Making the most of energy

Dr Alex Yakovlev is employing unconventional approaches to engineer high performance resource-driven computer systems that obtain energy from alternative sources and maximise energy utilisation

As an introduction, what attracts you to the area of electronic systems engineering?

I am attracted to intellectual challenges or human creations that are hidden from the public eye. Electronic system design is often underestimated: it is actually multifaceted, can be full of creativity, and its innovations are paramount for success in developing information and communication technologies. That's what fascinates me.

What is the Holistic Project?

The aim of this project was to investigate new ways of designing electronic systems powered by energy that is scavenged from the environment. We explored new ways of designing micro-generators that tune to their resonant frequencies to extract maximum power from mechanical vibration, new design methods for power conditioning electronics that track the maximum power point and produce regulated voltage to loads, new computational electronics that can operate in a wide range of power modes and supplied voltages, including not fully rectified voltages. We also developed new modelling methods for such mixed, electromechanical and computational systems, and even some computer-aided design tools for exploring optimisation routes in designing energy-harvesting electronics from the holistic perspective.

For those who are unaware, what is energy proportional computing and why would you want to design a system that 'does nothing well'?

Energy-proportional computing is about making computing systems deliver their 'computational yield' in proportion to the energy we put into them. The other side of the energy-proportionality model is to consume energy in proportion to the required level activity or performance. This concept is closely related to the 'idea of doing nothing well'. Indeed, a system must not simply burn electricity if it does not deliver anything useful.

Could you explain the key differences between traditional and energy-modulated systems?

Any system that is engineered for the real world requires two main physical resources – power and time. In traditional systems, power and time references are supplied independently and a large amount of electronics is required to coordinate them to synchronise switching of power levels to switching between clock frequencies in accordance with power levels. But, when the voltage supplied goes down, all the logic gates in our circuit also slow down, usually in proportion to the voltage. To avoid circuit malfunction, we also have to reduce its clock frequency.

But we can build systems to be energy-modulated, allowing a system to 'derive its own timing' directly in accordance with the power level provided.

What is meant by a power-adaptive system?

Power-adaptivity is a property of a system to match its activity rate, or even functionality in a broader sense, to the level of power that is supplied, or to make sure that it does not overheat in certain hotspots. Power-adaptive systems are not just power-efficient.

How would you describe the speed-independent Static Random-Access Memory (SRAM), which you have developed?

SRAM is traditionally the main type of storage in digital computers that contains programmed code and data. Conventional SRAM operates correctly within a narrow band of supply voltages. Speed-independent SRAM has the ability to tolerate fluctuations in voltage supply, using specially-designed 'completion detection' circuitry, which produces acknowledgement signals when the transient processes in the internal elements are finished.

Are you investigating knowledge-transfer routes for your new design paradigms for energy-frugal systems?

We are delivering demos of our speed-independent SRAM and reference-free voltage sensors to various showcase and networking events, promoting our patent of power sensing based on charge-to-digital converter to industry, discussing possible alliances with companies in developing new methods for on-chip sensing for many-core architectures, and studying and exploiting energy-reliability trade-offs in system design.

Have you made any contributions to the field of which you are particularly proud?

The contribution I am most proud of was pioneering and developing the model of Signal Transition Graphs, which has become a de facto standard formal notation and tool for synthesis of controllers and interfaces in multi-synchronous systems on chip and beyond. This and associated methods have a pivotal role in making Petri nets a formal semantic kernel of the new asynchronous system design flow, similar to how finite state machines are perceived in synchronous system design. My methods helped to reduce the cost and complexity of asynchronous design, one of the stumbling blocks to promoting the clockless system design discipline to industrial practice.

An holistic approach to energy usage

Creative approaches to designing energy-modulated systems that are both performant and resourceful are the focus of a Dream Fellowship supported by the **Engineering and Physical Science Research Council**

AS MINIATURISATION CONTINUES and the range of devices controlled by computer chips grows, accompanied by ever more miniaturisation, virtual intelligence is steadily being incorporated into most aspects of everyday life; people are becoming even more dependent on its services. Sustainability is, however, an issue: devices and machines driven by computer chips consume vast energy resources – this applies not just to the vast farms of servers and data processing operations dotted around the world, which can consume a level of energy that would meet the needs of a small city, but also to the collective population of personal devices, such as mobile phones and tablets. Greener and more frugal means of powering computer-based systems are becoming a priority.

Whether megawatts or microwatts are required is determined by the functional requirements of each system; there are systems, for micro-scale applications for example, that consume hardly any energy. But as a general rule, all systems are built to operate with a predetermined energy usage profile; the presumption is that the need is to consistently or exclusively perform at peak. There may be some variations, such as automatic shutdown or computer screen dimming that are designed to conserve energy, but ultimately most systems consume energy even when they are inactive. The need for a more ecologically-aware approach to system design is clear.

Conventionally, systems design methodologies consider functional requirements (the features that the end-user wants) and non-functional requirements (such as performance, resilience, confidentiality, integrity and availability) separately. Over the last few decades, with the decline in costs of storage and decreasing size in components, system design methodologies have developed with the primary goal of delivering functional requirements in the most performant and feature-rich way, without giving much attention to the resources they consume. Most contemporary system architectures therefore take little account of energy management and control issues.

According to Dr Alex Yakovlev of Newcastle University, what is needed is a hybrid that delivers performance and quality of service in both low and high power scenarios. That is, a power-adaptive systems architecture designed to be more resourceful and more resilient at any level of power and able to cope with fluctuations in supply; at the junction of energy supply, system application and usage, the system needs to be elastic in terms of energy. The question is how such a system can be achieved, taking into account a range of scenarios including such applications as prostheses, bionics or high data volume throughput.

Yakovlev recently led one of three themes in a project funded by the Engineering and Physical Science Research Council, in partnership with Imperial College London and the universities of Bristol and Southampton, to define a holistic approach to next-generation energy harvesting electronics.

POWER-ADAPTIVE SYSTEM DESIGN PRINCIPLES

An adaptive system essentially alters its behaviour in response to changes that it senses in its environment and applies rule-based logic to establish patterns within these changes. Energy harvesting systems, for example, need a two-way channel of control and adaptation to evaluate power source changes and determine optimal computational load, so that they schedule tasks according to the power profile of the environment and optimise usage of the power supply available.

For Yakovlev, it is imperative therefore that adaptive systems are designed holistically, taking into account the relationship between computational functionality and power electronics, and maximising computational output per task, while minimising the amount of energy used; for example, mobile computing technology is driven either by battery power or through energy harvesting techniques, so the mobile circuits must be capable of switching between energy modes depending on the level of processing in progress, such as powering up and then adjusting performance according to activity. According to Yakovlev, full characterisation of inputs and outputs, logic, memory and radio frequency loads is a fundamental step to assessing the requirements of such a system. The design process must then consider these in conjunction with the physical components, circuits, system level power sensing and controls, to achieve the balance required.

Yakovlev is convinced that he and his team have found a way to design the hybrid adaptive system, the key being asynchronous – self-timed – logic design. This approach improves efficiency and performance by detecting completion of processing and reducing power leakage intervals to a minimum: "The timing of events will actually be automatically generated inside the system from the elements that will switch slower if the voltage goes down, and it will be smooth, without any malfunctioning because the switching action in the electronics will be modulated by the power," Yakovlev explains.

When power interruptions occur, data loss should be prevented. For this, Yakovlev and team have devised speed-independent Static Random-Access Memory (SRAM). The Speed Independent controller uses completion

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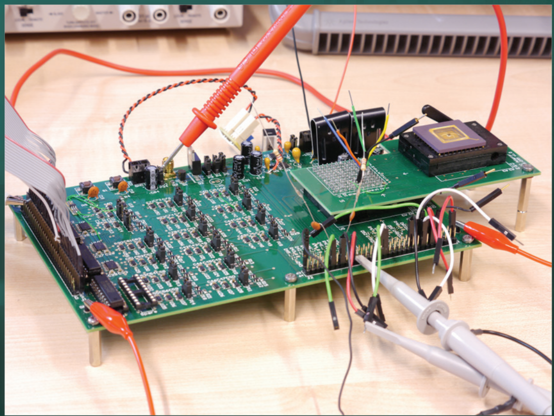
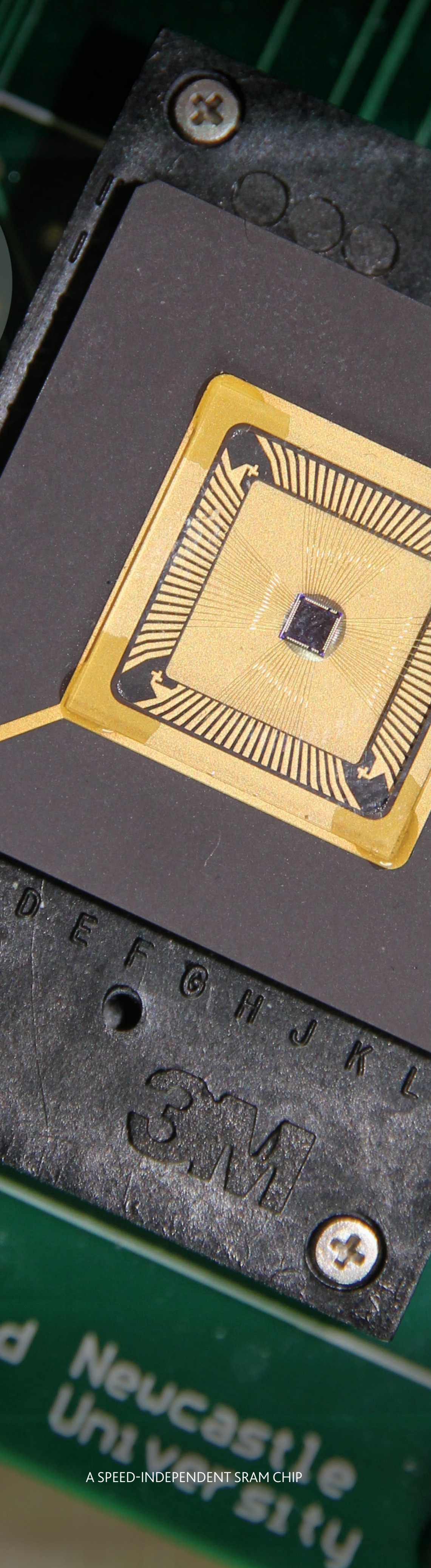
TEST BOARD WITH A FIRST SPEED-INDEPENDENT SRAM CHIP





A SPEED-INDEPENDENT SRAM CHIP

detection in the memory and handshake protocols to manage SRAM functions. The hybrid design also embodies a feature that Yakovlev deems mandatory: voltage sensors that need little or no referencing. "By designing power supply electronics that are aware of the presence of self-timed computational load and, vice versa, by building the logic circuits self-timed and hence resilient to instabilities in the power supply, it was possible to create an entirely new 'breed' of systems able to survive on scarce levels of power and not die," he reflects.

DREAM FELLOWSHIP

Currently undertaking a Dream Fellowship, Yakovlev is exploring further creative solutions to energy-modulated computing. His mission is to identify challenges and formulate research problems for future research projects, and to help to devise new methods and tools for resource-driven system design. The Fellowship has involved active networking with universities and major companies in the electronics industry in the US and Europe.

Yakovlev views the Fellowship as a route to transferring knowledge to industry, as well as to young researchers: "Today is the right time to bring energy-modulation into many industrial spheres in electronics, computing and communications," he reflects. "Applications for such systems will soon be mushrooming in the area of wireless sensors and implanted medical devices, or will be in the category of 'something we don't know that we don't know'!"

Inspiration for this work is drawn from what Yakovlev terms 'real life': the needs of society and directions in electronics-enabled technology. As part of this, he has been reviewing links and synergies between the key areas of information technology and computing: quality of service, usability, cost-efficiency, performance, dependability and interactions with resources. He is now developing an evolutionary roadmap for energy-modulated electronic system design, building on energy characterisation of components and devices of different functionality and nature, interplay between energy and dependability, power constraints and quality of service, using the idea of 'energetic effort' for design criteria and various modelling, meta-modelling and design automation techniques.

Yakovlev is continuing work on system design at the circuit and architectural level, though further work is also needed in terms of theory, models and algorithms to underpin the energy-modulated computing paradigm. He and his team are thus investigating new solutions for on-chip power delivery that exploit the robustness of self-timed circuits to power variations and droops, recently creating Petri net-based models with energy tokens and exploring power management using game theory.

INTELLIGENCE

ENERGY-MODULATED COMPUTING

OBJECTIVES

- To investigate key principles behind energy-modulated computing, such as power-proportionality and power-adaptive system design
- To develop a vision for designing electronic systems that will survive and operate in energy-constrained environments with wide-band power supply
- To investigate the potential for applying self-timed design methods in energy-modulated computing
- To design and test new circuit solutions for logic, memory, sensors and power regulation

KEY COLLABORATORS

Andrey Mokhov; **Delong Shang**; **Danil Sokolov**; **Fei Xia,Terrence Mak**; **Abdullah Baz**; **Reza Ramezani**; **Xuefu Zhang**; **Maxim Rykunov** and **James Docherty**, Newcastle University

FUNDING

Engineering and Physical Sciences Research Council

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PROFESSOR ALEX YAKOVLEV is an electronic and computer systems engineer with an international reputation in self-timed (asynchronous) circuits and systems and use of concurrency models such as Petri nets in digital design. He obtained his PhD from St Petersburg Electrotechnical University in 1982, and DSc from Newcastle University in 2006.

Amongst his recent inventions is a method of self-powered sensing based on charge-to-digital conversion. He has published over 300 journal and conference papers, supervised nearly 30 PhD students and led 25 research projects. He has been awarded the SAgE Faculty Innovator of The Year – 2012 at Newcastle University.