber communications***

There is actually a vigorous revival of phase-modulation formats in optical fiber communications, powered by the perspective of ever growing bandwidth capacities, using advanced phase/intensity modulation formats. In ultra-dense wavelength division multiplexing (WDM) systems, it becomes more and more difficult to generate tens of such independent sub-carriers when they have to be controlled carefully and individually. An elegant solution to circumvent simultaneously all these drawbacks is to use the output signal of an optical frequency comb as a multi-wavelength coherent source.

In our case, the comb generator would be an ultra-high Q whispering gallery mode resonator pumped around 1550 nm. This multi-wavelength output (the so-called Kerr comb) will consist in a set of equidistant and phase-correlated spectral lines which will be used as sub-carriers in our coherent communication scheme. This intrinsically nonlinear photonic component is also fully compatible with the paradigm of silicon/crystalline photonics, as well as with the on-going trend of compact full-optical components in lightwave technology, which enable ultra-fast data processing [up/down conversion, (de)modulation, amplification, multiplexing, mixing, etc.].

Two research lines will be the focus of in-depth research: the theoretical modelling of the generation and propagation of optimal combs; and the evaluation of the bit error rate performance during transmission experiments. This research line, which is at the intersection of microwave and optical communication engineering, will also be extended to include microwave photonic systems and optoelectronic oscillators for aerospace engineering.

Involved peoples

Coordinator: Matthieu Bloch
Permanent members: Matthieu Bloch, Yanne Chembo, Steve McLaughlin, Michel Barret

C2 - Robotic for Environment Assessment and Monitoring

Strategy

The robotic group at the UMI 2958 is focused on long-term observation of large-scale environment with complex spatiotemporal dynamic. To this end, it has a recognized expertise on robotics, image processing, machine learning, mechatronic design and most topics required to develop and evaluate robotic and automation systems. This expertise is currently applied in two main area that will be continued in the next five years: on one hand, the use of robotic and automation for natural environments monitoring and the development of autonomous systems for natural environment, and on the other hand on the development of robotic solutions for structure inspection.

The main strength of the robotic groups lies in its well-recognized expertise in France and Europe, its breadth of scientific knowledge covering the complete development chain for robotic systems and creating interdisciplinary opportunities, its network of collaborators and wealth of on-going projects.

However, in its current state, the main weakness of the robotic group is obviously its size: with one permanent faculty at GTL, no support staff and associate-members in related topics with little overlap, the group will be severely limited regarding the scope of projects it can address. A number of opportunities are currently arising with new collaborative projects submitted or in preparation in robotic inspection and automation for environment sciences.

In particular the interdisciplinary nature of the UMI creates daily interaction between scientists from multiple fields, which can lead to research innovation that cannot be done elsewhere. Ultrasonic inspection, analysis of terahertz images, new sensing technologies, machine learning for life and material sciences are examples of the opportunity we expect in the next five years. Associated to the group weakness, the main threat to this activity comes from its human resources: without recruitment it will be extremely difficult to maintain a significant impact on the breadth of topics currently investigated. Additionally, opportunities will have to be left aside by lack of human resources to address them. Similarly, a significant risk for this activity is its reliance on a single faculty at this stage.

Nevertheless, our strategy it to keep developing a strong collaborative and interdisciplinary activity, where the core skills of the team can be used as a catalyser to achieve a high impact despite the small number of UMI researchers currently involved.

Topics

- ***Environment Monitoring:***

Our core research objective is the long-term observation of large-scale environments with complex spatiotemporal dynamic. The main challenges we intend to address are the following:

1) Perception in natural environments is made difficult as a result of appearance being a superimposition of structure, biological state, weather situation and lighting conditions, all with complex and hard-to-predict dynamics, and most observations with a large dynamic range. Furthermore, observation of natural environments over long durations raises interesting but complex questions on change detection, identification of smooth change vs step changes, changes resulting from superimposed phenomenon with different natural frequencies, periodic change detections. A partnership with the Rhin-Meuse Water Agency will be supporting this topic.

2) Large environments also require special care regarding complexity, computing performance or active observation (i.e. observation of a well selected subset of the environment) when a complete observation is not practically feasible. A partnership with Thales will be supporting this activity.

3) Autonomy over long duration in large environments will also require a high-level of adaptation capabilities and learning from experience. This is particularly true for drones in agriculture environment. An Interreg project will initially support this action.

4) Infrastructure Monitoring is the last topic that will be addressed through the use of robust and long-term instrumentation of the road infrastructure.

- ***Interdisciplinary Outreach***

In addition to the core topics mentioned above, we intend to continue a number of on-going interdisciplinary projects and expand them in the next 5 years. In particular the following direction will be explored:

1) Application of automation technologies to Life and Material Sciences. Our approach so far has been to use our strong interdisciplinary network to identify area of low penetration of automation, data science, image processing and robotics and opportunistically propose solutions representing ground-breaking step transitions in the corresponding field. At this stage, this strategy initiated a number of projects on EBSD images, antibiograms, paleo-ecology, ecosystem services... These activities, although apparently very diverse, gather a number of very similar tools that allow us to capitalize on our core skills. So far, we have reached out to scientist outside of the UMI and linked with the Université de Lorraine (UL) and the local scientific ecosystem.

2) Joint development of robotics and sensing for inspection of large structure (NDT/NDE/SHM). We intend to take advantage of the interdisciplinary skills within the UMI to focus sensor development (in particular acoustics) on solution applicable to autonomous robotic systems (size, weight, power requirements) and in parallel, focusing inspection robotics to take advantage of the new sensor development (sensing modality, scale, uncertainty). We also expect to introduce machine learning, state estimation and data science in the tool chain of sensor processing for inspection, especially for defect detection, identification and localization. This activity will exploit the internal collaboration opportunities within the UMI (N. Declerq, J.P. Salvestrini, E. Patoor) and potential outreach to UL/LEM3.

Involved peoples

Coordinator: Cédric Pradalier
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Associate members: Mario Marchetti (LMOPS)

C3 - System Design and Integration

Strategy

Some of today's most compelling societal Grand Challenges are large, complex, multidisciplinary, and multi-scale. They exist at both the system and system-of-systems scale. These problems can be difficult to solve because of fuzzy, changing, or even contradictory requirements, and can occur in application domains including energy, infrastructure, healthcare, aerospace, manufacturing, national security, public policy, etc. The Aerospace Systems Design Lab (ASDL) has been the leading group for conceptual system design and integration, including system of system design, for the past 25 years.

The expertise ASDL has gained in these areas will be utilized to create a research lab that works with the other units within this UMI proposal to provide a coherent approach to connecting these capabilities to enable analysis at large, multi-disciplinary systems-of-systems scales. Computing infrastructure will be leveraged to link models and analytics into virtual test beds, methodologies will be devised for validating models for use in virtual experiments, e.g., for testing of cyber-physical systems. There are two main research focus areas proposed within Multi-Disciplinary System Integration and Analysis: system design and integration and system of system exploration and assessment.

The design of complex systems requires an exploration of the design space to identify feasible configurations that meet the requirements provided for the system in question. Furthermore, specific technologies must be identified and decisions on the appropriate technologies to pursue must be determined. Early in the design process, these types of assessments can be greatly supported and facilitated through high fidelity modeling and simulation environments. However, these models must be calibrated and validated so the results they produce can be trusted by the stakeholders. Therefore, the entire process of system design, testing, and analysis is a coupled simulation-based and hardware testing process.

Physical experimentation has always played a key role in the engineering design lifecycle. However, physical experimentation can be cumbersome, time consuming, and expensive. As systems increase in complexity and are increasingly networked together into system of systems, it is becoming less feasible for physical experimentation to play the same role it has played historically. In addition, modular and collaborative cyber-physical systems require a more integrated approach to design, requiring extensive testing of software implementation with potential hardware concepts.

As computational power continues to increase, higher fidelity modeling and simulation has become more commonplace, and is used more frequently earlier in design to replace or supplement physical testing. However, the creation of validated high-fidelity modeling environments is also not trivial, and many of these models are kept as proprietary information and not available for general use. However, when these models exist and are validated, they can be coupled with a high-performance computing environment to create a virtual testbed which can then be used to better focus prototyping and physical experiments.

This research conducted through the UMI will focus on exploring the design of next generation, complex aircraft concepts, such as a hybrid-electric propulsion aircraft. The design of a hybrid electric aircraft will require integrated propulsion-airframe design starting at the conceptual design level. Furthermore, a hybrid electric configuration will involve complex subsystem design and integration due to power allotment complexities.

Topics

- ***Requirement Setting and Design Space Exploration***

New aircraft systems are designed for a given purpose and to meet a specific set of requirements. These systems can provide incremental performance improvements or fill an extreme void or need in the industry. When these requirements are set, they may not be of the quantitative nature and therefore need to be transformed into measureable metrics for designers to strive for. Once high level performance requirements, or metrics, are set, they need to be mapped to the sub-system and component level. This enables engineers to pinpoint the types of solutions they should be investigating.

System, or metric, decomposition can be achieved through the use of sensitivity analyses. Quantitative sensitivity analyses can be performed if an integrated modeling and simulation environment with a baseline vehicle model exists. Once this model and environment exists, it is exercised to determine the key sub-system and component metrics that greatly impact the requirement metrics provided by stakeholders.

This research will focus on establishing an appropriate modeling environment for advanced concepts, such as a hybrid electric vehicle. Different modeling components will be explored and the final selection will be based on the ability of the resulting environment to capture the appropriate metrics at an acceptable level of fidelity. Once this environment is set, sensitivity analyses will be performed to map the system requirements to lower levels of the system and explore the design space of the vehicle in question.

- ***Technology Modeling and Evaluation***

The ability of new vehicles to meet aggressive performance goals relies on advanced concepts as well as new technologies. Through previous research ASDL has developed a method that focuses on identifying appropriate technologies, analyzing them based on their performance and risk, and down-selecting an appropriate technology portfolio. This method is the Technology Identification, Evaluation, and Selection (TIES) methodology.

The TIES methodology incorporates aspects of the Technology Impact Forecasting (TIF) method, but conducts an exploratory assessment of technologies instead of a normative assessment of potential impacts required to meet a goal. The TIES methodology includes eight steps between problem definition and technology portfolio selection. Once a baseline vehicle is modeled within a quantitative environment, the technologies are modeled.

TIES utilizes a concept called the technology k-factor modeling approach to represent the impacts of the technologies under consideration. Each technology impact, both beneficial and detrimental, are provided in the form of a technology impact matrix (TIM). The technologies are mapped to each of the k-factors with either no impact, a beneficial impact, or a detrimental impact. In addition to technology impacts, the compatibility of technologies must also be considered. The incompatibilities are tracked in a technology compatibility matrix (TCM).

Once all technologies are set in the TCM and TIM, the portfolios are assembled and assessed. A full factorial analysis of all compatible technology portfolios can be assessed if the computational resources are available. Otherwise, a subset of technology portfolios is formulated based upon the information in the TCM. The TIM is utilized to combine the impacts of each technology within a given portfolio to produce an input vector that represents the entire portfolio. The technology portfolios can then be evaluated deterministically or probabilistically by utilizing the selected modeling and simulation environment. After the portfolio alternatives have been analyzed with respect to performance and cost, the final portfolio is selected. Any multi-attribute decision making technique available and appropriate can be utilized, such as a genetic algorithm or technology frontiers. In some cases an overall evaluation criterion may be required, which involves applying importance weights to the performance goals. Furthermore, the robustness of each of the alternative portfolios with respect to different weighting scenarios can be assessed to determine the best overall technology portfolio.

- ***Probabilistic Analysis and Uncertainty Reduction***

New vehicle configurations and technologies under development introduce a lot of uncertainty into performance analyses. Therefore, it is important to incorporate these uncertainties into the design and analysis process of a new system. Technology development decisions should be made in a risk-informed manner to ensure the desired technologies are test-proven and ready for system integration. Experiment planning for developing entities is generally done through heuristic-based approaches and utilize deterministic, technology-level performance assessments and qualitative measures of readiness, such as the existing Technology Readiness Level (TRL) system. The TRL system is a tool for communication across disciplines; however it provides limited information on the risk a technology introduces to a system, and any information it does provide is subjective and qualitative.

Information from quantitative, probabilistic system performance assessments has not previously been synthesized with qualitative readiness assessments for the purpose of technology development experimentation planning. However, a combination of all of this information has the potential to provide the clearest picture of the development status of a single technology, group of technologies, or system, as well as characterization of its predicted performance attributes. This synthesis of information could aid risk-informed technology experiment planning decisions throughout technology and system development. To build upon the TIES methodology, ASDL has also developed a methodology that enables incorporation of specific uncertainty sources into the analysis process and tracks how they are reduced over time as experiments are performed and knowledge is gained. This methodology is called Quantitative Uncertainty Modeling, Management, and Mitigation ($QuantUM^3$).

$QuantUM^3$ provides the means for strategic decision making across all sectors in the presence of uncertainty. Furthermore, it provides a synthesis of information from quantitative performance assessments and technology readiness assessments for strategic decision making purposes. Advanced uncertainty quantification methods are utilized with a physics-based modeling and simulation environment to enable a prioritization of technologies and identification of the type of data an experiment should provide to reduce the uncertainty and overall risk.

Involved peoples

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C4 - System of System Exploration and Assessment

Strategy

The design of complex systems-of-systems (SoS) in the presence of changing requirements, rapidly evolving technologies, an uncertain and often unpredictable operational environment, and a constantly shrinking budget continues to be one of the most challenging design problems faced by engineers. Currently, systems like the National Airspace System (NAS) are becoming more interrelated and interoperable, meaning that the design of the underlying architecture is often more important to operational success than the design of any single system in it. The research we will conduct aims to address these complex interactions and attempt to optimize the system-of-systems at the macro-level.

A key enabler for reduced cost and cycle time is the ability to rapidly analyze the design space; we will explore the use of different methods, such as an architecture-based approach and physics-based modeling enabled approaches. The research will explore using a top-down, capability-based approach to decompose the problem space, create executable operational and system architecture products, use those products to execute modeling and simulation, and finally, pull the information obtained from modeling and simulation into a dynamic, real-time decision making tool.

Topics

- ***System Decomposition***

SoS design requires a complete understanding and description of the operational picture. To create this operational picture a set of hypothetical scenarios is generated and knowledge about previous conflicts is collected to ensure that problems being solved closely mimic those that will be faced by future warfighters. With a set of hypothetical scenarios in hand, the study progresses to attempting to find means of resolving the conflicts in the scenarios.

This is done by articulating a set of mission threads. These mission threads are then decomposed into sets of capability statements. These capability statements are used to define activities that enable their successful completion. Furthermore, all of the potential agents that may be a member of the SoS must be identified. This includes identification of key characteristics, such as vehicle performance details, and potential relationships among the different agents.

- ***Enumeration and Analysis of Alternatives***

Given the complexity of the new architecture, there are billions of possible alternatives in the hyperspace. Not all these alternatives can be quantitatively compared within the practical time limits imposed by the program management. To overcome this issue, a qualitative brain-storming exercise has been previously formulated by ASDL researchers to prioritize and down-select the important requirements and alternatives by feedback from disciplinary experts and program management. This allows the quantitative process of the down-selected alternatives to be much more manageable.

The Interactive Reconfigurable Matrix of Alternatives (IRMA) is a systematic qualitative procedure that is unique to the conceptual design process. The IRMA is a combination of Systems Engineering techniques such as Matrix of Alternatives, Multi-Attributes Decision Making (MADM) and Technique for Ordered Preference by Similarity to Ideal Solutions (TOPSIS). These tools provide a process for functionally decomposing the problem, identifying alternatives and technologies to meet the functions as well as identifying the solutions the meet the top level needs. These tools and processes provide a mechanism for encouraging collaborative communication at the early stages of conceptual design.

- ***Technology Evaluation***

Technology evaluation is an important element in SoS architecture design because future capability needs typically cannot be met with state-of-the-art technologies, thus requiring new technologies. In order to meet the requirements or goals set for a SoS, such as safety requirements when unmanned aircraft systems (UAS) are integrated into the NAS, an optimal set of technologies must be identified and developed. This “portfolio” of enabling technologies, when matured and integrated into future systems, will provide the SoS with the required capabilities.

The creation of this technology portfolio requires sorting through the myriad of possible alternatives and selecting those that are most "useful." To do this, each and every technology must be evaluated. This evaluation must be based on quantitative and objective assessments that measure each technology's impact on subsystem, system, and system-of-system level metrics.

Evaluating technology contributions at the system and system-of-systems level is a difficult and time-consuming process. It requires a transparent and traceable mapping of functions and metrics from system-of-system level all the way down to the system, sub-system, and component levels where the technologies directly affect the functions and metrics. The complexity of this process is increased when the technologies being assessed have not been fully researched or tested.

These "immature" technologies introduce an element of uncertainty into the process because it is nearly impossible to predict their impacts on the functions and corresponding metrics with absolute certainty. The variability of these lower level elements "flow up" and result in corresponding variability in the top level system and system-of-system level functions and metrics. This variability in potential technology impacts drastically increases the risks of the entire acquisition program because if the selected technologies do not mature in time or do not perform as expected, the program will be delayed and go over budget. Such delays cost not only money and time, they could potentially cost lives because the warfighters did not get what they needed on time. Therefore it is imperative that the risks associated with immature technologies be accounted for and minimized, if possible.

- ***Strategic Portfolio Prioritization***

In previous research ASDL formulated the Architecture-based Strategic Portfolio Prioritization (ASP2) as a framework to aid in architecture-based, multi-attribute decision making for complex systems and systems of systems problems. The framework was specifically designed to handle complex systems-of-systems-type problems, where systems are not geographically co-located and require complicated communication networks to relay information among the entities. This application is an evolution of accepted systems engineering and quality engineering methods (i.e., Quality Function Deployment) and incorporates various dynamic aspects to form a portable and powerful decision making environment. The ASP2 Environment balances capability needs with economic and programmatic constraints to aid in selecting a spiral development plan for the development of an architecture.

This plan includes the selection of systems, technologies, services, and standards to be included in each phase of development, as well as consideration of how the operational activities may change as a result of new system or technology.

Involved peoples

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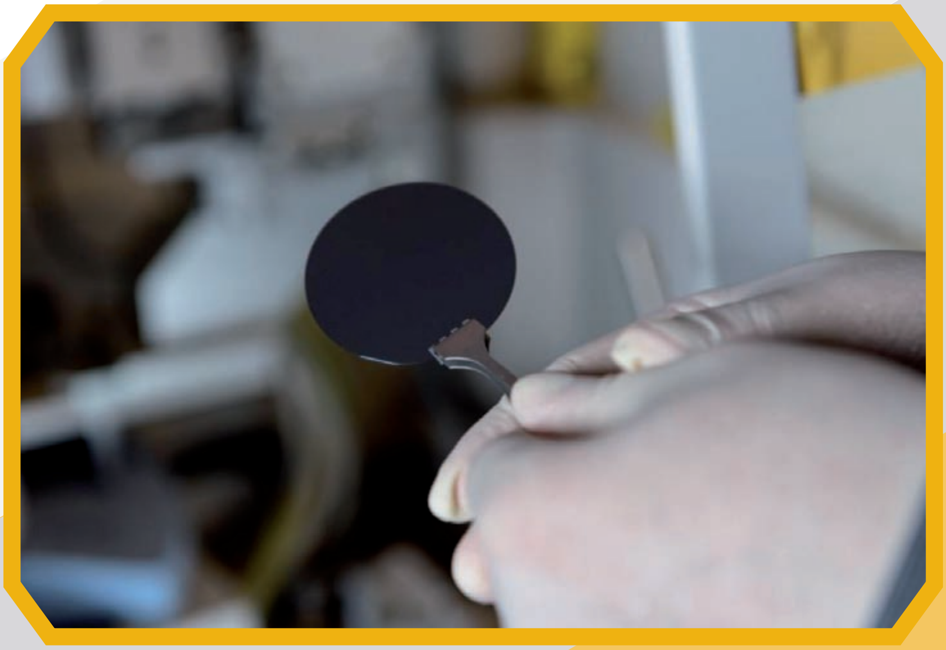

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