

# MICROELECTRONICS FOR AUTONOMY AND SURVIVAL

Professor Alex Yakovlev, an EPSRC Dream Fellow, talks about building computer systems that will live without batteries, by taking energy from the environment

**I**n our lives we could benefit from the use of electronics systems that are entirely autonomous, i.e. they can extract energy from their environment in order to perform their main functions, namely sense, store, compute and communicate data. There are numerous examples in health and wellbeing, such as implantable pacemakers and hearing aids that could operate without a battery, in civil engineering, e.g. a network of self-powered sensors embedded in the concrete of a road to measure traffic, or 'listening walls' that could extract power from audio waves and perform speech processing.

Our imagination can go far as we could potentially think of autonomous electronics that could be placed on spacecraft to perform remote space exploration, where energy is scavenged from the light of stars or cosmic radiation. The key challenge for all such applications is the ability of electronics to operate in highly unpredictable and variable energy supply conditions, including the need to survive on extremely low energy, and the ability to 'resurrect' when energy comes back. The grand challenge is to build systems that can live unlimited life, with or without power, at some point in time. Whenever the power source comes back, the system should get back to performing its functions, ideally in proportion to the level of power.

Such electronic systems are referred to as energy-modulated, which means that their activity is determined by the flow of energy that comes through their power channels. Are today's electronics anywhere near such abilities? Yes and no. Yes, because elementary electronic devices, such as complementary metal-oxide-semiconductor (CMOS) logic gates, are highly power efficient. They consume very little energy in their idle state, i.e. when they don't switch (of course, there are so called leakage currents in them but this usually concerns very tiny, less than 100 nanometre, devices and, indeed, the proportion of the leakage power is significant in them). However, the most important point about CMOS gates is that they can be brought into switching action if the power given to them reaches a certain level (a minimum supply voltage is around 0.1V). No, because the way the circuits and systems are conventionally designed is not appropriate for operating in such conditions. Conventional systems are not sufficiently power proportional, i.e. they need a certain level of power, typically well regulated (such as when power is kept at least at the level of 0.7V and stable), in order to operate consistently with the system's specification.

Traditional approaches to building electronic systems to be power efficient are not fully applicable in achieving that goal. Most of the current research aims at constructing electronics that can approach the so called Landauer's limit on energy consumption to switch a device from logic state 0 to logic state 1. This is fine and I am fully in support of such efforts. But this is similar to attempting to build a 'perfect energy efficient calculator' – and could be applicable for new energy efficient data centres where perfect conditions enabling their operation at the Landauer's limit would need to be created. But at what cost? Again, this would be at an energy cost, which is outside the box of Landauer's principle.

In my opinion, talking about energy efficiency of a specific element of the system, such as its computational part, when we want to build an autonomous system, is meaningless. It only takes us away from the goal of building surviving systems. What is discussed here is different – we need to think about systems that are not energy efficient in perfect conditions, but systems that are truly energy driven.

## Energy-modulated systems must be energy proportional

Energy proportionality is the key principle here; it is two-sided. One aspect of it is that a system delivers the quality of service in computations and communications in proportion to the energy put into it. The other aspect is that energy consumption is proportional to the required quality of service or activity level (for example, the more events the system has to process, the greater its energy consumption). The exact law of proportionality (for example linear or logarithmic) and the efficiency factors (such as growth rate of the throughput as a function of power) at different power levels is another, complementary issue.

The important element of energy proportionality is avoiding various dead zones where power is available, but the system does not deliver anything useful. We have recently developed and fabricated a microcontroller (based on Intel's 8051 instruction set architecture) which can operate in the broad range of supplied voltages between 0.25V and 1.5V, and deliver different levels of functionality depending on where exactly the system is. For instance, between 0.9V and 1.5V the full functionality of the processor is guaranteed. Between 0.74V and 0.89V, the system uses internal registers for storage whereas the main memory is

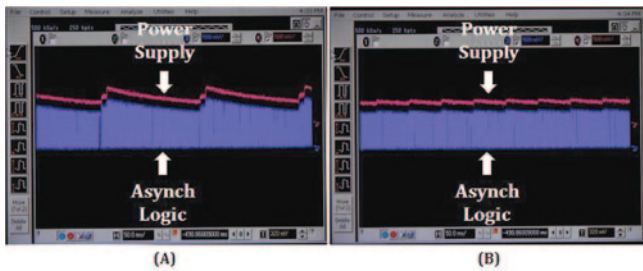


Fig. 1 The effect of power-modulation on asynchronous logic operation

not functional. Below 0.74V, parts of the data path in the processor may ‘freeze’, but the control logic still works normally.

**Power adaptation**

Another important property in this realm is power adaptation, which means that the system actively adapts its data-processing to the levels of incoming energy, or makes sure that it does not overheat in certain hotspots. Power adaptation then implies greater self-awareness in the system, namely the ability to determine energy incomings and outgoings, which means the presence of good sensors of power and temperature. Due to the last factor, self-awareness, and its pivotal role to support autonomy and survival, (one may compare self-awareness with the notion of instinct in biological systems) research has been focused on the development of new types of sensors, which we called reference-free sensors, due to their ability to operate in the realm of changing supply voltages and rely on time or voltage references that can only be produced inside the system rather than taken from outside.

**Energy proportional sensor**

We have recently patented a voltage sensor based on the principle of energy proportionality. Sensing (S) is essentially a process of measurement of a physical quantity and presenting its value in a form that can be used for subsequent electronic or human data manipulation and comprehension. It is effectively a (sequential) composition of transduction (T) and conversion (C), i.e.  $S = T;C$ .

If we had a way of transduction of a sensed quantity, i.e. turning it into an electrical parameter, such as voltage or current, one way of transduction could be to turn the sensed parameter into energy. The energy can then be turned into a computation whose final result could represent the energy used in this computation, which, in its turn, could represent the original parameter. To make such a sensor we need two aspects of proportionality (ideally, in linear relationship). One is that the original parameter is turned into the amount of energy in a proportional way, and the other is that the obtained amount of energy is turned into an information representation, also in a proportional way. Our proposed and patented voltage sensor is based exactly on this principle. The input voltage is converted into an electric charge (energy) in a sampled capacitor, and then this charge (energy) is converted into a binary code produced by the electronic circuit which is fed

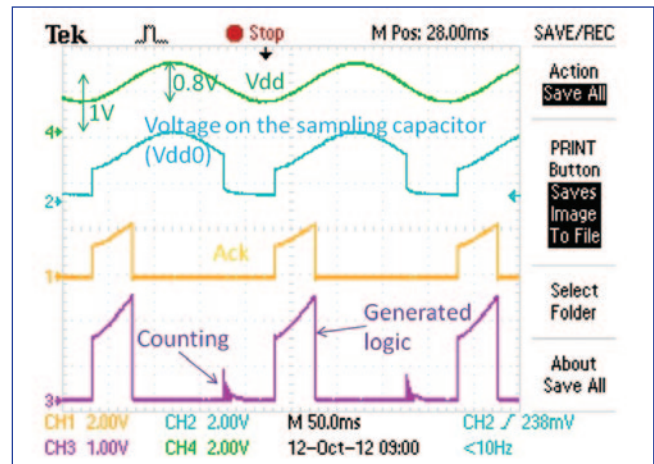


Fig. 2 Input voltage is a sine wave with offset of 1V and amplitude 0.8V (so the range is [0.2V-1.8V]). The sensor happily works from this varying Vdd supply and reports of its value



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by the energy of the charge. So, our sensor idea is actually very simple – it is quite similar to that of an ancient water wheel. We are very different from conventional techniques for building electronic sensors, which usually rely on a stable power supply and a stable clock generator. Such reliance could potentially prove problematic for any project on an autonomous system.

One important aspect of our electronic circuits, and what helps them to support the above principles of energy modulation, is that they are self-timed, i.e. that the timing of all internal switching events is entirely determined by the power given to the system, and in fact timing can be derived from such sources of energy like electric charge. Here, again we are different from conventional electronics, relying on stable power levels and clocks. In my group at Newcastle we have been working for more than 20 years to pioneer methods for self-timed (aka asynchronous, speed-independent, clockless) logic and developing software tools for automated synthesis of asynchronous circuits. Above all, we fabricated a number of asynchronous chips in CMOS processes, among the most recent is our first power-proportional speed-independent static random access memory (SRAM).



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