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# Introduction

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Technological innovation has shaped human lives across generations, but what are the basic forces driving the innovation process? Arguably we can state that the drive for innovation is rooted in the genuine human curiosity for knowledge, the desire to realize ambitious visions, and, at the same time, in the need for progress and comfort in our daily lives.

Automatic control, as an elegant multidisciplinary science that sets systems in motion, has enabled key steps in the history of technological innovation, from the Kalman filter that empowered humans to reach the moon, to optimal and robust controllers today pervasively present in every system and every process across industry sectors. In an environment where the complexity of engineering systems is ever-growing and technology is developing toward more digital and data-based solutions, automatic control is undergoing a transformation by integrating classical methods with data-driven approaches to address the new complexity, thus opening the door to a new chapter in its history. In this context, it is valuable to identify the way automatic control can enable the next innovation steps in different industrial sectors and thus realize its full potential. To address this question from an application perspective, in [1] we proposed a framework at the interplay between incremental improvement and disruptive innovation. The framework, named *the cradle of innovation*, will be presented in Section 1.2 and consists of a sustainable innovation process driven by a long-term vision and market requirements, where system know-how, economical and technical requirements are considered to ultimately bring a brilliant idea into practice.

*The Impact of Automatic Control Research on Industrial Innovation: Enabling a Sustainable Future*,
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The work presented in this volume is part of a broader ongoing effort within the IFAC Industry Committee formed by academic and industrial members and established by IFAC in 2017 with the objective of bridging the gap between industry and academia in the field of automatic control.

Besides providing a framework for the innovation process, the scope of the paper [1] was to link automatic control research to technology innovation. Within this scope, different industrial sectors and government institutions were surveyed, the data were analyzed and translated into technical requirement specifications. Finally, the paper provided pointers to research directions that would address the sustainability challenges across industries.

Starting from this point, with the present volume, we aim to apply the framework of *the cradle of innovation*, expand and detail this concept across six industry sectors.

Building on this vision, in the present volume we invite the reader to join a journey toward the birth of innovation across six specific industry sectors. The journey is inspired by a story that took place in the eighteenth century; the story of the Turk [2], an eighteenth-century automaton that could beat human chess opponents (see Figure 1.1).

The Turk first appeared in Vienna in 1770 as a chess-playing robot dressed in Turkish clothing, seated above a cabinet with a chessboard on top. The operator would assemble a paying audience and invite a challenger to play chess. The automaton would gaze at the opponent's move, ponder, then raise its mechanical arm, and make a move. Of course, the thing was a hack – a clever magician's illusion. The only real ingenuity was a hidden chess player inside the machine.

It is true that the late eighteenth century was a great age of automatons, but the deeper truth that chess-playing was an entirely different kind of creative activity seemed as obscure to people at that time as it seems obvious to us now.

The great-grandfather of computer science, Charles Babbage, saw the Turk and though he realized that it was probably a magic trick, he also asked himself what exactly would be required to produce an elegant solution. What kind of technology would one need to develop in order to build a machine that plays chess? And his "difference engine" – the first computer – rose in part from his desire to believe that there was a beautiful solution to the problem, even if the one before him was not.

Taking inspiration from the story of the Turk, with this volume, we ask the same question for the next generation of products, processes, and services across several industrial sectors: What does the future look like? What is beyond hacking? What would an elegant solution look like?

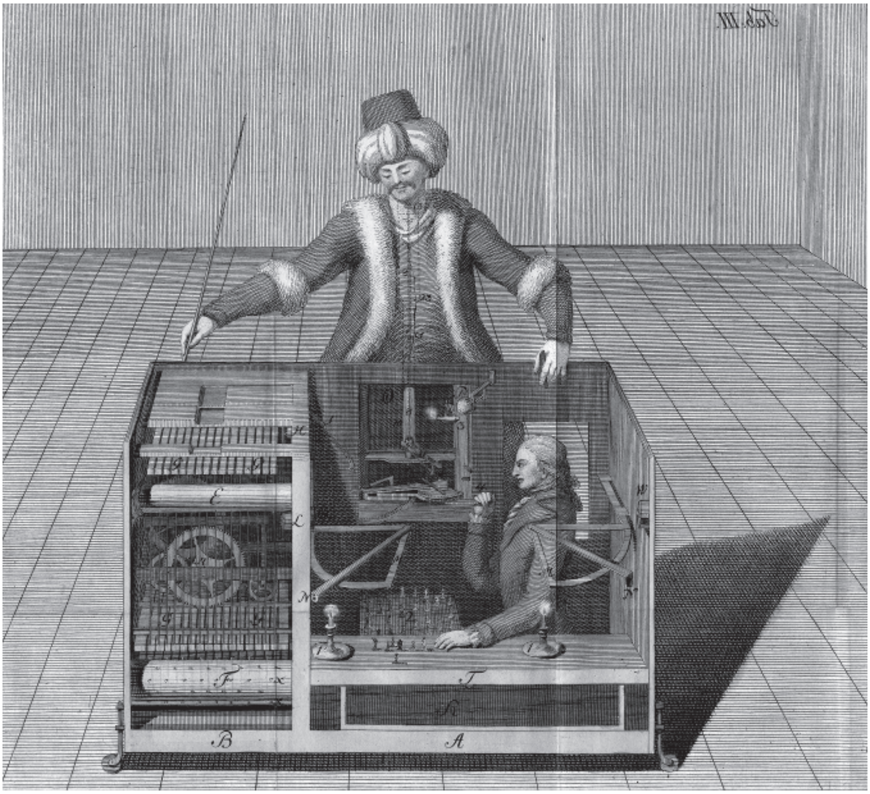

**Figure 1.1** Mechanical Turk or Automaton Chess Player was a fake chess-playing machine constructed in the late eighteenth century. Source: Joseph Racknitz/Humboldt University Library.

The volume includes six chapters and is organized into two main parts: Part I focuses on Infrastructure and Mobility and includes the following:

- Data Industry
- Building Automation
- Automotive Control

Part II addresses Energy and Production and includes:

- Power Conversion Systems
- Robotics and Manufacturing Automation
- Process Industry

Each chapter will discuss drivers and limits to innovation for a specific sector. Starting from customer needs and challenges, and system requirements, an applied research agenda will be formulated.

In addition to the research directions driven by industrial requirements, there are visionary ideas that promise to spark a new drive for innovation and where automatic control plays a pivotal role. Examples of such disruptive visions include the *city of the future* characterized by pervasive automation in the *transportation* (e.g. hyperloop and autonomous cars), *energy* (e.g. autonomous microgrids and $H_2$ economy), *manufacturing* (e.g. Industry 4.0), and *financial sectors*. Additionally, the adoption of control concepts in support of management decision-making could open completely new dimensions with great benefits for both fields.

## 1.1 Background and Motivation

The gap between fundamental control research and practice has been addressed by several authors from different perspectives. In 1964, Axelby [3] observed that "Certainly some gap between theory and application should be maintained, for without it there would be no progress . . . . It appears that the problem of the gap is a control problem in itself; it must be properly identified and optimized through proper action."

In a paper by Bennett [4], a historic overview is given of the landmark developments in automatic control. It began in the nineteenth century, when developments were mainly driven by industrial problems, e.g. the steam engine governor. Later on, the PID controller was developed by Elmer Sperry. The first theoretical analysis of a PID controller was published by Nicolas Minorsky in 1922. Another development highlighted in the paper is the feedback amplifier that enabled long-distance telephony, combining experimental data and mathematical models. In the era of classical control theory, the focus was on the development of rigorous mathematical foundations. Later on, the development was driven and sponsored by aerospace and defense, and the advancements in computing power allowed to solve more complex problems.

Rosenbrock, in his work [5], addresses the dilemma of whether automatic control should further develop toward fundamental theory backed up by rigorous mathematics or engineering more centered around experience and intuition. He points toward future developments where computers enhance the human skills rather than replace them.

Aström and Kumar [6] describe the dynamic gap between theory and practice as rooted in the open-loop process of theoretical research without feedback from practice. With current technology, deployment and implementation of complex control solutions have become simpler, thus reducing the gap between theory and application.

Lamnabhi-Lagarrigue et al. [7] build on this analysis and bring it a step further by describing the cross-fertilization and bi-directional interplay between five critical societal challenges (transportation, energy, water, healthcare, and manufacturing) and seven research and innovation challenges (cyber-physical systems of systems, distributed networked control systems, autonomy, cognition and control, data-driven dynamic modeling and control, cyber-physical and human systems, complexity and control in networks, and critical infrastructure systems). The main recommendation from their analysis is the fostering of both fundamental and application-oriented research in sector-specific programs and in ICT as a program that provides enabling technologies for all sectors.

In the paper by Deng [8], the author provides an overview on developments and application areas in automatic control that are driven by societal challenges such as food production, land use, water, logistics, and e-health.

In his 2020 editorial, Grimble [9] establishes a concise link between historical developments in automatic control and the need for a broader, systems-engineering-driven approach.

In summary, the evolution of automatic control has been driven so far by industry, the requirements for theoretically rigorous foundations, aerospace, defense, and the need to address various societal challenges.

In this volume, we aim to further establish control as a discipline that enables innovation in technology by analyzing the innovation dynamics in more detail for specific industry sectors. We introduce a cyclic process for innovation based on [1], where ideas evolve through various stages of selection and transformation and are finally brought to life. Within this process, we identify barriers, enablers, and key drivers for the process in various industry sectors, then through a thorough analysis, those drivers are linked to system requirement specifications and finally to a control research framework or roadmap.

## 1.2 The Cradle of Innovation

### 1.2.1 A Framework for Innovation

To establish an innovation enabling framework, it is required to identify factors that affect innovation. To this end, we consider two innovation processes depicted in Figure 1.2. The first process, referred to as *research-driven innovation*, starts from an abstract idea, a theoretical concept, that is transformed and finally realized in an application (product, process, or service). The second process, referred to as *market-driven innovation*, starts from customer requirements that define concrete required technology developments and leading to a research portfolio.

In the first process, "*from research to realized application*," a preliminary idea is proposed without considering technical feasibility and financial benefits. The idea is then developed and matured through different stages to be finally implemented in a product or process. At each stage, the idea undergoes a transformation and often does not survive the feasibility and profitability tests that are posed at each stage.

In the process "*from customer needs to research focus*," the starting point is the customer intended as the end user of a specific technology, the market, and in a broader sense, society and its needs. The customer might not have know-how about the technology, but he or she can provide user requirement specifications for a product or process, that is, what are concrete characteristics that he or she would like to see in the product. Those specifications are then translated into product requirement specifications and finally into technical requirement specifications.

In both approaches, once a vision of the next generation of product, processes, or services is formed, the next step is the identification of the key challenges toward the realization of the vision.

The flow in the cyclic innovation process described in Figure 1.2 is catalyzed by systematically translating customer requirements into technical requirements and finally populating the research portfolio. Similarly, an idea is matured through a multi-stage transformation process, where profitability and feasibility criteria are considered while shaping the idea from one stage to the next, until its realization into practice. This requires properly balancing the research agenda so as to include fundamental and implementation aspects.

Vision-driven innovation tools, like design thinking, but also agile and scrum methods, serve to increase the effectiveness and speed of the idea transformation process at each stage.

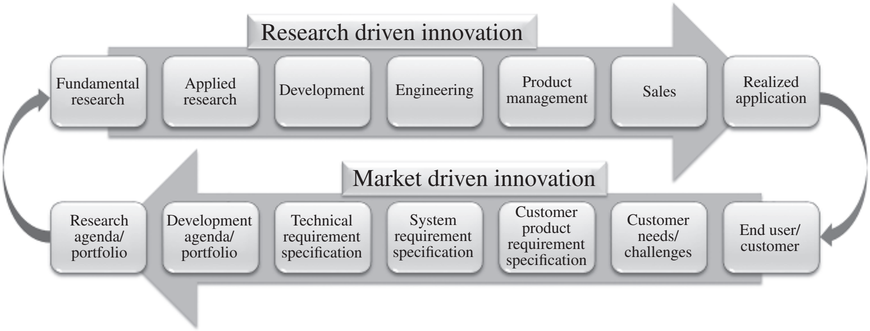

**Figure 1.2** From research to realized application, from customer needs to research focus.

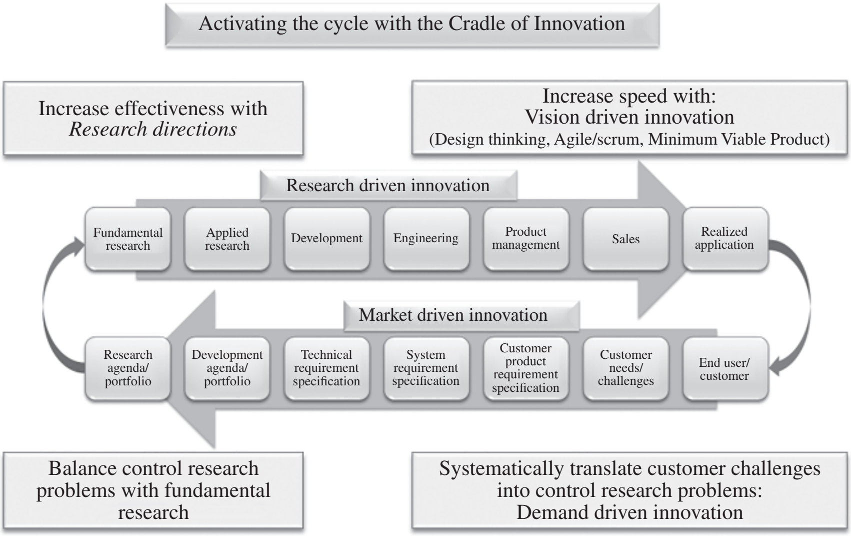

**Figure 1.3** The framework to close the gap, enabled by the cradle of innovation.

In both processes, we can additionally characterize innovation as disruptive or incremental. Disruptive innovation is mostly guided by a long-term vision that looks beyond the existing technology, and it is typically accompanied by larger risks. Examples of such disruptive innovations are the touch screen (invented first by IBM but really made disruptive by Apple's Steve Jobs) and the Solar-X program.

Incremental innovation is characterized by smaller improvements in the current technology as it takes into account the constraints and limitations in implementing the innovation, and it is a structured process and requires analysis of each step. It is, however, limited in its possibility to accommodate substantial innovation.

In the case of incremental innovation, the probability of successfully driving an idea into the market is estimated to be up to 60–75% for an innovation using existing technology in the company and intended for the company's current market, see [10]. This success rate decreases significantly to 5–25% for "out of the box" innovation.

Disruptive innovation is such a rare stone and without proper grounding in the majority of cases, the initial idea dies at some point between the vision and the implementation phase. On the other hand, the incremental innovation without a long-term vision can bring a technology to complete alienation as non-properly planned incremental steps will accumulate creating an unmanageable complexity.

Combining an incremental innovation with the vision of a long-term solution can lead to a sustainable and rich process that allows for the realization of a minimum viable product that can accommodate subsequent innovation steps. Starting from the two innovation processes depicted in Figure 1.2, the cradle of innovation offers the means to link the two in a circular process and activate the flow as depicted in Figure 1.3.

Disruptive innovation or vision-driven innovation is rare in most industry sectors due to the high risks that it entails. Typically, the most disruptive innovative sectors are those related to consumer products where there is enough demand for novelty and less for reliability. The trade-off between innovation and reliability seems to often require compromises, one interesting exception in the automotive sector is Tesla, where high demand drives disruptive innovation but also addresses safety requirements.

The literature on innovation processes is widely dominated by vision-driven innovation often referred to as design-driven innovation, where the concept of design thinking, as explained by T. Brown [11], with its focus on creativity and experimentation, plays a fundamental role; see [5]. Often those approaches to innovation begin with a brainstorming phase based on the dream question: imagining to wake up five years from now and all of industry and societal problems have been solved; how does this vision of the future look like? Some examples of those visionary ideas are: man to the moon, iPhone, touch screen, bullet trains, and flying reconfigurable cars running on solar energy. Realizing such visions will require an extensive combined effort from several interdisciplinary fields, from fundamental to applied results.

### 1.2.2 What Drives Innovation?

The probability to successfully introduce a new technology in the market is correlated to the measure in which the technology meets customer requirements at affordable time and cost. This principle is reflected in a standard product development process, where the customers are surveyed about the limitations of the current product and the desired features for the next generation. Based on those inputs, product requirement specifications are defined. In the second stage, those requirements will be translated into technical system requirement specifications by asking the critical question: what would it take to make it happen? Here a combination of creativity and technical know-how is required to understand possibilities and limitations.

Some key drivers for the next-generation technology that have been identified across industry sectors are: cost, time to market, energy, efficiency, process availability, performance, quality, reduction of variability, throughput, yield, sustainability footprint, and digitalization.

Different sectors exhibit specific innovation drivers related to the nature of their business, some examples of key differentiating factors are: B2C versus B2B business, market and business size, competitive versus niche markets and businesses, with or without safety requirements. Those factors determine to a large extent the dominance of one or more drivers. Interesting differences across sectors are the focus on quality and reliability, for example, in the aerospace sector, where factors such as safety and human psychology play a dominant role. In sectors where safety does not play a dominant role cost and time to market tend to be key drivers. This is typically characterized by sectors that focus on consumer products but not exclusively.

Other interesting differences can be observed in robotics, with the main focus on productivity, and IT, with a focus on time to market; as typical consumer product businesses, the high competitiveness requires agile development. In the energy, oil and gas sector, cost, and reliability play a dominant role in addition to availability. In some applications, the optimality of the process performance is secondary with respect to the process availability. As an example, for a power converter driving a gas pipe, every hour of inactivity leads to major losses or blackouts in an electric grid. For the process industry, cost and quality dominate the scene, here, the proximity to consumer product defines the high priority of quality. The drivers presented here provide a lighthouse to identify the direction of the research effort; the next step is to determine the path to reach this goal and specifically identify what are the obstacles in the way.

### 1.2.3 Challenges Toward Enabling Innovation

Identifying innovation drivers contributes to shaping a vision and defining a direction for technological innovation. The next step is the identification of the obstacles toward the realization of the vision. From the survey results reported in [1], the following limiting factors related to technology have been identified across different industrial sectors: *abundance of data – but limited contextualization*, *data acquisition from the field and data reliability*, *design and development time, agile approach*, *complexity of system and solution*, *solution integration within the full process or product*, *security*, and *cost*. Additional context-based points have to be considered that are not directly related to technology, but represent obstacles toward establishing the innovation processes. Some examples are: maturity of the industry and its adaptation to the deployment of new technology, training of developers and operators, legacy processes, change management, open platforms across vendors, IT, human factors, and market acceptance.

Similarly, we can identify innovation enablers that are beyond technology and related to societal factors. Starting from the education system, we may ask whether we are shaping the new generation to be free thinkers and innovators and whether we are offering stimulating study and work environments. To innovate requires thinking out of the box, exploring nontrivial directions as well as a comprehensive system understanding and knowledge of the process through which an idea is implemented in a product.

Business and industry broadcast that future-ready employees need to have multiple areas of expertise or at least appreciate how a range of skills fit together. Grimble [9] especially highlights the need for control engineers to have additional skill sets, including broader system understanding, implementation aspects, application knowledge, and economic aspects, to identify potential and limitation.

Additionally, a greater need for the education system has been recognized in order to integrate science, technology, engineering, and maths (STEM) concepts with the arts (STEAM) across the wider curriculum. Control design is also an "art" [5]. Human minds excel in pattern recognition, assessment of complicated situations and have an intuitive leap toward new solutions. Those skills should be cultivated in young innovators. As for the work environment, as argued in the Free innovation paradigm [12], companies like Google have been experimenting with ideal environments for creation, with large spaces for thinking, discussing, and generating ideas. But there is more when it goes to motivation and creation. A series of studies on work motivation carried out at MIT, and summarized in [13], describes the intrinsic nature of human motivation, highlighting the main aspects that drive sustainable motivation: autonomy, mastery, and purpose. The author argues against old models of motivation driven by rewards and fear of punishment, dominated by extrinsic factors such as monetary reward. Finally, the drive for innovation does not stop at the formulation of an idea, the knowledge, and capability to bring the idea into the real world requires the alignment of economic and technical requirements. This process can be simplified if the idea was originally conceived with the techno-economical aspects of the end product.

## 1.3 Final Remarks

With this volume, we offer an industrial perspective on the future of control research, highlighting its impact on technological innovation and opportunity for technology transfer. The main scope is to create a bridge between the control research community and the various industry sectors.

The volume is dedicated to three main groups: (i) the scientific and technical control community, including researchers and control engineers in academic, government, and industrial institutions. For this group, the volume offers a possible research agenda leading to sustainable technological innovation. (ii) Industry representatives: product managers, project managers, and business owners who are aware of the key innovation steps required in their specific fields. This group has a vision for the future product/process/service and wants to learn how it can be enabled. (iii) Academics that use the volume as reference material for graduate courses or continuing education, e.g. graduate course: "Control practice and its impact in the future of industry." The volume provides students with links between theory and practice and insights into the various industry sectors where control can enable technological innovation.

Finally, the next chapter in the history of technological advancement has to consider the reality of limited natural resources. A large portion of the industry will focus in the next 10–20 years mainly on moving from fossil fuels to electricity (energy transition) and further reducing the ecological footprint, according to the UN's sustainable development goals. But energy is only one of several limited resources we rely on, water, mineral, energy, and biological resources will pose our next challenge.

Performance and efficiency can no longer be the only criteria considered for innovation. Sustainability has to become part of our objectives, constraints, incentives, and decision making when we engineer new solutions.

Automatic control, as a rigorous discipline that connects the foundation of elegant mathematics with the application aspects of engineering, has a pivotal role in orchestrating the multidisciplinary group to address the societal and technological challenges for a sustainable future.

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