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# The impact of control research on industrial innovation: What would it take to make it happen?

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ABSTRACT

The history of automatic control narrates how this pervasive discipline has enabled large leaps in technological innovation as well as impacted our everyday lives by driving our energy and transportation systems, industries and cities. Automatic control has evolved in time in synchronicity with the surrounding technology, from analog to digital control, from linear to nonlinear and hybrid control. In an era of further technology transformation, encompassing digital and energy transitions, it is paramount to define how control is evolving to take part in this transformation. Looking at the innovation process led by societal needs and long term visions, we propose a framework to increase the impact of control research on technology innovation. Our journey begins by formulating an idea, a vision and asking the fundamental question: *what would it take to make it happen?*.

## 1. Introduction

Technological innovation has shaped our 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 sent the man to the moon, to optimal and robust controllers today pervasively present in every system and every process across industry sectors. In a framework where the complexity of engineering systems is ever-growing and where technology is developing towards more digital and data-based solutions, automatic control is undergoing a transformation by combining classical methods with data-based approaches to address the new complexity, thus opening the door to a new chapter in its history. In defining this transformation, it is valuable to identify how 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, we propose a framework at the interplay between incremental improvement and long term vision. This framework, that we name *the cradle of innovation*, consists of a complete innovation process driven by a long term vision and market requirements, where system know-how, economical and technical requirements are considered to finally bring the idea into practice.

The work presented in this paper is part of a larger ongoing effort within the IFAC Industry Committee formed by academic and industrial members and established by IFAC in 2017 with the objectives of bridging the gap between industry and academia in the field of automatic control.

Besides providing a framework for the innovation process, we aim 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 and finally pointers to research directions to be pursued in order to continue enabling societal and environmental progress.

In this paper we invite the reader to join a journey towards the birth of innovation inspired by a story that took place in the 18th century. That is the story of the Turk (Standage, 2003), an 18th Century automaton that could beat human chess opponents, see Fig. 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 stiff but certain move of its own. It played games with several historical figures including Benjamin Franklin. Of course, the thing was a hack - a clever magician's illusion. The only real ingenuity was a hidden chess player inside the machine.

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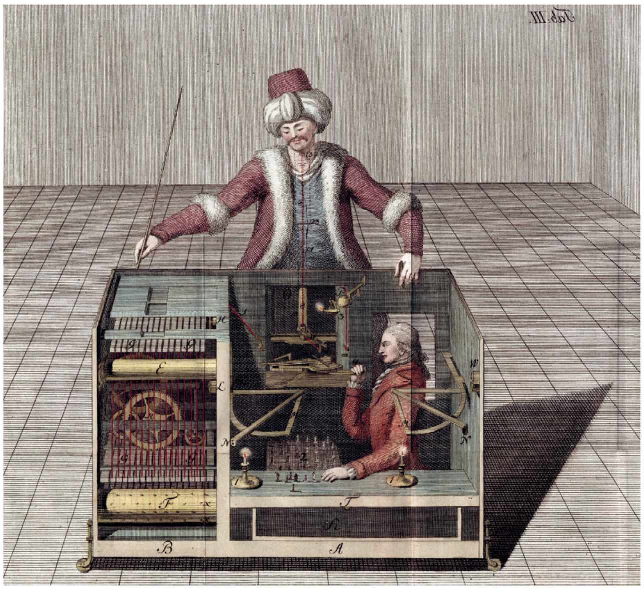

**Fig. 1.** Mechanical Turk or Automaton Chess Player was a fake chess-playing machine constructed in the late 18th century. (Joseph Racknitz).

It is true that the late 18th Century was a great age of automatons, machines that could make programmed looms weave and mechanical birds sing, but the deeper truth that chess-playing was an entirely different kind of creative activity seemed as obscure to them 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 a beautiful solution. What kind of technology would one need to develop 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 it.

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

The paper is organized as follows: in Section 2 we provide a background and reference to previous literature on the gap between research work and applied results in automatic control. In Section 3 we introduce the *cradle of innovation* as a framework for generating technological innovation. In Section 4 the initial part of the survey is presented and the results analyzed focusing on identifying industry clusters and their products, processes or services and within those determine the current utilization of control technology. Section 5 is dedicated to define the key drivers for innovation. Section 6 describes the key limitations for innovation in each cluster and Section 7 presents the research directions in automatic control that will enable the technological innovation process in the various clusters. Section 8 discusses limitations and enablers beyond technology, and Section 9 is finally dedicated to reflection and conclusions.

## 2. Background and motivation

The gap between fundamental control research and practice has been addressed by several authors from different perspectives. In 1964 Axelby (1964) 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 (1996), a historic overview is given on the landmark developments in automatic control. It begins in the 19th century, where 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. His observations grew out of efforts to design automatic steering systems for the U.S. Navy. 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 (Rosenbrock, 1977), addresses the dilemma of whether automatic control should further develop towards fundamental theory backed up by rigorous mathematics or engineering more centered around experience and intuition. He points towards future developments where computers enhance the human skills rather than replacing them.

Aström and Kumar (2014) 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 has become simpler, thus reducing the gap between theory and application.

Lamnabhi-Lagarrigue et al. (2017) 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 & human systems, complexity and control in networks, critical infrastructure systems).

The main recommendation from their analysis is the fostering of both fundamental and applications-oriented research, in sector-specific programs and in ICT as a program that provides enabling technologies for all sectors.

In the paper by Deng (2012), 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, e-health. In his 2020 editorial, Grimble (2020) 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 theoretical rigorous foundations, aerospace, defense and the need to address various societal challenges.

One example of a systematic approach to industrial innovation was provided in 2009 by the German process industry automation end user association NAMUR, presenting an analysis of research directions for industry and academia (Hagenmeyer & Piechottka, 2009).

In this paper we provide a framework 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 where ideas evolve through various stages of selection and transformation and are finally brought to life. The tool adopted to identify barriers and enablers in the process is a systematic survey that reveals the key drivers for control in various industry clusters, through a thorough analysis those drivers are then linked to system requirement specifications and finally to a control research framework.

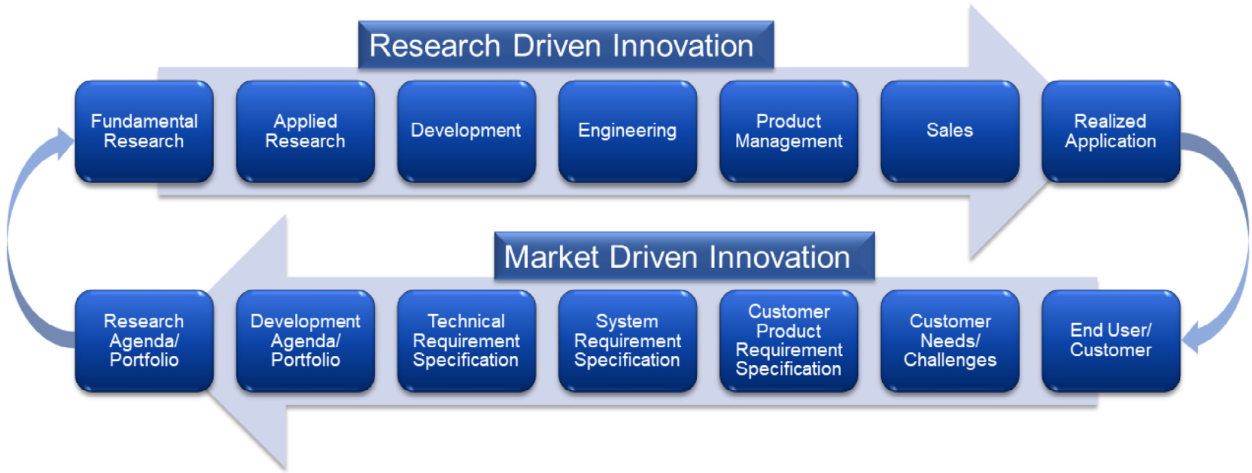


**Fig. 2.** From research to realized application, from customer needs to research focus.

## 3. The framework explained

Following Axelby's formulation of the theory-application gap as a control problem (Axelby, 1964), we consider two linked innovation processes depicted in Fig. 2. The first process, referred as *research driven innovation*, begins from fundamental research and ends into a realized application (product, process or service). The second process, referred as market driven innovation, starts from customer needs and ends into a research portfolio.

In the first forward process *"from research to realized application"* a preliminary abstract 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 goes through a transformation and often does not survive the feasibility tests that are posed at each stage. In the process *"from customer needs to research focus"*, the starting point is the customer intended as end user of a specific technology. The customer might not have know-how about the technology, 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 in technical requirement specifications.

In both processes road blockers and opportunities are identified, ideas and requirements are selected based on technical and economic considerations. The five societal challenges and the seven research directions proposed by Lamnabhi-Lagarrigue et al. (2017) already provide high level selection criteria for the ideas and requirements at each stage. However, a selection process based on local bias carries the risk of missing important information. We argue in this paper that the idea selection process should also be driven by a long term vision with focus on overcoming local limitations.

The purpose is to activate the flow in the innovation cycle by identifying obstacles and enablers at each stage driven by a global view.

The survey results presented and analyzed in this paper capture industry specific challenges and the associated research directions to address the challenges. The survey was carried out in 2019 among

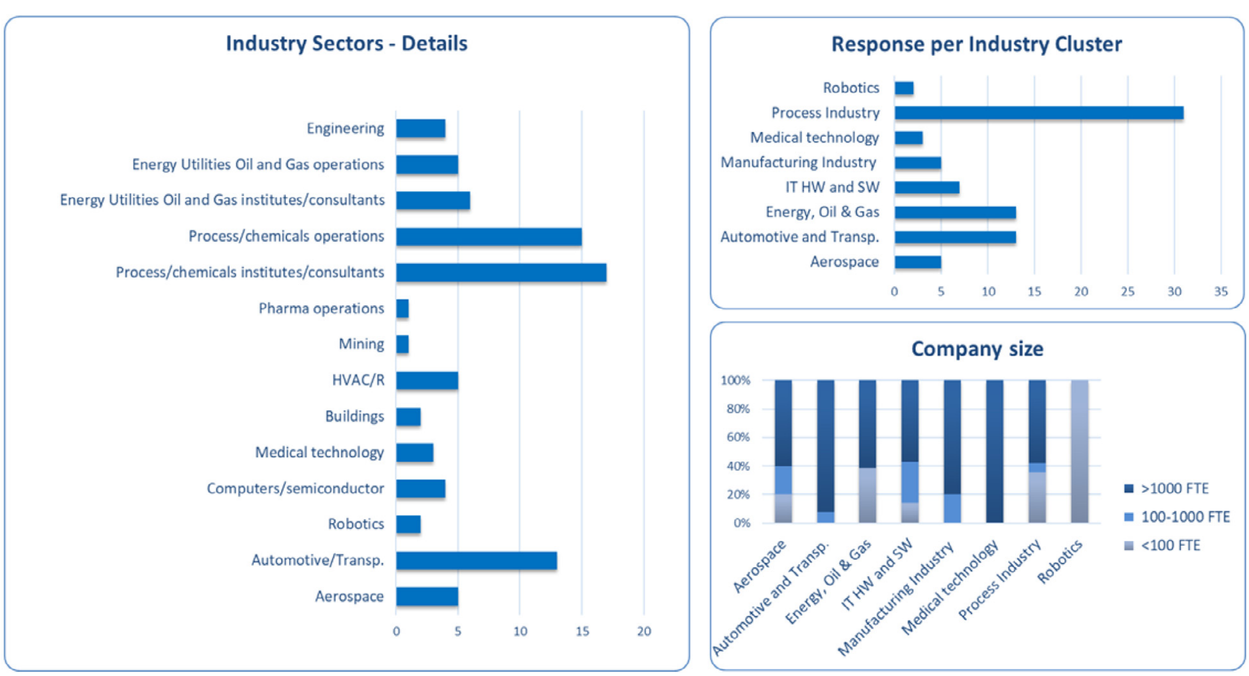


**Fig. 3.** Respondents from all industry sectors, translated into 8 clusters relevant for further processing of results.

a variety of academic and industrial participants and the results are summarized in the following sections.

## 4. Industry clusters and their key products, processes or services

In order to effectively analyze the survey results, we have divided the respondents from all industry sectors into eight relevant clusters (see Fig. 3): automotive and transportation, energy, oil and gas, aerospace, robotics, process industry, medical technology, IT hardware and software, discrete manufacturing industry. This organization in clusters was chosen as it best reflects the distinctions between industry drivers and associated control research problems. As an example, we may expect the process oriented industry clusters (process industry, energy, oil & gas) to be more focused on the application rather than control technology itself, since their prime deliverables are processed products (see Fig. 4).

In a second step of the survey we investigated the actual employment of control solutions into existing technology and their pay-back time, as represented in Fig. 5 and Fig. 6.

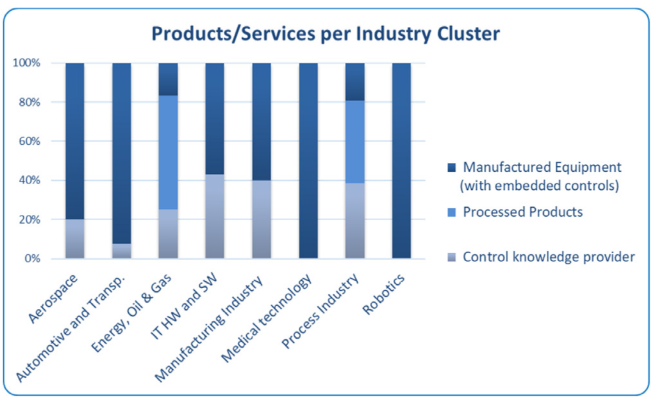


**Fig. 4.** Process oriented Industry clusters more focused on application rather than control technology itself.

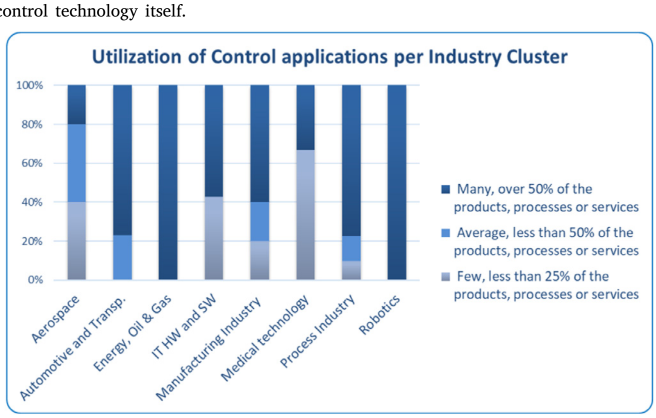


**Fig. 5.** Aerospace, IT, Medical and Manufacturing are applying less than the other clusters.

## 5. The cradle of innovation

In Section 3 we considered two processes in technological innovation: research driven and market driven innovation. The former approach is mostly guided by a long term vision that looks beyond the existing technology, it is typically accompanied by larger risks and does not account for the present constraints. Examples of such disruptive innovations are the touch screen of Steve Jobs and the Solar-X program of Elon Musk. In the latter approach the starting point is the customer, the market and in a broader sense the society and its needs. This path is often composed of incremental improvements as it takes into account the constraints and limitations in implementing the innovation, it is

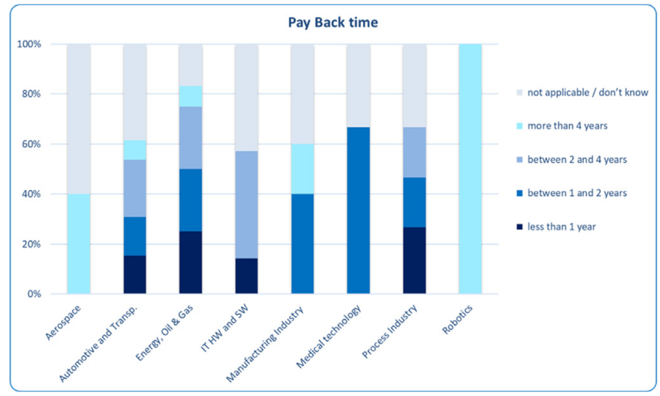


**Fig. 6.** Process oriented clusters, Automotive, IT and Medical: best pay back. Less benefits in Robotics and Aerospace.

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, customer-driven innovation, the probability of successfully driving an idea in the market is estimated up to 60%–75% for an innovation using existing technology in the company and intended for the company's current market, see Day (2007). This success rate significantly decreases down to 5%–25% for "out of the box" innovation. Disruptive innovation is such a rare stone and without proper grounding in the majority of the 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 to realize a minimum viable product that can accommodate subsequent innovation steps. Starting from the two innovation processes depicted in Fig. 2, the cradle of innovation offers the means to link the two in a circular processes and activate the flow as depicted in Fig. 7.

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

The flow in the cyclic innovation process can be catalyzed by systematically translating customer requirements into technical requirements and finally populating the research portfolio. Similarly an idea can be accompanied through a transformation process considering at each stage, which issues have to be addressed to move the idea forward so that it can take shape into practice. This requires to properly balance the research agenda so as to include fundamental and implementation aspects.

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

The proposed framework is aligned with Lindegaard (2010), who states in his work on *The Open Innovation Revolution*: "Embracing the outside requires that you understand the inside". The topic of different innovation paradigms in academia and industry has also been addressed by von Hippel in the article (von Hippel, 2017), where the author refers to the *Free Innovation paradigm* as driven by individual rewards rather than market requirements. In contrast, the *Producer Innovation paradigm*, begins with and relies solely on market requirements.

### 5.1. Demand driven innovation: next generation of products and processes

The probability for a new technology to be successfully introduced in the market is correlated to the measure in which it meets customer

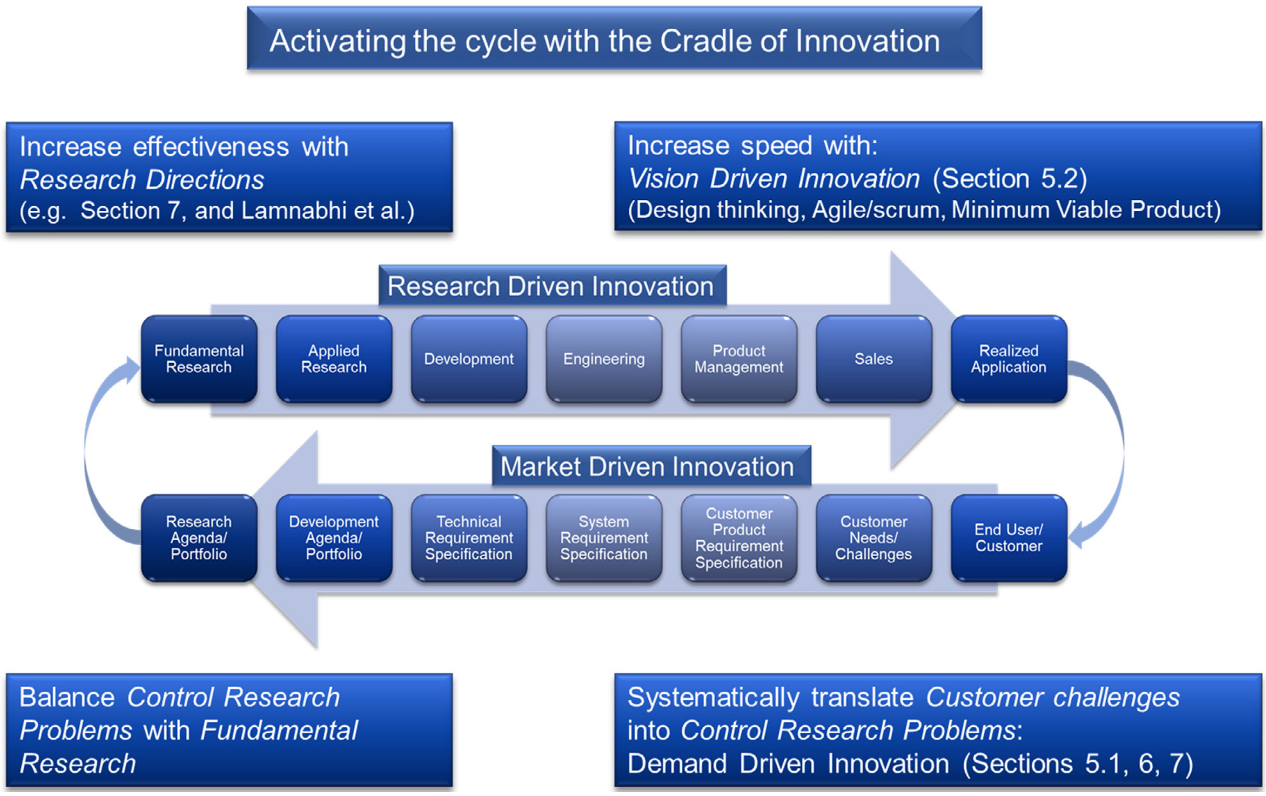


**Fig. 7.** The framework to close the gap, enabled by the cradle of innovation.

requirements at affordable time and cost. Following this principle, a good measure of the potential success of a product can be captured by the degree in which it matches the requirements of the end user. In a standard product development process the customers are typically surveyed to learn about the limitations of the current product and the desired features in the next generation. Based on those data, the strategy is established by defining drivers and product requirement specifications. The descriptive requirement specifications are at this stage still qualitative, often non-technical. In a second stage those requirements will be translated in technical system requirement specifications by asking the critical question: what would it take to make it happen? Here a combination of creativity and insight in the technology is required to understand possibilities and limitations, as stated by Rosenbrock (1977). To identify possible visions of future technology in each industrial cluster, we asked the participants in the survey to rank some key drivers for the next generation technology that have been identified across industry clusters: cost, time to market, energy, efficiency, process availability, performance, quality, reduction of variability, throughput, yield, sustainability, footprint, digitalization. The results for each cluster are reported in Figs. 8 and 9.

Different clusters exhibit specific drivers profiles related to the nature of their business, some examples of key factors are: B2C versus B2B business, market and business size, competitive versus niche markets and businesses, with or without safety requirements. Those parameters determine to a large extent the dominance of one or more drivers. Interesting differences across clusters are the focus for the medical cluster on quality and for aerospace on reliability, here factors such as safety and human psychology play a dominant role.

With the exception of medical technology, in all other clusters cost and time to market are key drivers. This is typically characterized by clusters that focus on consumer products but not exclusively. Both those aspects have been often addressed by outsourcing the product engineering and development to low cost countries. We believe that the aspects of cost and time to market can alternatively be addressed by elegant technical solutions. One example is the cost saving associated with replacing hardware based inertia solutions, such as reactive elements in power converters or grids, with stabilizing control solutions.

Other interesting differences can be observed in robotics with the main focus on productivity and IT with focus on time to market, as typical consumer product businesses the high competitiveness requires agile development. In the energy, oil&gas cluster, cost and reliability play a dominant role additional 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, again here the proximity to consumer product defines the high priority of quality.

Digitalization is for many clusters a relatively new entry in the drivers and did not appear in practice to have the urgency and strong requirements initially expected, despite the strong global trend. On the other hand digitalization, as a driver towards innovation belongs closer to the more disruptive vision driven innovation. The drivers presented here provide a lighthouse to identify the direction of research effort, the next step is to determine the path to reach this goal and specifically identify what are the obstacles in the way.

### *5.2. Vision driven innovation: how does the future look like*

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, with its focus on creativity and experimentation, plays a fundamental role, see Rosenbrock (1977). 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. To realize such visions will require an extensive combined effort from several interdisciplinary fields, from fundamental to applied results.


**Fig. 8.** Key drivers for innovation in the aerospace, automotive, energy and robotics clusters.

## 6. What prevents to make it happen: identify challenges towards enabling innovation

The identification of the drivers to innovation contributes to shaping a vision and defining a direction in which the technology is expected to evolve. The next step is the identification of the obstacles towards the realization of the vision. We questioned the participants of the survey about the key challenges in enabling innovation. The identification of the bottlenecks provides a pointer towards the work required to unblock the stream of technological progress. From the survey results the following limiting factors have been identified

*Abundance of data — but limited contextualization*: In the last decade the importance of data in condition monitoring and control has been recognized. As the complexity of systems and processes increases, first principle models reach their limitation and data driven approaches become key. However often there is still not a clear characterization of the role that data can play in a specific context.

*Data acquisition from the field and data reliability*: The form, rate and quality of data have a strong impact on the performance of the algorithm that will use the data. In other words, any data-based algorithm is as good as the data that it uses. Classification methods have to be established to evaluate data quality based on the specific application.

*Design and development time, agile approach*: Time-to-market is key in any competitive business, in particular in consumer products, as shown in Section 5. Once the research and development is complete, the deployment process requires as much effort and attention. Here a concept of automated deployment could eliminate critical barriers.

*Complexity of system and solution*: The increase of the plant and control solution complexity results in a unmanageable system often prone to failure and at best to under performance. Here the challenge is to handle a highly complex system in all its parts while maintaining structure and overview. Modularity is a key aspect in handling complexity. Modular automation, already adopted in the manufacturing industries, is gaining importance in the process oriented clusters as well.

*Solution integration within the full process or product*: One additional aspect correlated with the growth of system and control complexity is the integration of the controller within the whole system. This interoperability requires a system level approach that considers components as well as their interconnection.

*Security*: The topic of wireless secure data networks and cyber security is strongly related to the deployment of controllers within IoT applications. Additionally, the tendency towards more data-based approaches requires a special emphasis on security for the data. Data security issues for field measurements, modularity and optimization for encrypted data have to be addressed.

*Cost*: Cost represents across all clusters one of the key challenges towards innovation. Cost reduction can be tackled from different directions, here we focus on modularity of solutions, automated configuration and maintenance, requiring less human support/oversight. Intelligent control to reduce hardware cost, improving efficiency can also contribute to cost reduction.

## 7. Research directions in automatic control

To complete our journey towards technology innovation, we identify here the research directions in automatic control that have the potential to drive technological innovation in the various industry clusters. In the final step of the survey we asked the participants to suggest how could automatic control contribute to remove roadblocks and enable an innovation leap. The results of the survey are analyzed and presented in the form of research directions in which the automatic control research community should focus its efforts to enable technology evolution.


**Fig. 9.** Key drivers for innovation in the manufacturing, medical technology process industry clusters.

*Integrated plant design optimization and control*: Control, often referred to as a "Hidden" technology (see Aström & Kumar, 2014) is in many cases an add-on feature consequent to plant design that determines how the process will be operated. Simultaneous plant and control design leads to increased overall performance and optimal plant operation, reduced cost, improved stability and safety (Grimble, 2020; Rijnsdorp, 1991).

*Control based on data and system model know-how*: In many applications data-based methods provide high performance system operation. However, in all applications where the model is even partially known, model-based methods bring clear benefits including performance guaranteed, structure and a systematic approach. One possible evolutionary step for automatic control is to combine the classical model-based approaches with the newly data-driven methods, Bennett (1996).

*Industrialization of the established advanced control techniques*: One point that has been recognized as critical across industrial clusters is the substantial gap between the research results and solutions effectively deployed and adopted in practice. To overcome this limitation more research effort should be placed towards the deployment of existing research results, for example by considering additional constraints in the problem, address computational and complexity aspects, (Grimble, 2020; Rosenbrock, 1977).

*Data-driven and model-based methods for diagnostics and prognostics*: Once the plant architecture and the controller that defined its operation are designed, the system will go in operation and begin its life-cycle. With increased system complexity another topic becomes of paramount importance across the whole system life-cycle: monitoring for diagnostics and prognostics. Being able to locate a fault and scheduling predictive maintenance has a significant financial impact on the value of a product or process.

*Improve reliability and availability of products and processes, i.e. self-healing systems*: In some applications optimal performance is secondary with respect to continuous system availability. That is the case for large production plants, power installations, gas and oil plants and even more critical applications where human lives are at stake, automotive, railways, med-tech. The research direction here should lead towards self-calibrating systems that can dynamically and autonomously adapt.

*Improved man machine interface, design tools*: The deployment of any solution requires integrating and maintaining the solution in an application considering the complete product life cycle. This includes not only training of the operators from the industrial side, but also efforts from the research community to develop user interface and design tools that will reduce the complexity degree in implementing and maintaining the solution.

In addition to the research directions listed above, which are mainly driven by industrial requirements, there are currently visionary ideas which promise to spark a new drive for innovation and where automatic control plays a pivotal role. Those visions include the *city of the future* characterized by pervasive automation in the *transportation* (e.g. hyperloop, autonomous cars), *energy* (e.g. autonomous microgrids, H2 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.

Finally, we offer one concrete example for traction power converters to demonstrate how system requirement specifications can be translated to technical requirements specification and finally research directions in control. In Table 1 the user requirements for the traction power converter are summarized in the left column as: space and weights reduction, improvement of the all life-cycle cost, capability of meeting stringent standards requirements such as limiting harmonic injection. The technical experts are then responsible to define specific technical requirements for the design and operation of the converter that will fulfill the customer requirements. Note that there is not necessarily a one to one map between the customer and the technical

**Table 1**
User requirements vs technical requirements and research agenda for traction power converters.

| User requirements specifications | Technical requirements specifications | Control research agenda |
|---|---|---|
| UR1 — Volumes and weight reduction | TR1 — Improved power flow dynamics across the chain [UR1–UR5] | RA1 — Optimal control [TR1–TR3, TR5] |
| UR2 — Standards with strict requirements | TR2 — Reduced switching losses [UR1, UR5–UR6] | RA2 — Control with multiple data-rates [TR1] |
| UR3 — Improved system life-cycle cost | TR3 — Increased robustness margin [UR2–UR4, UR7–UR8] | RA3- Data driven Control [TR1, TR4–TR5] |
| UR4 — Reliability (panto bounce, slip/slide, sensor loss) | TR4 — Adaptive recovery [UR4] | RA4 — Estimation [TR1, TR3–TR5] |
| UR5 — Energy efficiency | TR5 — Maximized traction effort [UR3, UR6–UR7] | RA5- MPC [TR2] |
| UR6 — Reduced cost | | RA6 — Integrated plant design and control [TR3] |
| UR7 — Fast deployment and reduced engineering effort | | RA7 — Adaptive and nonlinear control [TR1, TR3–TR5] |

requirements. Each technical requirement can serve one or more customer requirements that, similarly, can be fulfilled by several technical requirements. Once the technical requirements have been defined, with a similar procedure control engineers map the technical requirements in one or more control frameworks.

As an example, it is possible to consider how many of the technical requirement specifications such as maximizing the traction effort, increase robustness margin and improve power flow dynamics can be linked to technical problems that are addressed by various control areas.

## 8. Limitations and enablers beyond technology

The limiting factors and enablers to innovation described in the previous sections can possibly be addressed by technological means where research problems can be formulated. Additional context based points have to be considered that are not directly related to technology, but represent however obstacles towards 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 systems, 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 and to set innovation into practice requires the capability of thinking out of the box, exploring non trivial 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 (2020) specially highlights the need for control engineers additional skills sets including broader system understanding, implementation aspects, application knowledge and economical aspects to identify potential and limitation.

Additionally, a greater need has been recognized for the education system to integrate science, technology, engineering and maths (STEM) concepts with the arts (STEAM) across the wider curriculum. Control design is also an "art", Rosenbrock (1977). Human minds excel in pattern recognition, assessment of complicated situations and have an intuitive leap towards new solutions. Those skills should be cultivated in young innovators. And for the work environment, as argued in the Free innovation paradigm (von Hippel, 2017), 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 the book (Pink, 2009) argues that human motivation is largely intrinsic, and that the aspects of this motivation can be divided into 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 to the formulation of an idea, the knowledge and capability to bring the idea into the real world requires the alignment of economical and technical requirements. This process can be simplified if the idea was originally conceived with the techno-economical aspects of the end product.

## 9. Conclusion

Within the context of the IFAC Industry Committee mission, in this paper we propose a framework to close the gap between fundamental control research and practice towards catalyzing technology innovation. Key elements of the framework are: systems and process thinking, vision driven innovation, a systematic identification of customer requirements, addressing profitability and implementability aspects.

The purpose of the framework is to activate the flow in the innovation cycle finalized in order to achieve sustainable innovation.

Developing a brilliant elegant solution and establishing it in the market requires a strategic and committed effort, coordinated between academia and industry. For the academia it is desirable to consider more applications aspects and constraints. In this respect the paper by Samad et al. (2020) provides an overview of ten messages for researchers interested in the practical impact of their work. From this collection, we highlight here the following two: "The control research community is broadly unaware of the impact of advanced control", and "Real-world success requires domain understanding".

For the industry, more emphasis should be placed on creating an environment to discover and experiment and not only go for predictability and risk avoidance as analyzed in Section 8.

The literature on organizational change refers to the key ingredients for creating a behavioral change and sustainable results see Leavitt (1965): Tools/systems (concepts), Processes (how to deploy) and People (how to operate). Working on new tools and systems is not sufficient for sustainable application of control research results into practice. Consistent integration of the process and expertise can define a path towards innovation realized in the field.

We are currently witnessing an evolutionary phase where the complexity of engineering systems is continuously growing and, at the same time, technology is developing towards more digital and data-based solutions. These aspects create a major challenge when it comes to the systems individual and collective control to meet the ever-growing stability, performance, safety and reliability requirements.

This calls for a new way of looking at those systems and requirements, where multidisciplinary groups of sciences and technologies have to work together to develop new advanced solutions.

Automatic control, as a rigorous discipline that links the abstraction of elegant mathematics with the more concrete aspects of engineering, has a pivotal role in orchestrating the multidisciplinary group to address the societal and technological challenge of our future.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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