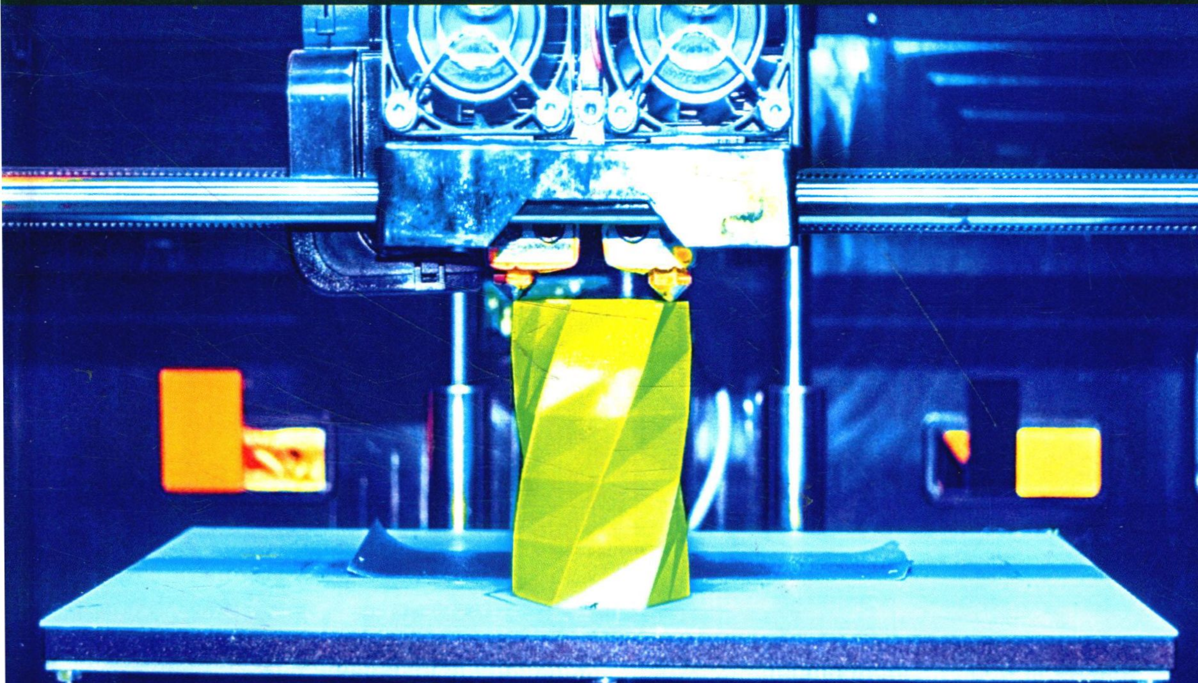
SYSTEMS AND INDUSTRIAL ENGINEERING – ROBOTICS SERIES

From Additive Manufacturing to 3D/4D Printing 1

From Concepts to Achievements

Jean-Claude André



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In 1984, additive manufacturing represented a new methodology for manipulating matter, consisting of harnessing materials and/or energy to create three-dimensional physical objects.

Today, additive manufacturing technologies represent a market of around 5 billion euros per year, with an annual growth between 20 and 30%.

Different processes, materials and dimensions (from nanometer to decameter) within additive manufacturing techniques have led to 70,000 publications on this topic and to several thousand patents with applications as wide-ranging as domestic uses.

Volume 1 of this series of books presents these different technologies with illustrative industrial examples. In addition to the strengths of 3D methods, this book also covers their weaknesses and the developments envisaged in terms of incremental innovations to overcome them.

Jean-Claude André is a Researcher with the CNRS where he works on light–matter interactions. He is responsible for the first ever patent in stereolithography, granted in 1984, and patented a non-layer 3D printing process in 2016. His research focuses on 4D printing and bio-printing.

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Jean-Charles Pomerol

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UK

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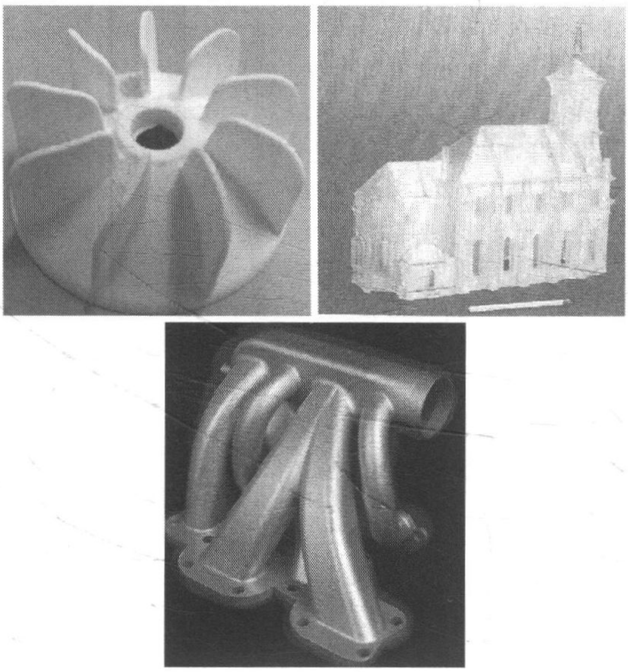

Prototype part (3DCeram, 2017), reproduction of the Église de Bonsecours in Nancy (LRGP, 1994) and metallic part (3A – Applications Additives Avancées, 2017)

Foreword

The evocative expression “3D printing” has been overtaken in everyday speech by the expression generally preferred by scientists and engineers, “additive manufacturing”. In both cases, it is a matter of manufacturing objects in successive layers, and soon every workshop and every school will have a 3D printer and engage in additive manufacturing. Self-service workshops known as fab-labs already offer users the possibility to create their own objects. However, the adventure is not over, as “4D” is coming up over the horizon with materials that evolve over time, not to mention “bio-printing”, which aims to create organs to be used to repair the living. Furthermore, the 3D printing of tomorrow, which will be performed without layers, threatens to make the term “additive manufacturing” obsolete, thereby making it possible to return to the initial concept of 3D printing. Whatever the case may be, we are faced with not only a very active and booming world, but also a complex world that calls on numerous skills in physics, engineering, chemistry of materials and mechanics with a resolutely multidisciplinary and convergent approach.

To understand the origin of the ideas in additive manufacturing/3D printing, learn about the current state of what is known and explore the developments to come, what could be better than to ask one of the inventors of the technology and one of the first French patent holders in the field, Jean-Claude André, to share his knowledge with us? This led to the idea of this 3-volume edition that I am pleased to present; a work that is both erudite and prospective, as its intention is to start at the genesis of the ideas that led to additive manufacturing to anticipate the impact and future of still “additive” technologies and, beyond this, to encourage reflection on the interactions between science and society of today and tomorrow.

If the first patents date back to 1984, an era where lasers, photo-materials and computer-aided design had already been mastered, was the idea of additive manufacturing completely disruptive as would be said today. What was creative was to put all of this knowledge together to come to something entirely new. Nevertheless, approval for the concept of additive manufacturing came rather quickly. It is on this basis that other additive methodologies, currently many of them with very specific niches, could be developed. These range from prototype and industrial parts to art, variable spatial scales – from the decameter to the nanometer –, from the inert to the living, from industrial organizations to very delocalized forms of manufacturing, etc.

On the basis of these works with varied applicative and societal spectrums, some of which are in the process of becoming stabilized, others to be invented, the principles of additive manufacturing can serve as an example, even as a "laboratory" to better understand how the interactions between research and society can (and must) develop, whether this is through new scientific concepts and the associated concepts of creativity, interdisciplinary scientific and technological operations, the popularization of public research, links with society in terms of the creation of new markets and jobs, and also forms of responsibility and ethics.

Throughout these three volumes, the author would like to invite you to reflect on the circuits between the applications that pose new scientific questions and prior research which opens the door to new applications or new products. The more we progress in the field of new niches, the more previously unasked scientific questions are considered, questions whose answers (if they exist) are supported and encouraged by public authorities and industry, which are gaining awareness of an immense industrial and/or medical market, as is the case for bio-printing. From dream to reality, scientists are often in the position to anticipate the length of the path; however, a dynamic is created. This leads to cultural changes and changes in practices, particularly concerning the importance of creativity, sharing enthusiasm for research, openness with others, the multiplying (and sometimes inhibiting) effect of public actors, on the one hand, and the economic world, on the other, as this work illustrates wonderfully.

This saga of additive manufacturing, told by one of its inventors, teaches us that creativity alone does not suffice; it is necessary to have a good dose of perseverance as well, and it is, of course, necessary to keep moving after the first failures. In addition, this shows us that sometimes the research structures and the environment are not entirely receptive to innovation, even when success comes relatively quickly.

Jean-Claude André also explains with great enthusiasm how we give shape to an idea to feed our intuition, which in turn increases creativity. On the whole, these three volumes provide a wealth of information on additive manufacturing, and additionally, they illustrate and encourage veritable reflection on the task of a researcher and research structures, as well as the role of creativity in research, and finally, they invite us to rethink and reinforce the relations between science and society.

Jean-Charles POMEROL
President of the Incubateur AGORANOV
and the ISTE Editions Scientific Committee

Preface

"We have too often forgotten that specialists are created from amateurs, just as soldiers are made from civilians". [LAT 07]

"In France, strangely enough, it is not those used to sailing the seas, the specialists of the real and tangible, who are asked for advice guiding the flagship, but the members of a caste who stay at port and who, for the most part, have only purely theoretic knowledge of the sea". [BEI 12]

"Technology has taken on a new breadth and organization. Here, I am searching for its specific structure, and I have noticed that it exists as a system, in other words, as an organized whole". [ELL 04]

"Those in the organization who have ideas to do things otherwise or better are divided into two categories: those who do not dare and those who dare. Those who do not dare understand very well the risks and the importance of new ideas, but they are paralyzed by risk taking and the fear of displeasing. Having never tried anything, they have not known failure and are thus unharmed by reproach […], they are quitters. Those who dare, the innovators, move forward by challenging conventional ideas, organizations, and sometimes procedures. They stir up fears and a lack of understanding and are truly criticized…". [PHI 12]

"Science has largely renounced an interdisciplinary vision allowing the merits of different results to be faced". [THO 83]

"Theory is when everything is known and nothing works. Practice is when everything works and no one knows why. Here, we have united theory and practices: nothing works... and no one knows why!". [EIN 07]

"These creatures of man [machines] are exacting. They are now reacting on their creators, making them like themselves. They want well-trained humans; they are gradually wiping out the differences between men, fitting them into their own orderly functioning, into the uniformity of their own regimes". [VAL 57]

"Speaking of discipline is designating the scientific activity as a particular form of the division of labor in the social world". [FAB 06]

"The imagination is brilliant in that it produces images that enlarge reality and really invent it". [GUÉ 15]

"In cultural terms, no enterprise is built with dreams alone and none without. Action, if it is to be successful, is by necessity guided by practical circumstances. But the goal of any action is defined, implicitly or explicitly, by the deep nature of the human being, his dreams, his vision of life, his culture. The dynamics of life, the challenge of risk and uncertainty, today require from us a new creative effort leading to the reconstruction and to the re-conquest of the notion of progress, which the philosophies and the ideologies of certainty have shuttered almost to the point of destruction". [GIA 90]

"Researching is inventing the world, it is setting new rules of functioning for an ephemeral world. Not like the tyrants who also invent a new world for themselves, but impose it upon others. The researcher does not recreate the world, but rather unravels it to make it. He/She imagines one, then compares it with the real world to clarify it and not to exhaust it. Researching is an endless quest". [ROS 01]

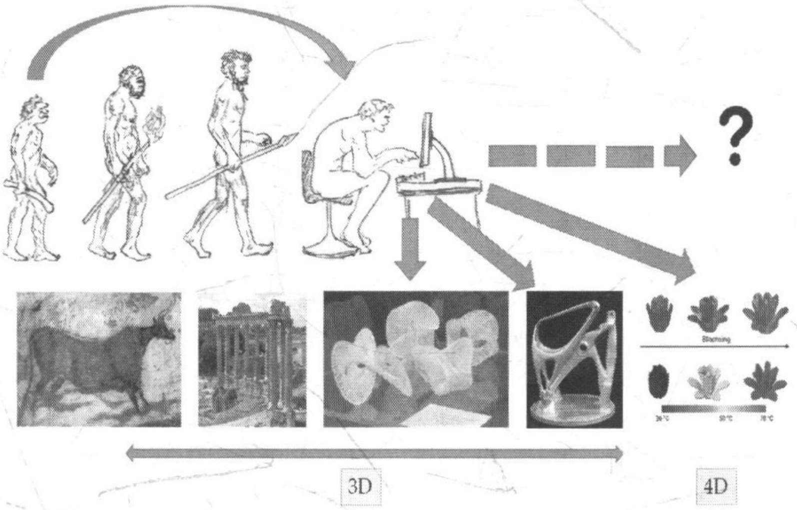

Figure 1. *From additive manufacturing to 3D/4D printing*

This book (in three volumes) is the result of a demand that has been repeated countless times for different reasons, notably among these, of the oversight and the reminder of the oversight to cite a French school that in 1984 succeeded to patent the first additive manufacturing process, stereolithography, several weeks before the Americans (who were working on the same subject, without either party knowing it). However, at the same time, thirty or so years later, it is a history lesson that can be told about a process concept, tossed out in France, without any malice of course, by "clairvoyant hierarchists", the explosion of the research team who felt their future was blocked and an American technical-economic development which has today led to several books and more than 50,000 scientific publications on additive manufacturing, because consequent applicative markets exist with profitable enterprises (and also because there is an immense attraction field around this subject that conditions the actions of a great number of researchers).

So why have we entitled these three volumes "From Additive Manufacturing to 3D/4D Printing"? First, it was about locally bringing material and/or energy to perform a transformation (e.g. from a powder to a solid or from a liquid to a solid). The expression "additive" then takes on its true meaning. But for a short time now, researchers have been developing (or working on) new processes that allow this change to be avoided through the additions mentioned at the start of this paragraph. It thus becomes possible to create an object in one go. Moreover, the use of so-called "smart" materials authorizes the introduction of a complementary parameter, i.e. time or functionality. The 4D aspect is thereby introduced.

The first volume on additive manufacturing is strongly linked to the existence of an effective economic market, one that is already significant, stemming from technological research in the engineering sciences connected to an essential component, that of materials (and of manipulating them to prepare them for manufacturing). It will take several decades for 3D technology to emerge and find its place as a robust technology for manufacturing objects in quite diverse domains. This situation, linked from the start to a strong attractiveness on the part of industrial R and R&D services, has allowed for "field" experimentation with competent users who are more and more demanding in terms of manufacturing qualities (without seeking in this preface to define what this quality, a true portmanteau, represents). Mastery by users, on the one hand, and competition between the bearers of knowledge pertaining to different 3D printing knowledge, on the other, are translated into new demands to be satisfied. In this framework, this demand has in fact made up one of the driving forces of incremental research, a "technology pull" described in Volume 2 (at least as much as is known (or published)).

A solution is good if and only if the concept, its demonstration with the right people, a culture of industrial innovation, and time and finances effectively come together. Maybe at that time, in 1984, there was a closed system of opinion and self-centered management that had not even thought of a possible debate on futuristic technological openings. This conformity to a manufacturing follower style of thinking was more and more often considered to be obsolete. But there was also, beyond socio-economic milieus, an incredible viscosity with many scientists: the most common attitude was not openness to other explicative schemata, but in the majority of cases, the ignorance and/or refusal to accept their existence. Tricks that only imperfectly fit into our ethics as researchers (at the time) must be made and likely developed.

According to estimation methods, the revenue from additive manufacturing lies somewhere between 5 and 40 billion euros (we could think that this is an estimation of the number of protesters in a claim by the police or trade unions!). Some speak of a revolution and others imagine senseless promises (which, according to Audétat [AUD 15], could put every emerging sector in danger); in short, things are booming at present with seven main stabilized technologies and a new kind of governance (Jeremy Rifkin's "makers"). This appreciative placement of the normalizers into categories is indeed rather artificial. Beyond a recent manufacturing technique that associates computer science and matter, 3D printing, with cheaper and cheaper home machines (down to a few hundred euros), constitutes a paradigm shift that impacts product design (which can even be defined, thanks to "open-source" systems), creation (from heavy industry to one's "garage"), consumption and the business models that result from them (from market activity, a new handicraft and DIY (Do-It-Yourself) to counterfeiting).

In fact, the progression rates are always in the double figures (between 20 and 40% per year), which leads some to believe that the additive manufacturing processes will continue to evolve for a long time to become a widespread technology, as they increasingly occupy ever-new applicative niches, quashing the other manufacturing methods that made up the skeleton of 20th Century industrial manufacturing. But what do tens of billions of euros per year represent for the world relative to France's "small" debt amounting to 2 trillion euros? It is therefore difficult to project a future which leads to a possible hegemony of additive manufacturing; besides, it would be more interesting to explore how intelligent synergies can be implemented with technology that emerged long before 1984. Yet, as is resurfaced in Volume 2, there are spaces, still relatively empty, where an attempt is made to challenge the very concept of adding material to processes.

The early 21st Century is marked by the "hegemonic" presence of the digital transition with the technological and practical complements of additive manufacturing processes likely to affect Western society in a quick and profound way. "In the face of radical innovation markets, where the first arrivers can acquire decisive, dominant positions and make the passage of other markets and the economic actors in place disappear, keeping a distance and watching things happen can lead to considerable social and economic costs" [FRA 17]. To go beyond this already uncertain space and become involved in disruptive innovations implies taking risks, thus accepting potential failure, facing their possible negative consequences, and being capable of learning all the lessons this teaches. "If we do not proactively incorporate innovation, this will end up being imposed all the same, in an even more disruptive manner" [FRA 17]. In short, it may be useful to anticipate.

In roughly a century, the number of researchers in Europe has gone from a few thousand to a few million, and despite some disturbances, this trend is continuing. Research activities have been the subject of reassuring discourse on the researcher's independence, on the one hand, and on the other, of a certain programming of research with the aim of achieving goals: security (before the fall of the "Iron Curtain", for example) and economic developments (from mass production with ECSC projects to information and communication sciences and technologies) participating in different forms of competition from France and the European Union.

On this basis, the stereotypical image of the scientist, responsible for the truth and good, is still part of the idealized image, which often positions him/her very highly in relation to a social reality of which he/she only has an imperfect mastery. The will to achieve the best "research efficiency" has led to the promotion of rather mono-disciplinary processes that are easier to manage from "peers", referents of a discipline. On the one hand, in-depth scientific study is maintained by actors from the same field provided that the guarantee of excellence is defined and respected; on the other, for the State, it is easier to realize international comparisons discipline after discipline. Indeed, and this is necessary to remember, without really noticing it, we have gone from a limited worldwide scientific elite to mass research (with tens of thousands of scientific journals) which represents a characteristic that is not discussed by developed nations: research must indeed allow society to respond to the great challenges that loom today: employment, progress, security, global warming, health and quality of life, sustainable development, etc.

Without seeking to speak of two worlds exploring different paradigms, one of in-depth study, the other of responding to social demand (even its anticipation), for this aim would be too limited, rather we look at evolutions translated by a research program that takes account of the different and sometimes antagonistic imperatives (see Volumes 2 and 3). This situation actually shows, at least in part, that the researcher is an element of society who is not independent, even if forms of "grand isolation" have long protected him. But, in the European Charter for Researchers signed by France at the CNRS (National Center for Scientific Research) in 2005, a reminder is given that "Researchers should focus their research for the good of mankind and to expand the frontiers of scientific knowledge, while enjoying the freedom of thought and expression, and the freedom to identify methods by which problems are solved, according to recognised ethical principles and practices."

Without this having been noticed by most of the research actors financed by the State, even if the notion of good is not easily defined (in any case, it does not simply mean the absence of evil), this sentence is a reminder of the role of research centers as a social (or societal) actor, implying new approaches like functioning through interdisciplinary projects and strategic reflections negotiated by stakeholders, stemming from a new prospective work. Considering their importance for the development of citizens' quality of life, research associated with technology is an element that is really starting to be discussed. Indeed, it has participated in the "natural" evolution of things and technological progress has long allowed man to be free from a number of material constraints. In this framework, the rhythm of implementing research results has been greatly modified and complicated, thanks