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The Potential of Printed Electronics and Personal Fabrication in Driving the Internet of Things

Paulo Rosa ^A, António Câmara ^B, Cristina Gouveia ^C

^A Faculty of Science and Technology, New University of Lisbon, 2829-516 Caparica, Portugal, pavr@campus.fct.unl.pt

^B Faculty of Science and Technology, New University of Lisbon, 2829-516 Caparica, Portugal, asc@fct.unl.pt

^C YDreams, Madan Parque - Sul, 2825-149 Caparica, Portugal, cristina.gouveia@ydreams.com

ABSTRACT

In the early nineties, Mark Weiser, a chief scientist at the Xerox Palo Alto Research Center (PARC), wrote a series of seminal papers that introduced the concept of Ubiquitous Computing. Within this vision, computers and others digital technologies are integrated seamlessly into everyday objects and activities, hidden from our senses whenever not used or needed. An important facet of this vision is the interconnectivity of the various physical devices, which creates an Internet of Things. With the advent of Printed Electronics, new ways to link the physical and digital worlds became available. Common printing technologies, such as screen, flexography, and inkjet printing, are now starting to be used not only to mass-produce extremely thin, flexible and cost effective electronic circuits, but also to introduce electronic functionality into objects where it was previously unavailable. In turn, the growing accessibility to Personal Fabrication tools is leading to the democratization of the creation of technology by enabling end-users to design and produce their own material goods according to their needs. This paper presents a survey of commonly used technologies and foreseen applications in the field of Printed Electronics and Personal Fabrication, with emphasis on the potential to drive the Internet of Things.

TYPE OF PAPER AND KEYWORDS

Research Review: *Ubiquitous Computing, Internet of Things, Personal Fabrication, Printed Electronics.*

1 INTRODUCTION

This paper reviews the concepts behind the Internet of Things, Printed Electronics and Personal Fabrication (Figure 1), and explores how the emergent realities of Printed Electronics and Personal Fabrication can democratize technologies and innovations, thus enabling users to develop their own embedded digital devices and their own Internet of Things according to their needs.

If we carefully look around us, it is possible to perceive how computers have become an integral part of our lives. They have profoundly and irrevocably changed the way we perform most of our daily tasks, including the way we work, shop, bank, and communicate with our friends and relatives. Simple tasks such as writing a letter, listening to music or reading the news have been utterly altered by computers to a point where most of us cannot imagine realizing them without the aid of one computer.

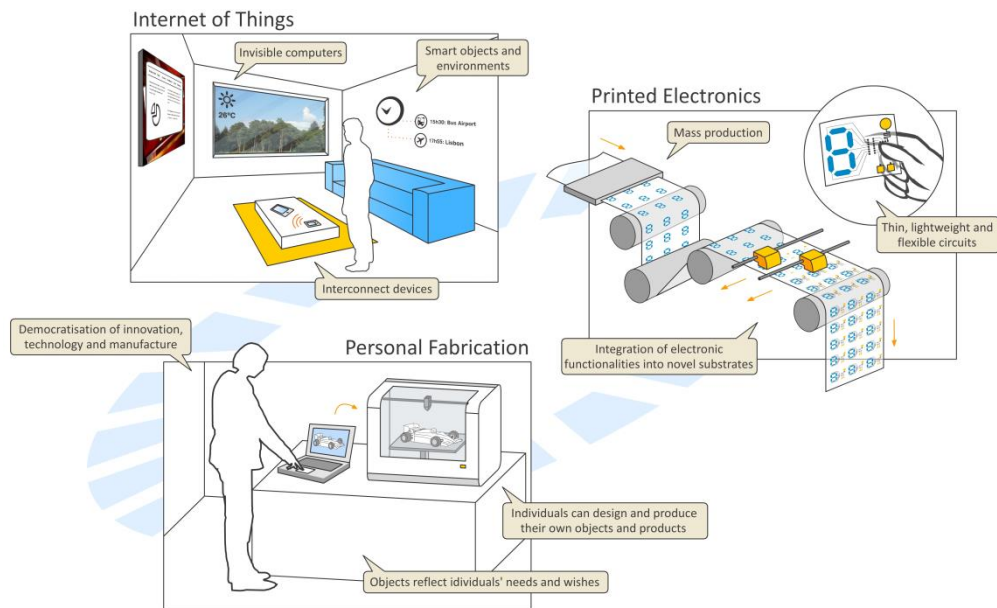


Figure 1: Connecting the Internet of Things to Printed Electronics and Personal Fabrication

The continuous miniaturization of microprocessors, as well as of other digital components, drove this reality. Nowadays, computers can take various forms and sizes, from the credit-card sized Raspberry Pi to smartphones and tablet computers. Furthermore, they are present and a crucial component of numerous artifacts and appliances such as wristwatches, music players, televisions, washing machines, and microwave ovens.

It is foreseen that in a near future computers will not only be an integrant part of every product we buy but they will in fact be embedded within us and into our environment, inevitably occupying our physical world as natural elements [52][55][107][136]. Indeed, computers will become part of the very fabric of our lives, after all, “*The world is the next interface*” [48].

In the early nineties, Mark Weiser, a chief scientist at the Xerox Palo Alto Research Center (PARC) [142] wrote a series of seminal papers that introduced the concept of Ubiquitous Computing. According to Weiser [136][137], the idea of *personal computer* was misplaced and a new way of thinking was necessary. Computers required too much attention from the user, drawing his focus from the tasks at hand. Instead of being the center of attention, computers should be so natural that they would vanish into the human environment. After all, only when we became unaware of things we are able to freely use them without thinking and therefore fully able to focus on our goals. Within this vision, computers and others digital technologies are integrated seamlessly into everyday objects and activities, hidden from our senses whenever not used or needed.

The proliferation of computers into our physical world promises more than the obvious availability of computing infrastructure anywhere, any time. Computers will enhance our human capabilities and our environment, promoting a reality that is more responsive to our needs and expressive to dynamic changes in its environment. Moreover, it implies a new paradigm of user interaction. The essence of this new paradigm lies in transforming computation, until now essentially focused on point-and-click graphical interfaces, into a new type of user experience, where everything is controlled by natural actions based on our daily activities. We will then be in the presence of intelligent environments, where people do not interact directly with computers but instead are engaged by computer devices of all sizes and types, without necessarily being aware of them. Computers become not only truly pervasive but also effectively invisible and unobtrusive to the user.

The ability of each digital device to interact with the nearby ones is another important facet. They will all be wirelessly interconnected, creating an Internet of Things [28]. Information will flow from one device to another seamlessly and will be accessible to users anywhere, anytime. Moreover, each user will be able to interact with several computational devices simultaneously without necessarily realizing them.

From a conceptual point of view, the Internet of Things is created based on three assumptions related to the ability of any smart objects, either among them or by the users [102]:

- Smart objects can identify themselves.

- Smart objects can communicate.
- Smart objects can interact.

2 TOWARDS AN INTERNET OF THINGS

In the last two decades, various efforts have been put forward in making the Internet of Things a reality. The research done at the Auto-ID Center on RFID technology [11][121] paved the way for the architecture of the Internet of Things and novel technologies, such as near field communications (NFC), Bluetooth low energy (BLE), and embedded sensors enabled new ways to transform everyday physical objects into smart objects that can understand and react to the environment.

Indeed, not only human environments have been augmented with diverse computational devices that enable people to engage and access information and services when and wherever they desired [17][20][37][67], but also our bodies have been augmented digitally, providing overwhelming amounts of data about our surroundings, our movements and our health [97][103].

Smartphones with internet capabilities, wristband fitness sensors, electronic labels, RFID (radio-frequency identification) tags, wearable sensor patches, miniature cameras and flexible displays are just some examples of devices and technologies currently available, and they are clear indicators of this new technological revolution. In fact, devices such as the e-book reader and the tablet computer are roughly overcoming the paradigm of the general-purpose personal computer in favor of simple, specialized digital devices integrated in our life style. As Mattern [101] points out, the technological bases for a new world are already here.

2.1 Exploring New Forms of Interaction

It is evident that the creation of an Internet of Things “*does not concern objects only; it is about the relations between the everyday objects surrounding humans and humans themselves*” [119]. Understanding how users will interact and experience these novel technologies, and how these can be integrated into human activities, along with its consequences, becomes essential for the creation of suitable and useful user experiences and interfaces.

This implies the focus on usability aspects and standardized interaction patterns as well as simplicity and transparency, such that people can understand effortlessly how to control and interact with the various smart objects of the Internet of Things. Hence, it becomes necessary to explore new techniques that support interaction with, and through, new types of computational devices [24]. Gesture-based approaches exploiting movement in relation to surfaces and

artifacts, haptic approaches exploiting the physical manipulation of artifacts, and speech-based interfaces, are just some examples currently being explored [36][45][54][72][90][96][103][132][133][140][141].

However, not only new interaction techniques and technologies need to be considered. New ways to provide and present information, both visually and non-visually, also need to be envisaged. Users must be able to easily access the information, in a comprehensive and clear way. In order to effectively design systems that can be perceived both in the periphery as well as in the user center of the attention, a detailed understanding of not only how information can be presented but as well how it is perceived at the different levels of the human attention must be procured. Naturally, it becomes also important to consider how these transitions between the different levels of awareness can be eased and smoothed for the user experience [12][19][39].

It is also evident that the technical challenges as well as the social and legal implications necessary for a full deployment of an Internet of Things are still high [10][44][61][102][135]. Always present are concerns about invasion of privacy, security, data protection and trust, ownership and accountability of systems, and loss of control. Users will want to be able to engage and be engaged by every smart object they encounter effortlessly and without worrying if it is a secure system and if their information will be protected.

It is argued here that technologies should enhance our competences and productivities as well as our enjoyment of life in an invisible and unobtrusive way. This, naturally, implies the perfect integration between computers and the human environment. Hence, instead of a fixed display, a keyboard or a mouse, the objects around us become the means we use to interact with both the physical and digital worlds. For instance, tables, walls and floors are transformed into interactive displays, providing us with subtle information about our surrounding, along with the means to act upon it [26][47][77][116][139]. This requires not only for smaller, cheaper and low power consumption computers and display solutions, but also for novel fabrication processes and materials.

3 THE ADVENT OF PRINTED ELECTRONICS

Printed Electronics promises to revolutionize the existing electronics field by enabling the mass production of low-cost, flexible digital devices in a wide array of substrates, such as paper, plastic or textiles. Electro-optical functional inks are used for this purpose, which are directly deposited on the substrate, creating the various active and passive elements (e.g. transistors, resistors, capacitors, antennas, and alike).

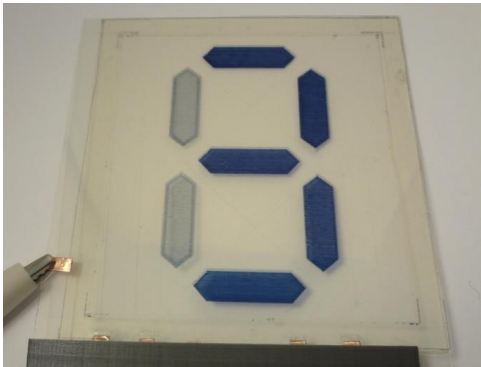


Figure 2: Example of a printed 7-segment electrochromic display

The potential for cost savings comes from the fact that Printed Electronics is based on the use of purely additive processing methods, in contrast to the photolithography-based subtractive methods currently used in the semiconductor industry [14]. Not only is the material only deposited where it is required, but also the overall complexity of the manufacture process is greatly simplified. Typically, only two steps are required to go from a bare substrate to a working functional layer on a substrate: the printing process in itself and a curing process. If we consider that in subtractive methods multiple steps, materials and equipment are necessary to produce a single functional layer on a bare substrate, in addition to being consumed materials that do not end up on the final device, the cost savings can be relatively high, particularly when the device does not have a high surface coverage on the substrate [50].

However, there is a trade-off. Printed Electronics components do not have the same high performance and reliability as their non-printed counterparts [127]. Hence, it is not expected that Printed Electronics will substitute conventional silicon-based electronics, at least in a near future. Instead, it can be seen as an entirely new market and industry. There have been concerns related to Printed Electronics regarding ink toxicity and recyclability. Actually, several regions already require new electronic products to conform to norms on those areas.

Printed Electronics represents a ground-breaking new type of electronics that are characterized for being lightweight, thin, flexible, robust, and easily disposable. Thus, the initial aim is the high-volume market segments, where the high performance of conventional electronics is not required, as well as the low level prototyping. A new group of opportunities and possibilities for products and applications is being discovered by incorporating electronic functionalities into objects where it was previously not possible or viable, such as in packaging. The conjugation with electrochromic inks, for example, allows the creation of

simple displays (Figure 2) in these products. Indeed, Printed Electronics can become a mean for transforming lifeless objects and surfaces into sensing, interacting interfaces, capable of reacting and exchanging information with users and the environment.

3.1 Applications

At present time, the market drivers for Printed Electronics are radio frequency identification (RFID) tags [25][128][129][145]; memory [4][7][75][94] and logic components, including field effect transistors (FETs) [60][123] and thin film transistors (TFTs) [21][74][76]; sensor arrays [56][65][88][92]; photovoltaic cells [13][84]; batteries [16][40][53][63]; and displays [9][33][62][146]. The practical applications envisaged are various, and include, for example:

- *Dynamic newspapers, magazines, and signage applications* [31][62]:

By taking advantage of the combined benefits of paper with dynamic digital content, companies can create novel formats to present information and publicize their products. This will likely include the incorporation of animated advertisements in magazines and newspapers, or the creation of dynamic signage and billboards. Other possibilities include, but are not limited to, posters, business cards, bumper stickers, and product labels.

- *Intelligent packages / Smart labels* [29][81][99]:

Printed Electronics systems can be incorporated into products packages with the aim of making them more useful and helpful as well as more visually appealing and attractive. For example, sensors can be printed directly into product packages or attached in the form of smart labels allowing the tracking of movement and as well as the monitoring of variables such as temperature and humidity in real time of item-level products. This would allow companies to easily check the conditions of a product and can, for instance, prevent its spoilage or validate its freshness.

Also, simple printed displays can be used in packaging to improving the legibility and detail of the information available about the product, and thus improving the information that consumers have access in the act of purchase, or can be used to show notice messages about the conditions of the product, highlighting changes that occurred in the surround environment and that are incompatible with the preservation of the product. Furthermore, smart labels can also be used as an anti-counterfeiting measure that can be implemented directly into the products, validating its authenticity and preventing or at least complicating its falsification.

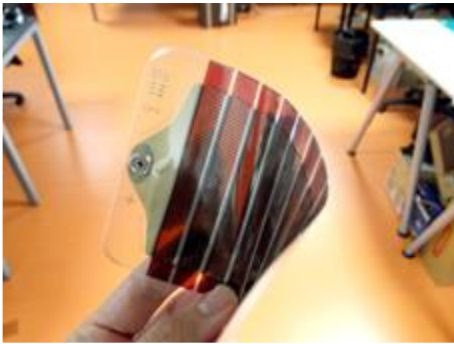


Figure 3: Flexible photovoltaic cell

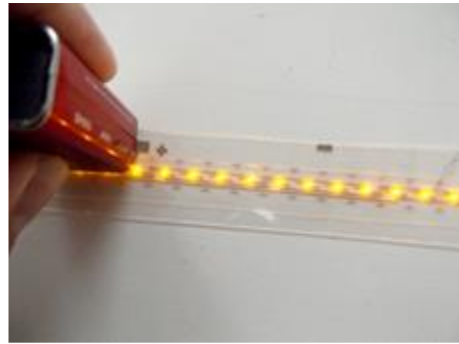


Figure 4: Flexible LED strip

- *Electronic labels* [57]:

Electronic labels can be low-cost, low-power and remotely updated electronic shelf labels and pricing tags in supermarkets and stores.

- *Smart cards* [100]:

The implementation of Printed Electronics systems in smart cards could allow users to rapidly access information contained in the card, wherever and whenever they wanted. This would enable, for instance, customers to easily check the amount of credits still remaining in a public transportation smart card, or the validity of their subscription. Frequent flyer card, or in any other type of loyalty system cards could indicate the fidelity points gathered, or alert the user for promotions. Healthcare smart cards could also be enhanced, allowing users to easily check certain information on their medical file, such as the blood type, whether the vaccines are up to date, when it was the last time he went to the doctor or when he is supposed to have is the next medical visit. Furthermore, Printed Electronics solutions could also be used to improve the security of smart cards, especially of debit and credit cards (e.g. by implementing digital watermarks).

- *Healthcare diagnostic devices* [58][80][143]:

The disruptive potential of Printed Electronics can be enormous in the healthcare sector. By enabling the fabrication of disposable printed biosensors at a fraction of the cost of equivalent non-printed solutions, they can make complex healthcare examinations not only cheaper but also faster to do. These biosensors are traditionally used in medical monitoring, diagnostics, and drug delivery. Examples include biosensors for monitoring vital signs (e.g. heart rate, body temperature, blood pressure); for testing metabolic variations (e.g. blood glucose, cholesterol, lactate); and for detecting pathogens elements (e.g. bacteria and virus).

- *Energy harvesting and storage devices* [63][82][86]:

Various printing technologies are already being used as fabrication tools for manufacturing photovoltaic cells and batteries. As printed photovoltaic cells become

more efficient and more reliable as a power source, they will eventually become more widespread. Low-cost printed photovoltaic cells (Figure 3) will allow energy to be generated where it is needed. Considering their flexible nature, they can be easily integrated into building structures, such as wall coverings, or made into window shades. Likewise, printed batteries provide lightweight, flexible power sources that can be integrated into mobile electronic devices, or in any other type of low-power consumer application or Printed Electronic system.

- *Dynamic walls and lighting panels* [83][104]:

Printed Electronics systems can be integrated into walls and be used as information screens or, alternatively, as dynamic wallpapers or lighting panels (Figure 4).

- *Active/smart clothing* [70][93]:

Printed Electronics systems can also be integrated seamlessly into textiles. They can be used to improve the functionality of clothes, for instance, by using embedded biosensors and displays to monitor and show the user vital signs, or instead, in a more fashionable way, to simply display dynamic patterns in the fabric. The physical flexibility of Printed Electronics devices provides a favorable form factor that can translate into new and more fashionable wearable products.

Naturally, the development of these applications is greatly conditioned by the formulation of suitable functional inks as well as of adequate substrates where they are printed [73]. After all, the practicality of Printed Electronics relies primarily on the development of novel inks used to create the electronic components. The inks used must provide a print film with an adequate cohesion and adhesion to the printing substrate whilst maintaining the electro-optical properties of the functional elements. In fact, the formulation of adequate and cost-effective functional inks is one of the main limiting factors to the widespread adoption of Printed Electronics. As for substrates used, so far the most common ones are polymer films, ceramics, glass and



Figure 5: Roll-to-roll manufacture of an integrated printed biosensor
(Used with permission from [1])

silicon. Printing of functional inks on paper is also possible, but can present some challenges due to the paper's rough, fibrous surface at a microscopic scale. The optimization of current printing technologies for real mass-manufacturing of Printed Electronic systems also has to be undertaken. As Schmidt et al. [122] points out that printing technologies were developed for visual output and therefore classical printing products undergo completely different requirements when compared to electronic devices. Significant modifications in processes and materials are necessary.

3.2 Printing Technologies

Within the context of Printed Electronics, the most commonly used printing technologies are screen

printing, flexography, offset lithography, gravure printing, and inkjet [91][127]. Naturally, each process has its own strengths and limitations in regard to the production of Printed Electronics. The choice of one process over another is typically related to the type of ink, substrate used, and the final application intended (for instance, prototyping versus high-precision). Hence, each process tends to be the ideal method of production for a different range of products or substrates. In order to fully take advantage of the production capabilities of conventional printing technologies, their applicability in Printed Electronics should be target to roll-to-roll processing (R2R) (Figure 5).

R2R essentially consists in adapting the printing technologies to allow rotary printing. The process typically involves several rotating cylinders around which the printing substrate is routed through a number of fabrication operations. Hence, during the printing process, the substrate is on a constant move and the print is done in a continuous process at high speeds, enabling large area capability, high throughput, and ultimately increasing the cost-efficiency of the overall manufacture process. Below is highlighted the advantages and limitations of the mentioned printing technologies (see also Table 1):

- *Screen printing* (Figure 6):

Screen printing is one of the most versatile processes. When compared to the other printing technologies, it provides the widest range of applications with regard to the choice of substrates. Apart from paper and cardboard, other possible substrates are plastics, glass, metal, textiles, ceramics, and the like, in the form of endless webs or of single sheets. Moreover, the substrate surface does not need to be planar, and thus objects of the most varying shape can

Table 1: Comparison of printing technologies commonly used in Printed Electronics

	Screen Printing	Flexography Printing	Offset Printing	Gravure Printing	Inkjet Printing
Printing Form	Stencil	Relief	Flat	Engraved	Digital
Image Transfer	Direct, wrong reading	Direct, wrong reading	Indirect, right reading	Direct, wrong reading	Direct, non-impact
Resolution (lines/cm)	50	60	100 to 200	100	60 to 250
Line Width (μm)	50 to 150	20 to 50	10 to 15	10 to 50	1 to 20
Ink Viscosity (Pa·s)	> 1 to 50	0.05 to 0.5	40 to 100	0.05 to 0.2	0.001 to 0.03
Film Thickness (μm)	up to 12	1 to 2.5	0.5 to 1.5	<0.1 to 5	0.5 to 15
Printing Speed (m/min)	10 to 15	100 to 500	200 to 800	100 to 1000	15 to 500

(Source: Adapted from [22][79][117])

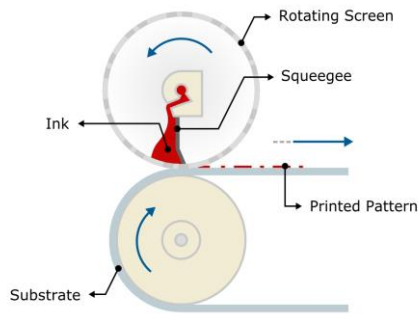


Figure 6: R2R screen printing

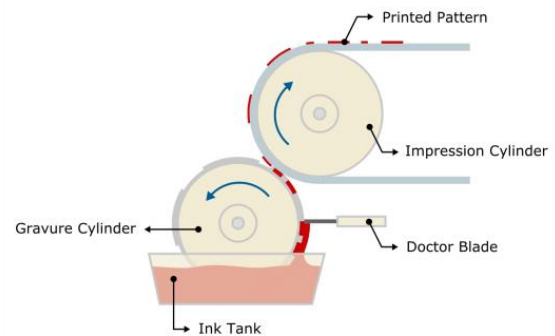


Figure 7: R2R gravure printing

also be used as printing substrate. The range of suitable inks is high as well. However, these need to have a paste-like behavior (inks with low viscosities simply run through the mesh and cause excessive spreading). Furthermore, the use of high viscosity inks raises some issues in the field of Printed Electronics.

High viscosity inks are typically manufactured by adding polymer binders to the ink, and these binders can destroy the functionality of semiconductors, introduce excessive leakage and dissipation in dielectrics, or degrade the conductivity of conductors [127]. Screen printing has been widely used in the production of polymer photovoltaic cells to print both the front and back electrodes of complete cell modules (see, for instance, [2][85][86][124]). Other examples include the production of displays, from electrochromic displays [18][32][111] to organic light-emitting diode (OLED) displays [15][68][108] and field emission displays (FED) [149][150], RFID antennas [78][125], and various types of sensors [58][59][65][88][109].

- *Gravure printing* (Figure 7):

Gravure printing is a mechanically simple process, compared to flexography and offset lithography printing processes, with fewer variables to control. In conventional printing, the surface of the gravure cylinder is plated with copper, which is quite expensive. Gravure printing is typically used to produce long run printings such as magazines and newspaper inserts, catalogs, postage stamps, plastic laminates and packaging [117]. The inks used must have a liquid behaviour, in order to fill the image forming cells of the gravure cylinder at high speeds (up to 15 m/s). From a process point of view, these inks have a simple composition and manufacture process. As a result, the range of workable inks is rather large. Gravure printing also allows a wide range of printing thicknesses, from 50 nm to 5 μm . In the context of Printed Electronics, gravure printing is demonstrating its applicability, and its use for patterning conductive traces has been widely reported [112][113][130], for example, in the production of OLEDs for lighting applications and

displays [83], organic photovoltaic modules [82][144], and various sensors [114][115].

- *Flexography printing* (Figure 8):

Flexography printing allows printing on a wide variety of substrates, including these be chosen based on their functionality rather than their printing characteristics. For example, the softness of the printing plate enables the printing on compressible surfaces such as paperboard and corrugated board, as well as in metallised films or any other type of pressure sensitive coated films and foils. Glass and textiles can also be printed with flexography. A wide variety of inks can also be used, and these inks are either oil-based or water-based. They are typically characterised for having a low viscosity and quick drying. However, the potential of flexography printing as a fast printing process for Printed Electronics has been, until now, only demonstrated in a small number of applications, including printing conductive traces [35][87] and transistors [71], and preparing electrodes in polymer solar cells [148]. Another interesting application is its use to print large-area piezoelectric loudspeakers on paper [66].

- *Offset lithography* (Figure 9):

Offset lithography is currently the most used printing technique in conventional printing, and is widely employed to produce large volumes of high quality prints, such as newspapers, magazines, brochures, and books. The inks used in offset lithography are required to have a high viscosity, paste like behavior. Furthermore, they must be prepared in such a way that the drying components in the ink do not harden while being spread over the ink rollers in the inking unit or at the printing plate and blanket cylinders. The ink film transferred onto the substrate is extremely thin, having usually a thickness of approximately 0.5 to 1.5 μm . The biggest disadvantage of offset lithography is related to set-up costs, which are rather high, although the actual printing process is relatively inexpensive. The standard offset lithography printing processes have already been

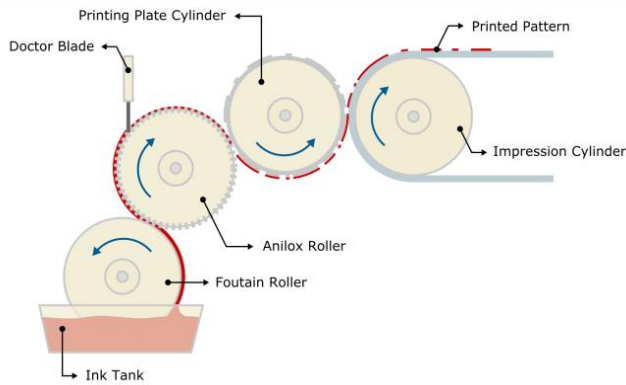


Figure 8: Flexography printing

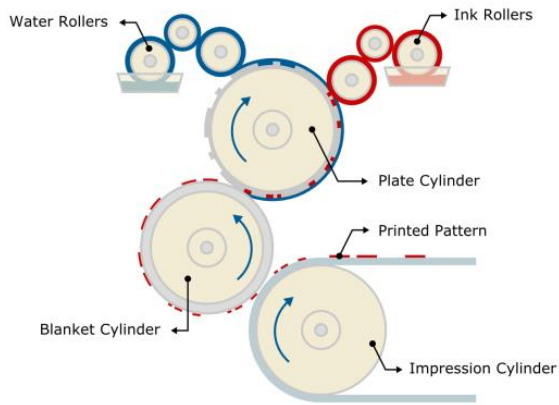


Figure 9: Offset lithography printing

used to deposit electrically conductive films onto a wide range of flexible materials. Composite structures containing conductive, resistive, dielectric and ferromagnetic layers have also been produced [42].

- *Inkjet printing:*

Inkjet printing is one of the most attractive and versatile technologies for the fabrication of Printed Electronics devices. The biggest advantages of this process, compared to conventional printing processes (i.e. screen, flexography, offset lithography and gravure printing), are the possibility to easily change and adjust the printed pattern on a computer without the need to manufacture a physical printing form, and the ability to produce high quality prints in a variety of substrates at a relatively low cost. The process has also the added value that multiple print heads can be implemented and used during printing. However, the productivity of these systems is still lower than conventional printing technologies. Inkjet printing is a relatively new technology and presents some limitation with respect to processing speeds and ink formulation. The use of inkjet printing in Printed Electronics is extensive, and reported in various applications, from printed memories [4] and

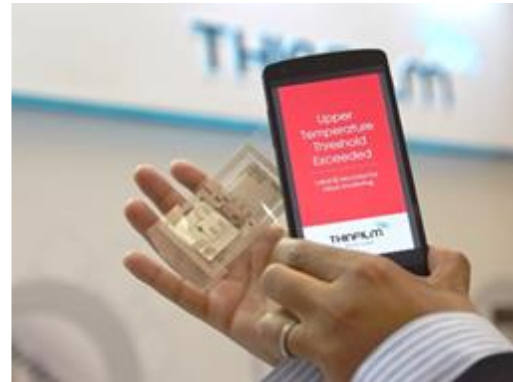


Figure 10: Printed Electronics smart label.
(Used with permission from [131])

transistors [74][76], to displays [27] and photovoltaic cells [41][46], including RFID modules [145] and sensors [89][92].

3.3 Printed Electronics and the Internet of Things

The authors believe that the disruptive potential of Printed Electronics in driving the Internet of Things can be high, and offers unique opportunities both in terms of fabrication processes and in terms of applications and services. By making it possible to introduce electro-optic functionalities directly into materials, not only electronic devices with novel form factors can be produced, but also more interestingly, objects and materials commonly seen as lifeless can be transformed into sensing systems and interacting interfaces capable of reacting and responding to users and to changes in the environment. For instance, a printed antenna can be connected to a microchip or a printed battery to transmit its identity or a short message to another digital device every time it is activated. More complex Printed Electronics systems can be created by combining other components (e.g. using printed electrochromic displays).

The examples provided in section 3.1 are intended to illustrate some of the possibilities of Printed Electronics in the field of the Internet of Things, from the manufacture of cost-effective smart labels and RFID tags to the development of flexible batteries to low-power display solutions. Indeed, smart labels are being presented as the replacer of RFID tags in enabling the Internet of Things [29]. Printed Electronics smart labels can be produced at a fraction of the cost of silicon sensors and can be attached to a variety of packages, which previously had no way of being tracked or to provide real time information about the surrounding environment (printed smart labels can contain a multitude of sensors, such as temperature, humidity,

light, pressure and strain sensors, and all are printed onto a single object). In addition, Printed Electronics devices are less energy consuming than traditional electronics products. The Internet of Things will be characterized by low resources in terms of both computation and energy capacity [10], and Printed Electronics can provide the required resource-efficient solutions.

The openness of Printed Electronics technologies and fabrication methods to end-users can also bring interesting new product ideas. In the next section explored is the disruptive potential that Personal Fabrication can have in the Internet of Things.

4 PERSONAL FABRICATION AND THE DEMOCRATIZATION OF TECHNOLOGY

Personal Fabrication refers to the ability of ordinary people to design and produce their own products using digital fabrication tools directly from their homes. By making accessible the capabilities of manufacture machines tools into the home, it enables users, even those without any special skills or training, to create three-dimensional (3D) physical structures as well as electronic circuits, sensors, and actuators that can be incorporated into these structures, thus creating complete functioning digital systems, from digital designs.

Indeed, Personal Fabrication enables individuals to manipulate atoms as easily as they manipulate bits. It brings the programmability of the digital worlds, which we invented to the physical world we inhabit. To Gershenfeld [48], a chief advocate of the potential of Personal Fabrication, the goal is to give back to users the control of the creation of technologies, while fulfilling their individual desires. It provides the means for almost anyone to make almost anything. Instead of being limited by what is available in stores and being obliged to purchase something that someone else believed they wanted, individuals become limited only by their creativity.

When a technology is developed by and for individuals, it undoubtedly better reflects their needs and wishes. Individuals can develop exactly what they want. The enjoyment of the innovation process is another important aspect. For certain individuals, the creation and learning process is of extreme value. Nonetheless, individuals do not have to develop everything on their own. They can benefit from innovations developed and freely shared by others [6][64]. Overall, Personal Fabrication is an empowering technology, enabling individuals to personally program the construction of their physical world as they see fit. Hence, it aims at democratizing not only the use of technology but also its development.

4.1 Makerspaces, Hackerspaces and FabLabs

To a certain extent, the vision of Personal Fabrication is today already a reality. Although most people do not have (yet) at their homes the required machine tools to make their own products, they can indeed have access to them, no matter whether through one of the thousand makerspaces and hackerspaces that exist throughout the world, or through a Fab Lab (fabrication laboratory) [43][95]. These unique spaces seek to provide communities, businesses and entrepreneurs the hardware tools and manufacturing equipment necessary to turn their ideas and concepts into reality, serve as a physical place where individuals can gather and share their experience and expertise. Fab Labs have a particular relevance due to its ideology and organizational model.

The Fab Lab concept was developed by Neil Gershenfeld (see [49]) from the Center for Bits and Atoms (CBA) of the Massachusetts Institute of Technology (MIT), with the initial aim to explore the implications and applications of personal fabrication in those parts of the world that cannot easily have access to tools for fabrication and instrumentation. Hence, when the first Fab Labs were created in 2002, locations such as rural India, Costa Rica, northern Norway, inner-city Boston and Ghana were chosen. In 2012, the number of existing Fab Labs worldwide was close to 130, spread through 35 countries [23]. A distinctive feature of Fab Labs is that they all share at their core the same hardware and software capabilities, making it possible for people and projects to be easily disseminated across them.

For now, the great majority of the adopters of Personal Fabrication are technologically sophisticated hobbyists, commonly called *makers* [6], who are more interested in the technology itself and its capabilities than its design and ease of use. They are the ones pushing Personal Fabrication forward. It is expected, nonetheless, that with the continuous evolution of technologies, Personal Fabrication will gradually become more affordable and easier to use. As a result, it will become progressively more accessible and common in places such as businesses, schools and even consumers' homes, ultimately tipping Personal Fabrication from a movement of pioneers and early adopters to mainstream, as an everyday activity done by everyone. It is at that point that the unique benefits of Personal Fabrication will become truly evident.

However, this does not mean that the first effects of Personal Fabrication are not already noticeable. Digital fabrication technologies are already giving a great number of makers the capability to produce their own personal objects (Figure 11). More interestingly, they are making makers to transform these objects into



Figure 11: Examples of objects and devices fabricated with 3D printers and freely shared by their makers

(Sources: from left to right, top to bottom: Big Ben [38], House Spider [34], Subdivision Bracelet [106], PLA Spring Motor [152], Spider Rover [69], and MiniSkybot Robot [51])

products and goods outside the traditional manufacturing model. Makers are making their products and goods accessible to others. The internet allows maker to reach potential consumers and through websites, such as “*Kickstarter.com*” and “*Indiegogo.com*”. It becomes possible, by means of crowd funding, to secure the necessary resources to move from the prototype stage to production. Consequently, we are witnessing an increasingly bottom-up entrepreneurship, associated with the emergence of numerous lightweight factories, as well as the expansion of micro production and mass customization [105]. As Anderson [6] points out: “*manufacturing new products is no longer the domain of the few, but the opportunity of the many*”.

4.2 Digital Fabrication Technologies

The core manufacture machine tools of a makerspace or a Fab Lab are fundamentally aimed at the creation of physical objects from a digital design. Furthermore, these spaces also provide environments for creation and innovation in the digital realm, thus facilitating the prototyping of electronic devices. The manufacture machine tools commonly available include, but are not limited to:

- *Laser cutter:*

Laser cutting is a subtractive process, and uses a high intensity focused beam of light to cut out shapes in a wide variety of material according to the digital information provided. Desktop laser cutters can cut almost all non-metallic materials, although they are not safe to use with materials that emit dangerous fumes when burned such as certain plastic materials. The most common kind of desktop laser cutters work with a carbon dioxide (CO₂) laser, i.e. they use carbon dioxide as the amplifying medium. As the cutting tool is a beam of light, it can move very quickly, providing fast cutting speeds as well as being capable of narrow cuts, thus enabling amazing levels of detail and precision. Laser cutting can be so accurate that the cut shapes can be made to snap together, thus allowing the quick assembly of complex 3D structures. At low power, laser cutters can be used to mark, through engraving, the processed material.

- *Water Jet Cutter:*

Water jet cutters work in a similar way to laser cutters. Water jet cutters use a highly focused and pressurised stream of water, which contains tiny abrasive particles, as the cutting tool, and these particles are responsible for the cutting. When they are accelerated to the speed of the jet, the particles gain so much energy that they become capable of cutting through almost anything. As a result, water jet cutters are capable to cut materials that laser cutters cannot do, namely hard materials such as metals and stone with several centimeters thick. The nature of the cutting stream also makes it capable of making fast and fine cuts with tight tolerances for complex shapes. Water jet cutting is also a preferred solution when the materials being cut are sensitive to the high temperatures generated by other cutting methods.

- *Sign Cutter:*

Sign cutters, also known as vinyl cutters, use a computer-controlled sharp blade to perform precise custom shape cuts out of thin sheets of materials like paper, cardstock, and vinyl. It is also possible to use them to cut thin copper sheets in order to quickly make functional flexible circuits. The applicability of sign cutters is, hence, limited to the materials that the blade can cut through. Sign cutters are relatively cheap and widely available at craft stores.

- *Computer Numerical Control (CNC) Milling Machine:*

In CNC milling, a high speed rotating cutting tool called an end mill, similar to a drill bit, is used to mill, cut and carve precise designs into a broad range of large dimension materials. Unlike laser cutters and water jet cutters, CNC milling machines can precisely contour

and cut three-dimensional shapes (normally, the cutting tool can move in its three axes). In more advanced milling machines, the milling head as well as the material being cut can also be rotated, resulting in four, five and even six-axis milling machines. Naturally, this provides extra flexibility during the cutting process, enabling more complex cuts.

There is a wide variety of end mills, and each is appropriate for a specific type of cut or material. Multiple passes using different end mills allow highly complex curves to be perfectly carved out of different materials from foam to wood and to steel. CNC milling machines are revolutionising the machining processes by allowing the rapid realisation of complex cuts with extremely high accuracy, which otherwise could not be easily duplicated by hand. Personal CNC milling machines are characterised by the equipment whose size, capabilities, and price make them useful and affordable for individuals. They are made to be easily operated by end-users without professional training in CNC technology. CNC milling machines, even small ones, are in particular ideal for creating large batches of items.

- *Printed Circuit Board (PCB) Milling Machine:*

PCB milling machines are high-precision (micron resolution), two-dimensional, desktop size milling machines, and are used to create circuit traces in pre-clad copper boards by removing the undesired areas of copper. PCB milling is a non-chemical process, in contrast to the etching process commonly used in the creation of PCBs, and as such it can be completed in a typical office or lab environment without exposure to hazardous chemicals. However, in mass production, PCB milling is unlikely to replace etching, being currently regarded essentially as a rapid PCB prototyping process.

- *Three-Dimensional (3D) Printer:*

3D Printing is an additive manufacturing process, which allows the creation of three-dimensional physical objects from a digital model. There are several 3D printing processes that can be implemented to print an object:

(1) One approach, called selective laser sintering, involves the use of a laser to selectively harden layers of liquid or powder resin in a bath (or bed). The laser sequentially plots cross-sectional slices of the model as the emerging object is lowered into the bath of raw material, until completed. An advantage of this process is that the raw material also serves as support structure for partially completed objects, thus allowing the construction of highly complex objects.

(2) A second approach, to a certain extent similar to the first one, uses a liquid binding material to fuse a powder resin in a bath. An inkjet print head is used to

deposit the liquid binder onto the fine powder, selectively fusing the powder where the printed droplets land. Hence, the object is created with one layer at a time by repetitively spreading and fusing layers of powder. This technology allows the printing of full colour objects by using equivalent coloured binder liquids and, as in the previous approach, the unfused powder serves also support structure for partially completed objects.

(3) The last approach, called fused deposition modeling (Figure 12), extrudes a thermoplastic material from a movable print nozzle, by melting it, into a chamber that is slightly cooler than the melting temperature of the thermoplastic. As the thermoplastic material is extruded, it hardens almost immediately, forming the various layers that compose the final object. Personal 3D printers typically employ this approach mainly due to its simplicity and easy implementation. The biggest disadvantage of this process is that it is not possible to create objects composed by various independent parts or with moving parts, at least already assembled. 3D printing is mainly used for prototyping and distributed manufacturing since its slow printing speeds make it not feasible for mass-manufacture. Hence, 3D printing can be regarded essentially as a complementing process to traditional subtractive manufacture methods rather than trying to replacing them.

From the technologies typically used in personal digital fabrication, 3D printing is the one that is obtaining the most attention and hype owing to its potential. There are already various examples of 3D printers in the consumers' market and almost every day appear news of 3D printers capable of printing the most various types of input materials, from plastic, metal and wood pulp to food [110] and even biological tissue [98]. In the framework of this article, the combination of 3D printing with conductive inks offers an interesting new approach to the design and making of objects, unleashing new fabrication methods and product ideas [120][138][151].

One of the current limitations of 3D printing is that it can only make unanimated objects. If the object is to, for instance, have movement or be able to show digital information, active components, such as motors and displays screens, along with the required microcontrollers and necessary wiring, have to be added after the object is completed. Ideally, the integration of these components would be done at the same time as the object is being printed. In the same way that common inkjet printers have several ink cartridges for different colors, 3D printers will have multiple print heads/nozzles not only to print objects with multiple color combinations but also to enable the printing on-the-fly of functional inks. The structural and functional elements are both co-print as one.

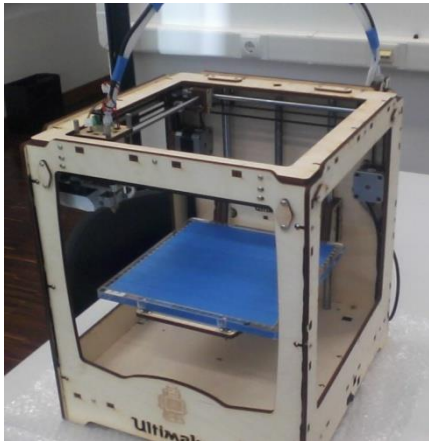


Figure 12: Example of an early model of a fused deposition modeling 3D printer

An example in this direction is Voxel8 [134] novel 3D electronic-device printer, and at the time of writing it is not yet available in the market. The printer allows the co-print of matrix materials such as thermoplastics and highly conductive silver inks. The integration of functional inks into a 3D printer is, ultimately, the route towards making a programmable personal fabricator that will be able to produce anything, including itself. It will be a self-reproducing machine [48].

Considering the current evolution of 3D printers, in part similar to what was seen in the past with computers and inkjet printers, it is expected that this technology will become common in the consumers' homes within the next few years. Although professional 3D printers are currently still expensive and mainly accessible to the public through online fabrication services, cheaper models of 3D printers aimed at home use are already available (e.g. Makerbot and Ultimaker 3D printers).

Even though these are often characterized as being somehow rudimentary, difficult to assembly and complex to use, with every new model release, they are becoming more reliable, easy to use, and ultimately cheaper. They will begin to appeal to the consumers that have no special training and soon after, and will become equally ever-present as today's personal computers and printers. One of the notorious achievements of inkjet printing was the democratization of printing. The affordability of desktop inkjet printers made it possible for ordinary people to print whatever they want from the comfort of their homes. With the materialization of Personal Fabrication, it is the democratization of innovation, technology and manufacture that is being embraced.

4.3 Personal Fabrication and the Internet of Things

Inevitably associated to Personal Fabrication is the principle of open source hardware and software. The Arduino [8] electronics prototyping platform is one of the most used development environments for experimenting with the world of the Internet of Things.

For example, the Safecast project [118] consists of a network of sensors aimed at mapping radiation levels in the environment. The project was born from the need that people want more accurate environmental data than what was available after the earthquake and resulting nuclear situation at Fukushima Daiichi in Japan. By owning an Arduino-based Safecast Geiger counter users are part of the Safecast network and able to share the data collected on an open data set.

Another example is the Smart Citizen project [126]. It consists of a global distributed sensing and data aggregation platform available openly on the internet. The Arduino based sensor kit that enables the Smart Citizen project stocks a handful of sensors capable of measuring the levels of air pollution, noise pollution, temperature, light intensity, and humidity. In the field of home automation, the SmartLiving platform [5] allows makers to use smart plugs in their homes to monitor power consumption and remotely control devices like the television or the lighting, and to create automation rules using a variety of online services.

4.4 Connecting the Dots

The combination of the principles and ideals behind Printed Electronics and Personal Fabrication offers a novel possibility for individuals to create their own smart objects and digital devices, thus re-imagining the Internet of Things reality as it best suits them. These new products are praised for being lighter, more flexible, and less energy consuming than traditional electronics products. But they may be also fabricated in a distributed fashion by the users.

By following a principle of open source, subsequent improvements and adaptations can be easily done by anyone as the devices "blueprints" are shared through the internet. This represents a significant departure from the broadcast model of production of conventional electronics. Each person may become simultaneously the fabricator and the consumer of a product. This "appropriation" will turn Printed Electronics products into extensions of our own selves, reducing or even eliminating the psychological barriers one may have regarding intrusive technological products.

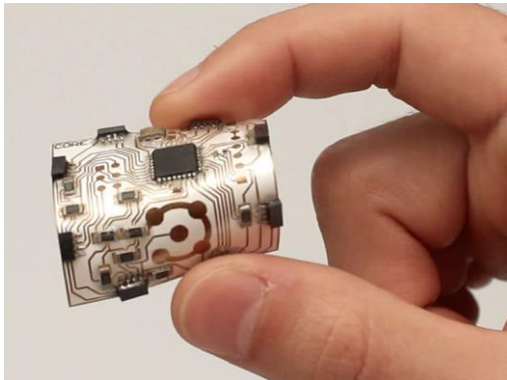


Figure 13: Printoo, a Printed Electronics prototyping platform for the Internet of Things
(Used with permission from [147])

Evidently, the effect that Personal Fabrication can have on driving the Internet of Things, as discussed, is greatly dependent on the advances of Personal Fabrication technologies. This contains the capabilities in enabling passive and active computing components to be directly printed into the materials by using electro-optic functional inks, similar to the ones already used in Printed Electronics. This also contains the capabilities in the fulfillment of what can be called the Ubiquitous Personal Fabrication vision, i.e. the wide spread access to Personal Fabrication technologies to everyone from the comfort of their homes.

From an ideal Personal Fabrication point of view, it would be interesting to explore and further develop fabrication technologies and processes that could make Printed Electronics accessible to the general public. Nowadays, Printed Electronics technologies are mainly available to specialized companies and R&D institutes. In an attempt to change this tendency, various companies recently launched crowdfunding campaigns to make their Printed Electronics products available to everyone. For example, Ynvisible successfully got Printoo (Figure 13) [147] funded, an open-source printed electronic prototyping platform of paper-thin circuit boards and modules on May 2004. AgIC, named after Ag Inkjet Circuit [3], got funded on April 2014, and its development kit transforms home inkjet printers into Printed Electronic circuit board manufacturing equipment. Another interesting example is Circuit Stickers [30], a set of adhesive peel-and-stick electronics for crafting circuits. The circuits can be used in combination with conductive materials such as conductive paint or thread to build interactive projects without any complicated equipment or programming skills.

All these examples illustrate solutions aimed at facilitating the fabrication process of electronic circuits whilst enabling electronics to be integrated in a range of

non-traditional material. They also have the potential to be an effective technology education tool for the general public. More approaches of this nature would be more than welcome. They will allow end-users to develop their own embedded digital devices, enabling them to create their own Internet of Things. In this scenario, technology is being pushed by its own users. Likewise the internet ends up being shaped by its users and its purpose adapted by each one of us, the same might as well end up happening with the Internet of Things.

4 SUMMARY AND CONCLUSIONS

The Internet of Things is unquestionably a compelling vision of the future. It inspires numerous scholars, and becomes a research endeavor embraced by many areas of computer science. It describes a world of connected and intelligent physical devices. Moreover, it entails a new paradigm of interaction between humans and computers.

In this article, it was argued that Printed Electronics offers a new set of opportunities and possibilities for the Internet of Things, by allowing the incorporation of electronic functionalities into objects where it was previously unavailable. It offers a ground-breaking new type of electronics that opens up entirely new markets for applications with novel form factors. Indeed, Printed Electronics has the potential to transform lifeless objects into sensing, interacting interfaces capable of reacting and exchanging information with users and the environment. In turn, Personal Fabrication promises to democratize the creation of technology. Digital fabrication technologies are already unleashing new means for end-users to design and produce their own real-world objects and material goods according to their needs.

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AUTHOR BIOGRAPHIES



Paulo Rosa has a Masters in Environmental Management Systems from the New University of Lisbon and is currently awaiting the defense of his Ph.D. thesis within the UT Austin-Portugal doctoral programme. His Ph.D. research focuses on Printed Electronics and the Internet of Things. It is established as well a connection with Personal Fabrication and the Maker movement, and how these can promote a new vision for the Internet of Things through the democratization of innovation. He is also part of the research team of the Center for Environmental and Sustainability Research (CENSE) at the New University of Lisbon.



Dr. Cristina Gouveia has a PhD on Environmental Engineering from Universidade Nova de Lisboa and has a Master on City Planning from MIT. She has been leading initiatives in the field of spatial data infra-structures and in the use of Information and Communication Technologies for public participation. She is currently Azorean COO, a company focused on developing a new generation of aquatic drones. She is also part of the research team of the Center for Environmental and Sustainability Research (CENSE).



Dr. António Câmara obtained his BSc in Civil Engineering at IST (1977), MSc (1979) and PhD (1982) in Environmental Systems Engineering at Virginia Tech. He was a Post-Doctoral Associate at MIT in 1983. He is a Professor at the New University of Lisbon. He was a Visiting Professor at Cornell University (1988-89) and MIT (1998-99). During his career, António Câmara supervised 40 PhD students, and published more than 200 papers and 4 books, including “Environmental Systems” by Oxford University Press in 2002. He has been the keynote speaker at more than 50 international conferences. António Câmara is a co-founder and CEO of YDreams, and the Chairman of Ynvisible, YDreams Robotics and Azorean, three companies he also co-founded. The work of his companies has been covered by Wired, Fast Company, Forbes, Business Week, Economist, Time, New York Times, Guardian, Liberation, El Pais, Huffington Post, Engadget, Tech Crunch, Cool Hunting, Gizmodo, CNN, CNBC, France 24 and many other international and national media. António Câmara is also a Member of the Board of Audience Entertainment, and of the Roundtable of Entrepreneurs of the European Institute of Technology. He received many national and international awards during his career, including Premio Pessoa 2006 in Portugal, and one of the European Entrepreneur Awards by the European Union in 2009.