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# Intelligent Industrial Processes
# - Automatic Control Perspective

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# Abstract

Intelligent Industrial Processes is an area of excellence in research and innovation at Luleå University of Technology (LTU), which was formed to promote multi-disciplinary research and innovation relating to Process Industrial Automation, also referred to as ProcessIT. LTU has a strong track record of research in close collaboration with process industries, where research results have often found their way into products and services strengthening the industries position on the global market.

For this area of excellence a road mapping study with respect to Automatic Control research was conducted and is summarized in this white paper. The study shows that current research activities in Automatic Control are very relevant to Intelligent Industrial Processes, dealing with techniques for process understanding (modeling), design and implementation of control systems, and process monitoring, only to mention some.

It is concluded that the design and establishment of an Open Research and Innovation Platform is essential for collaborative and multi-disciplinary research in the area. Such a software platform will enable industry partners to more efficiently work with their industrial processes and that in close collaboration with researchers and engineering businesses. At the same time researchers and innovators will have the opportunity to test and validate their results and innovations on real-life cases, enabling a swift exploitation of results. Some key principles for this software platform are the open source, open data and open innovation principles that need to be captured in the platform.

The results of that study suggest initial automatic control research activities and a time line for stepping stones towards a full scale implementation of an Open Research and Innovation Platform by 2030.

# Executive summary

The work for this white paper describing the automatic control perspective for Intelligent Industrial Processes (IIP) has been conducted during fall 2013. The aim was to assess the state of the art in research in the field of automatic control, map different topics (or technical areas) to IIP and identify different research directions and questions which are important to address.

The white paper should comprise research and innovation efforts that could stretch until 2030, and would have a substantial impact in the research and innovation community. Research and innovation are in this respect not exclusive and should go hand in hand. Naturally, innovation will lead to new research challenges that might have been unforeseen. In that respect, the work at hand should be regularly re-evaluated in face of new knowledge. Nevertheless, the white paper should contain a realistic work programme that could be executed.

Additionally, potential partnerships with researcher or research groups are important for the successful execution of a research programme, but also, to build alliances for funding proposals. Moreover, such alliances are important to getting more work done with a smaller amount of local resources.

Research and innovation is not only conducted at academic institutes but also in industry. The ratio between basic research and applied research/innovation is usually much smaller, since there is a need to deliver products to a market on a rather short term basis. Still, strategic agendas and road maps for industry sectors are facilitating to create a common research and innovation

focus, as well as informing the general public, policy makers and academic partners on important challenges. Thus, the industrial perspective has been considered.

This white paper should be considered in relation to other road mapping work for IIP that has been conducted in parallel. As a result a common strategy for the work within IIP can be defined.

## Acknowledgement

# Contents

# 1  Methodology

Conducting road map work should not be based on a hunch, and it is actually very important to think in what way to target the problem. It is also important to note that road mapping work can be conducted in a systematic manner, as described in [1]. In many ways this would mean that a vision should be defined which yields the basis for the road map.

Instead of using a vision as the targeting goal, the definition of the area of excellence in research and innovation together with an interpretation of its meaning will be used as the target.

Moreover, the state of the art relating to IIP will be derived from a general automatic control perspective, disregarding current activities in the automatic control area at LTU. Therefrom gaps will be identified which in turn are mapped into challenges that are worth while to be addressed from both academic and industrial perspective. Partnerships which would then be complementary to the competence available and relating to the challenges will be identified.

It is also important to stress that the road map targets need be aligned with the strategic agendas of industry and funding bodies, which is essentially due to the mostly collaborative character of the funding schemes.

Thence, the following line of actions was pursuit:

1. Interpretation of IIP targets

2. State of the art assessment Automatic Control

3. Analysis of other road maps and strategic agendas

4. Identification of gaps

5. Definition of challenges

6. Defining work programme and research questions to start with

# 2  Definitions and interpretation

## 2.1  Definition of Area of excellence in research and innovation

The area *Intelligent Industrial Processes* has been defined as follows:

> A versatile and competitive industry is important for Sweden's and Europe's future status as new players are emerging.To secure our position, constant improvement and development of industrial processes are required in order to increase productivity while reducing the pressures on the climate and the environment.
>
> A key area is ProcessIT (or Process industrial automation) in which several Swedish companies are world leaders in its development, delivery and application. The area is very important in order to maintain and further develop a competitive national process industry. The area constitutes a global market with growth potential for SMEs through which they can grow by developing and commercializing innovations via corporate, university and divisional collaborations.
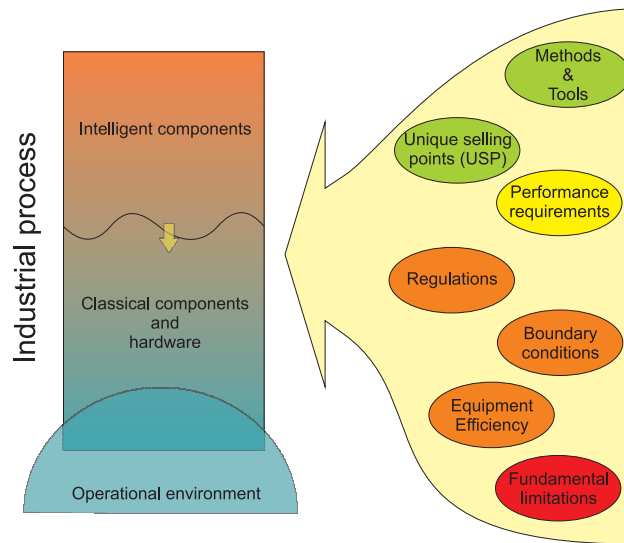
Figure 1: Abstraction of an industrial process with intelligent components.

> LTU is leading in Sweden within the area of rendering more efficient basic industries and other industries using information and communication technology, so-called ProcessIT.To establish ourselves as a player on the European stage, we make use of our multidisciplinary strengths and the networks within which we have a leading position.

While this definition is rather broad and does not in any way give specific interpretation to the labeling terms *intelligent* and *industrial processes*, it is important to define a common ground in this respect.

## 2.2  Industrial processes

A general definition of the term *industrial processes* can be found in several encyclopedia or dictionaries and reads:

> A systematic series of mechanical or chemical operations that produce or manufacture something.
>
> – *The Dictionary.com*

Obviously, any product that is derived in an industrial manner is the result of an industrial process. It ranges industries from food, pharmacy, bio medical over automotive to pulp & paper, iron & steel and chemical, but is not limited to those. In other words, industrial processes are found all around us and target the change of materials or substances into something which has a higher value to the society. Such processes may reduce the cost for a product which can make it a commodity. Thus, the industrial process has made the manufacturing of a product more economical and more feasible for society.

Thus, the reason for constructing an industrial process to begin with is a so-called unique selling point (USP), indicated in a green circle in Fig. 1. The USP is both the motivation but also an asset, which evolves over the life cycle of an industrial process, leading to the need of an adaptation of an industrial process. The USP has therefore a positive affect on the industrial process.

In Fig. 1 (right), some of the main impacts on an industrial process are given. There, green indicates an asset, yellow is both an asset but also a constraint. The orange items, indicate are constraining the industrial process, but they could be circumvented and therefore are soft. Finally, the red items indicate the constraints which limit the industrial process in a way that can not be circumvented and therefore are hard.

Most importantly, the these constraints are changing over time, but usually become more harsh, requiring adaptation. If an adaptation is not successful, then the need and cause of existence becomes questionable.

## 2.3 Intelligence

The term intelligence has been defined in many different ways including logic, abstract thought, understanding, self-awareness, communication, learning, having emotional knowledge, retaining, planning, and problem solving. Intelligence is most widely studied in humans, but has also been observed in animals and in plants. Artificial intelligence, on the other hand, is the simulation of intelligence in machines.

The latter means that Artificial Intelligence is technology and a branch of computer science that studies and develops intelligent machines and software. The field has been defined as "the study and design of intelligent agents" [2], where an intelligent agent is a system that perceives its environment and takes actions that maximize its chances of success, [3].

Clearly, both terms intelligence and artificial intelligence do not have a been rigorously defined and that may also indicate that the understanding is still not mature. A rather new interpretation of the terms is based on the idea that intelligence is not property but instead an ability. According to [4], it was concluded that intelligence measures an agent's ability to achieve goals in a wide range of environments. This conclusions has been further interpreted by MIRI, which uses the working definition that intelligence is characterized by efficient cross-domain optimization.

Interpreting intelligence as the ability to perform unattended optimization, as closer look at optimization in general is advised. As depicted in Fig. 2a, optimization can be envisioned as a process in which a selected method is used to maximize or minimize a cost function using an underlying process with constraints. Clearly, the selection of the method and the cost function affects largely the outcome. Also, the representation of the constraints and the underlying process is not straightforward. In an unattended scheme, it is necessary that the scheme has to take all the decisions on the cost function and method autonomously. Moreover, the representation of the processes and constraints has to be derived or updated by the scheme. Although it could be assumed that a-priori knowledge has provided the process and constraint representation, the update should be done autonomously.

From a practical perspective all selections could be done a-priori which reduces the autonomy of the scheme largely, or at least limits the ability to adapt. This renders a scheme where the user (human) is much more involved by pre-setting any of the selections that need to be made, as indicated by the $\mathcal{H}$ in Fig. 2a.

In that context, a fully unattended optimization scheme would require an autonomy on a level that would include a customers desires and needs. Therefore, the level of autonomy could be limited to the degree that the top-level requirements are provided by the user, rendering the scheme depicted in Fig. 2b
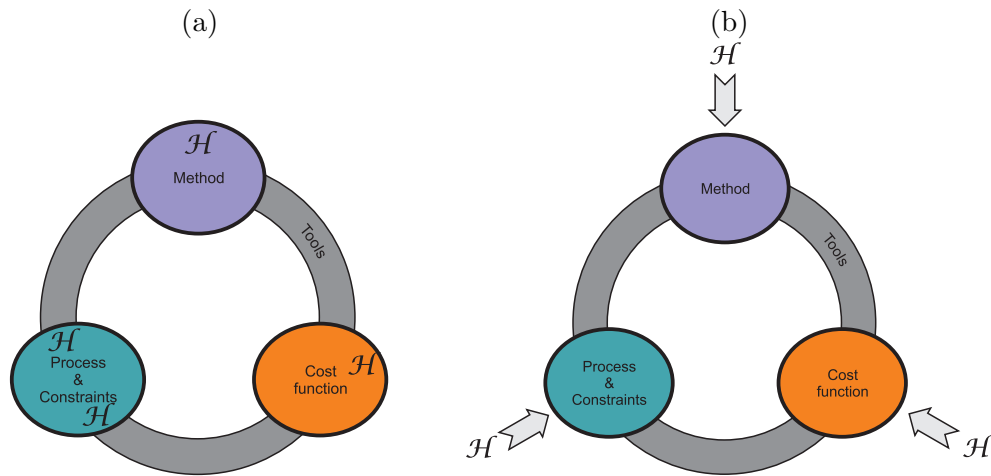
(a)                                                                (b)



Figure 2: General sketch for an optimization process with its components, where $\mathcal{H}$ indicates the user (human) involvement. Traditional situation (left), Desirable situation (right)

## 2.4  Towards intelligent industrial processes

Understanding an intelligent industrial process in the context of the definition of intelligence and of an industrial process, it becomes clear that the optimization will make use of the assets and constraints defined in Fig. 1, a selected method and a representation of the industrial process.

The representation of the industrial process will be a model that represents the internal workings of a process and thus, its behavior. It is also clear that an industrial process can have a large scale character, which means it will be composed of numerous subprocesses which are interconnected. At the same time the industrial process will be embedded in a larger setting, which will contribute with additional interconnections and constraints. Such a view is captured in the example depicted in Fig. 3.

There it can be seen that an integration into a larger setting yields additional constraints acting on the industrial process. To conclude, the optimization becomes more complex and its implementation is effected by more uncertainties. Nevertheless, a more integrated approach is assumed to be more efficient from a resource usage perspective.

In Fig. 1, it is already indicated that the industrial process can be partially composed of intelligent components. These intelligent components could essentially be sub processes which adapt and optimize their behavior. The most simplistic form of adaptation could be a traditional PI controller which adapts to new operating conditions by identifying the needed steady state control action to yield a zero control error. Clearly, both the adaptation or optimization scheme is very simplistic and in this context deterministic.

An obvious question would be if a process that is composed of disjoint intelligent component in the end would yield an intelligent industry process. It is the belief of the author that this is not true and that the implemented optimization is at the best suboptimal. Still, increasing the adaptability and unattended optimization would improve the current situation, even though the human is very much involved in the optimization process.

Targeting a more intelligent industrial process with an unattended scheme, the following abilities or properties need to be present:
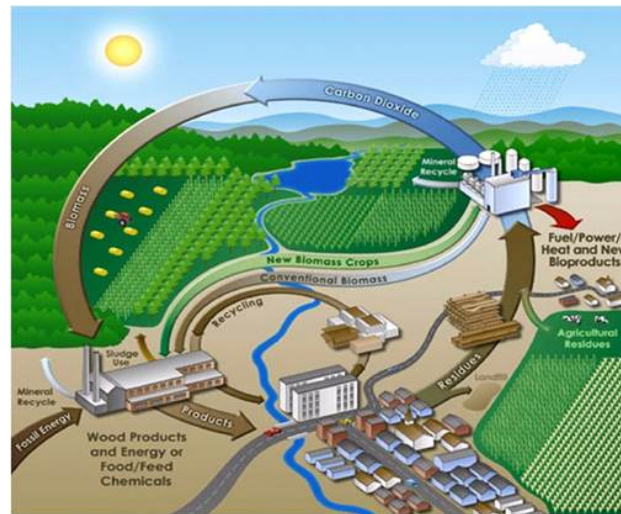
Figure 3: Example of an industrial process which is embedded in a larger setting. Source: Source: http://www.biorefinery.ws

**Representation of the process and the associated constraints** mean modeling of both process and constraints in an autonomous fashion with sufficient accuracy. Additionally, these models need to be updated continuously in order to be valid over the life span of an industrial process.

Without an autonomous scheme, the human user will fail to keep these models updated in the long run.

**Selection of the method and tools** that are used to adapt and optimize is usually conducted in an a-priori fashion by the human user. In this selection, the expert knowledge of the user guarantees that the methods or tools will be applicable to the case at hand, which is a combination of the cost function and the process with its constraints. Autonomous selection would require a scheme that can quantify the applicability for a certain types of cost functions, processes and constraints.

**Cost functions** are tailored by users to fit the optimization case and specifically, what should be achieved by the optimization. In the small scale case, where a local optimization is constructed, the goals are often well defined. In a larger scale setting, *i.e.* when there is competition on resources, the cost functions will have a faster fluctuation and their adaptation need to occur on a faster time scale.

**Implementation** is a critical aspect and especially in an autonomous and unattended scheme. One could conceive different types of adaptation and implementation patterns, offline, semi real-time and real-time. In the offline pattern, the adaptation and implementation would occur during times, when the industrial process is not in operation. In semi real-time, the adaptation would occur at certain pre-determined and known-to-be-safe points in time. Still, the adaption and implementation would occur during operation. The real-time pattern, would mean that an adaptation and implementation occurs during operation and on the fly. Clearly, there are dependability aspects which need to be considered.

**Fault tolerance and safety** is a necessary pre-requisite, since hardware failures will inevitably occur during the life cycle of an industrial process. Even if there is a scheme for conducting

maintenance and determining the remaining operational time, degraded modes and also failure modes need to be managed by an intelligent setup. Therefore, the operational envelope needs to include modes which deviate from normal and, in the worst case, might not have been anticipated during the process design.

Addressing a complete plant which is composed of a multitude of unit processes, will lead to a complexity problem that needs to be dealt with on top of the above challenges, when operating on the large scale. From this perspective, the bottom up approach where unit processes will be made intelligent, might be an advisable approach even though it will not lead to an optimal solution.

It should also be noted, that methods and tools should be developed and validated on unit processes with the large scale aspects in mind, can be an important step forward.

## 2.5 Intelligent systems and control

Within the research area *Automatic Control*, the term intelligence, intelligent systems and intelligent control has been used for many years. Within the International Federation of Automatic Control (IFAC) and Control Systems Society within IEEE, the following technical areas have a direct connection with intelligent systems and control:

- Adaptive and Learning Systems (includes Machine learning) (IFAC)

- Computational Intelligence in Control (IFAC)

- Human Machine Systems (IFAC)

- Intelligent Control (IEEE CSS)

In these areas various AI computing approaches like neural networks, Bayesian probability, fuzzy logic, machine learning, evolutionary computation and genetic algorithms, are used. Thus, within the Automatic Control area, the term intelligence has a very narrow interpretation which is not aligned with the much broader definition and interpretation from before.

From this perspective there is a risk that the Automatic Control community will misunderstand the aim of the area of excellence in research and innovation.

# 3 Related research activities

## 3.1 Publication activity within Automatic Control

The research area automatic control has a long going history and addresses fundamental questions of control theory and the application of control theory in practical applications.

When it comes to road mapping it is important to assess the publication trends within automatic control. For this end, the technical areas which are defined within automatic control by the International Federation of Automatic Control (IFAC) and the IEEE Control Systems Society are analyzed for the current publication trends between 2008 and 2012. For the different technical areas that are defined, certain keywords were selected and a search on *Web of Science* was conducted. There, the databases were limited to the technical sciences.

| Technical Area | 2008 | 2009 | Year 2010 | 2011 | 2012 | Avg Annual Growth |
| --- | --- | --- | --- | --- | --- | --- |
| *Systems and Signals* | | | | | | |
| System identification | 462 | 487 | 452 | 538 | 542 | 4% |
| Adaptive and Learning systems | 162 | 189 | 229 | 210 | 236 | 10% |
| Machine learning in control | 63 | 91 | 108 | 143 | 178 | 30% |
| Networked and interconnected systems | 72 | 81 | 91 | 114 | 147 | 20% |
| Discrete event and hybrid systems | 555 | 698 | 716 | 760 | 841 | 11% |
| Stochastic systems | 183 | 243 | 255 | 262 | 315 | 15% |
| | 1497 | 1789 | 1851 | 2027 | 2259 | 11% |
| | | | | | | |
| *Design methods* | | | | | | |
| Control Design | 989 | 1082 | 1056 | 1158 | 1362 | 9% |
| Linear and non-linear control systems | 108 | 109 | 111 | 113 | 129 | 5% |
| Optimal Control | 1167 | 1331 | 1202 | 1427 | 1478 | 7% |
| Robust Control | 1151 | 1268 | 1324 | 1481 | 1621 | 9% |
| Distributed parameter systems | 211 | 314 | 261 | 263 | 267 | 9% |
| | 3626 | 4104 | 3954 | 4442 | 4857 | 8% |
| | | | | | | |
| *Computers, Cognition and Communication* | | | | | | |
| Computers for control | 20 | 20 | 26 | 29 | 31 | 12% |
| Computational intelligence in control | 69 | 85 | 98 | 99 | 120 | 15% |
| Control via communication networks | 134 | 159 | 179 | 186 | 222 | 14% |
| | 223 | 264 | 303 | 314 | 373 | 14% |
| | | | | | | |
| *Mechatronics, Robotics and Components* | | | | | | |
| Components and Technologies for Control | 65 | 76 | 78 | 92 | 95 | 10% |
| Mechatronic systems | 91 | 78 | 100 | 115 | 126 | 10% |
| Robotics | 595 | 740 | 759 | 809 | 893 | 11% |
| Human Machine systems | 300 | 305 | 348 | 366 | 448 | 11% |
| | *1051* | *1199* | *1285* | *1382* | *1562* | 10% |
| | | | | | | |
| *Manufacturing and Logistic Systems* | | | | | | |
| Manufacturing Plant Control | 53 | 60 | 50 | 75 | 72 | 11% |
| Manufacturing Modeling for Management and Control | 123 | 142 | 144 | 145 | 148 | 5% |
| Enterprise Integration and Networking | 825 | 848 | 885 | 944 | 1016 | 5% |
| Large Scale Complex Systems (relating to control) | 126 | 142 | 158 | 162 | 201 | 13% |
| Large Scale Complex Systems (relating to modelling) | 404 | 452 | 470 | 507 | 586 | 10% |
| | 1531 | 1644 | 1707 | 1833 | 2023 | 7% |
| | | | | | | |
| *Process and Power Systems* | | | | | | |
| Chemical Process Control | 834 | 900 | 922 | 948 | 977 | 4% |
| Mining, Mineral and Metal Processing | 24 | 30 | 33 | 42 | 42 | 16% |
| Power and Energy Systems | 406 | 556 | 641 | 705 | 895 | 22% |
| Fault detection, Supervision and Safety of Techn Processes | 84 | 98 | 100 | 106 | 119 | 9% |
| | 1348 | 1584 | 1696 | 1801 | 2033 | 11% |
| | | | | | | |
| *Transportation and Vehicle Systems* | | | | | | |
| Automotive Control | 28 | 34 | 38 | 42 | 50 | 16% |
| Marine Systems | 95 | 97 | 111 | 117 | 121 | 6% |
| Aerospace | 105 | 117 | 143 | 145 | 152 | 10% |
| Transportation Systems | 88 | 95 | 96 | 103 | 126 | 10% |
| Intelligent Autonomous Vehicles | 23 | 39 | 48 | 50 | 63 | 31% |
| | 339 | 382 | 436 | 457 | 512 | 11% |
| | | | | | | |
| *Bio and Ecological Systems* | | | | | | |
| Control in Agriculture | 305 | 345 | 362 | 387 | 415 | 8% |
| Biological and Medical Systems | 44 | 49 | 61 | 66 | 69 | 12% |
| Model and Control of Environmental Systems | 132 | 145 | 153 | 177 | 190 | 10% |
| Biosystems and Bioprocesses | 50 | 51 | 64 | 72 | 75 | 11% |
| | 531 | 590 | 640 | 702 | 749 | 9% |
| | | | | | | |
| *Social Systems* | | | | | | |
| Economic, Business and Financial Systems | 36 | 41 | 44 | 44 | 49 | 8% |
| Social Impact of Automation | 12 | 13 | 19 | 22 | 29 | 26% |
| Control Education | 9 | 12 | 13 | 15 | 25 | 31% |
| | 57 | 66 | 76 | 81 | 103 | 16% |
| | | | | | | |
| *Total number of related publications* | 10203 | 11622 | 11948 | 13039 | 14471 | 9% |

Figure 4: Number of publications in the different technical areas between 2008 and 2012. The annual average growth of publications is related to the total average annual growth. Normal growth rates are in a span of $\pm 3\%$ of the total average (yellow). Growth below normal (red), and above normal (green).
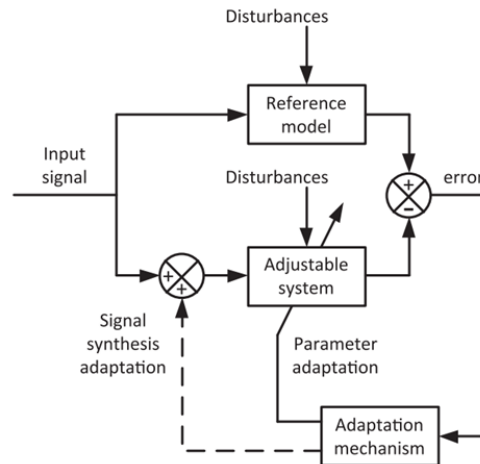
Figure 5: General sketch for an adaptive control scheme. Source: [7]

There it can be seen that certain areas which relate to IIP as indicated above experience a growth rate which is above normal in the last 5 years. These technical areas could be seen as emerging. Still, established areas with a large number of publications are highly active and should be considered as mainstream research.

## 3.2 Related research status and outlook

Adaptive control is a research topic in automatic control which has a long going history. Already in the 1950's it was realized that a fixed control scheme will fail to achieve its performance goals when there is time variation in the process or non-linearities which require adaptations for different operating points and conditions. A general sketch for an adaptive system is given in Fig. 5, where it can be seen that the adaptation scheme depends on the analysis of measurements and a reference model. Thence, adaptation requires a certain level of learning and in turn, intelligence.

Despite the large body of research that has been published, Zames stated in [5]: 'Despite the long history of research on adaptive control, a satisfactory definition of adaptation has remained elusive.' Essentially, the statement indicates that the are many adaptation schemes for a variety of problems and problem classes, but the underlying concept of adaptation is still not fully understood.

In one of the last articles published by Zames [6], before his death in 1999, it is stated: 'A more important question is whether adaptation is necessary or optional if specs are to be met for an ensemble of uncertain plants. Adaptation is necessary whenever the optimal non-adaptive performance is inadequate, and adaptation provides enough improvement.'

As indicated in [7], most issues in adaptive systems and control are already solved and only small gaps remain. But in relation to the latter two publications, there is no evidence provided for reliable solution in the large scale case. Moreover, the schemes and mechanism have to be developed by the human user and can then be taken into operation, and therefore not unattended.

To conclude, the first question has apparently not been answered and more importantly, it is suggested that adaptation is only necessary if the optimal non-adaptive scheme's performance is inadequate. Otherwise, adaptation adds a level of complexity which is superfluous. Thus, there is a need to conduct research which relates fundamental limitations of a process with achievable
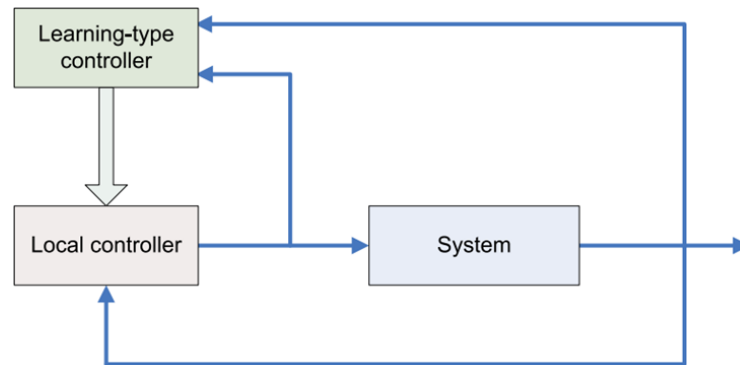
Figure 6: Sketch for the setup of a learning type control scheme. Source: [9]

performance of both adaptable and non-adaptable control schemes. Further, unattended modeling schemes need to provide process representations on which the decisions and adaptation are based.

According to [8], there are several open issues in modeling and in particular in system identification. The following are important issues in relation to IIP and there is a need to derive solutions on:

- Identification of nonlinear systems that operate in closed loop and are stabilized by an unknown regulator.

- Develop Model Error Models for linear or nonlinear models of nonlinear systems that can be used for robust control design.

- Find effective data-based nonlinearity tests for dynamical systems.

- Automatically polishing data and ?nding informative portions in large data sets.

- An efficient integration of first principle modeling with parameter estimation.

- Determining structural information from experimental data set.

- Models for control tuning and performance monitoring.

In contrary to traditional adaptive control, the learning-type control addresses the problem of adaptation not from a rigid representation of the system to be dealt with, but introduces more flexibility. It also relates in that sense to some of the issues in system identification where aspects like robustness and structural information need to be considered.

In Fig. 6, a general setup for the indirect form solution of learning-type control is given, as it is discussed in [9]. Clearly, the difference to an adaptive system is subtle. From both [9] and [10] it can be concluded that there are few general result but that the setup is promising from both optimization and robustness perspective. It is also very much in line with the previously discussed optimization approach to IIP. Thus, more research efforts in this directions can be considered as fruitful.

It was stated before that IIP can be seen as a system where optimization is an integral part of the system. As such control design schemes which makes use of an optimization scheme, as for example model predictive control seem to be favorable from a design perspective. MPC has proven to be a design methods which is both intuitive and renders well-performing controllers in industrial settings. Still, there are several remaining open issues according to [11]:
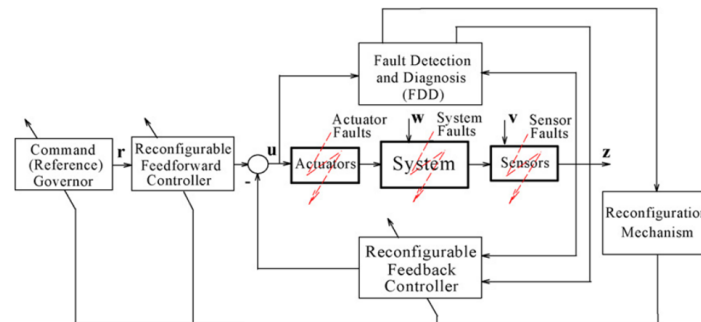
Figure 7: General setup for an active fault tolerant control system. Source: [12]

- Model changes or adaptations because of changing operating points.

- Safety-criticality.

- MPC formulations which offer guarantees of stability and robustness feasibility.

- Efficient solutions of the optimization problem both using an explicit and a numerical approach.

Moreover, when a large scale system is controlled, then there is an additional question on how to structure the control scheme. Optimality can be shown for a fully centralized approach, but renders a system which is vulnerable. Determining a control scheme of less complexity which provides sufficient performance and at the same time weighs in safety criticality from a vulnerability perspective is important.

Finally, when an IIP is in operation the fault tolerance is very important, and can be envisioned as shown in Fig. 7. As such, the IIP would need to reconfigure itself depending on the occurrence of faults. Failure modes might render degraded performance of the overall system, but need to be considered during operation in order to reduce down-time. AS long as the degraded performance is still sufficient for production, it might as well be possible to maintain operation. Fault tolerant control research has been reviewed in [12] and comes to the conclusion that such schemes are mostly used in small scale application.

Major problems in the design of such systems are stability and minimum performance guarantees, the tediousness of the design and the dependency on redundancy in the physical process design. One could think of the fault tolerance scheme as an integral part in the optimization, but this has not been addressed in the research until now.

Obviously, there are still many puzzle pieces that need to fall into place in order to design an IIP, which could run in an unattended manner and showing adaptability to unexpected events. Nevertheless, the current trends in automatic control research may provide promising solutions.

**Some grand challenges**

Despite numerous detailed research question, there are two general issues, which have not yet been addressed, although pointed out quite some time ago. Based on some of the conclusions made by [13] and [6], the following general open issues can be formulated:

1. Scalability of control methods for large scale application is rarely investigated. When do methods break down and why?
   This is especially of interest when it comes to automated methods for analysis, design, and decision making.

2. The applicability of methods is in some sense based on trial and error. In which cases is a methods advantageous to be used and feasible? What characterizes the successful application. When automated analysis, design and decision making is required, false results may not be detected. How can this be solved?

Although a significant amount of time has passed since the publications by Zames and Daum, these questions have not lead to scientific publications addressing these problems.


# 4  Strategic agendas and objectives

Despite the on-going efforts within the subject area Automatic Control, there is also an interest of industry and public bodies to investigate important future trends for both development and research.

During the last years, several important road maps and strategic agenda have been derive that have a large influence on potential research directions. These agendas are not limited to the subject area automatic control and should be considered from other perspectives as well.


## 4.1  Factories of the Future

Factories of the Future (FoF) is a strategic multi-annual roadmap [14] and was created in 2010. It was supported by the European Technology Platform *Future Manufacturing - Manufuture*, and states the agenda for the FoF Public-Private Partnership.

The agenda is split into several key areas, out of which the area *ICT-enabled intelligent manufacturing* has the largest relevance for the automatic control area. Therein, three levels were identified:

1. **Smart factories** addresses the manufacturing process itself. The usage of process automation control, planning, simulation and optimization technologies, robotics is assumed to be the enabling factor for an intelligent manufacturing process.

2. **Virtual factories** proposes the use of a virtual representation of a factory to facilitate the distributed management of manufacturing assets.

3. **Digital factories** are the representation of manufacturing systems in an virtual environment which leads to a better understanding and design of production and manufacturing systems. This will involve simulation, modeling and knowledge management from the product conception level down to manufacturing, maintenance and disassembly/recycling.

The partnership indicates several important research and development activities form the automatic control area which are

- Adaptive and fault tolerant process automation, control and optimization technologies and tools.

- Large-scale testing and validation of robotics based and other automated manufacturing.

- New metrology tools and methods for large-scale and real-time handling and processing of manufacturing information.

- Knowledge and analysis.

- Enhanced, interoperable models for products and processes.

- Design environments.

It need to be noted that these efforts were already indicated for the time frame 2011–2013. Looking at current research results indicate that these efforts render solutions.

## 4.2    Svensk Produktion 2025

The national agenda *Svensk Produktion 2025* [15] is largely influenced by strategic agendas and road maps on the European level. The main focus area for the prioritized research areas are not from the area of automatic control.

Nevertheless, there are areas where research in automatic control can be contributing to new solutions within other areas of expertise. In many ways, the efficiency and dependability of industrial processes is in focus. To a large degree this relates to the need of effective monitoring and fault mitigation schemes.

Moreover, flexible and modularized production systems and their automation requires systems which are easily reconfigured. Usually, this can be either achieved by the usage of standardized components which can interact, or by introducing a virtual concept which shortens the design and implementation of the reconfigured system with maintained product quality. Further, adaptive production systems and virtual factories are or large interest.

Clearly, modeling, simulation, adaptive and learning system thinking can contribute to this area. Again a multi-disciplinary approach in this direction may help to foster new innovative solutions.

## 4.3    Industrie 4.0

In [16], the strategic agenda for German manufacturing industries is formulated. The most promising technologies for the future development are internet of things and services, which can be represented in the framework of cyber-physical systems (CPS).

The main focus in Industry 4.0 is the increased flexibility for customer demands while maintaining resource efficiency and productivity. Therefore optimized decision making in industrial processes together with the surrounding environment is critical. The work group of Industry 4.0 pinpoints several key areas that need to be addressed, out of which the following are relevant from an automatic control perspective:

- Managing complex systems

- Resource efficiency

For the **management of complex systems**, it is assumed to be the key, that industrial processes are making use of a model-based approach both during development and design, and during production. A so-called interconnection between the real-life plant and the virtual plant will be an enabler for process monitoring and prediction of the performance and potential failures.

One of the challenges raised is the question if the needed modeling effort for such systems will be cost-efficient. Although not clearly stated, the remote access to plants using so-called tele-presence is also an important aspect and relates largely to the virtual plant concept. It is assumed that this would further increase efficiency.

In the key area **resource efficiency** not only raw materials, additives, operating supplies and energy carriers are accounted for, but also human and financial resources. This also leads to two different scenarios: resources productivity and resources efficiency. It is assumed that resources productivity is a prerequisite for production at a high level of quality, while resources efficiency targets the optimization of the used resources and is the secondary goal.

For both areas, the availability and implementation of CPS on a large scale seen as the enabler, but the implementation costs are seen as a great challenge. It is also required that the cost-efficiency of this approach still have to be proven. From an automatic control perspectives, this requires efforts in the technical areas modeling, optimization and control in large scale systems.

## 4.4 SPIRE Roadmap

The Sustainable Process Industry through Resource and energy Efficiency (SPIRE) is a proposal for a Public Private Partnership (PPP) driven by the European Process Industry and fully aligned with the strategic goals defined by the European Commission in the Europe 2020 strategy. The cross-sectorial and holistic SPIRE research and innovation roadmap [17] was finalized during 2013.

The road map is well aligned with the goals of Horizon 2020 and therefore of large interest when it comes to the definition of local research programmes. It should also be kept in mind that the research agenda is based on the needs of the process industry which is a major stakeholder in the region around the bottnic gulf in northern Scandinavia.

The road map details several key actions which are collected into certain key components. From an automatic control perspective, the key action *Process monitoring, control and optimization* details specifically, that any optimization of an industrial process needs to address the large scale problem and target the overall industrial process. Instead of traditional control concept predictive and intelligent control systems should be targeted.

Obviously, this is very much in line with the current in automatic control research and require advancement in both research, development and innovation. It is assumed the following need to be realized:

- Implementing measurement devices for all aspects of intermediate/final product quality and their integration into process control;

- Robust optimization methods to local targeted process control and energy supply;

- Simulation methods for the analysis, characterisation and study of systems, material, equipment and processes;
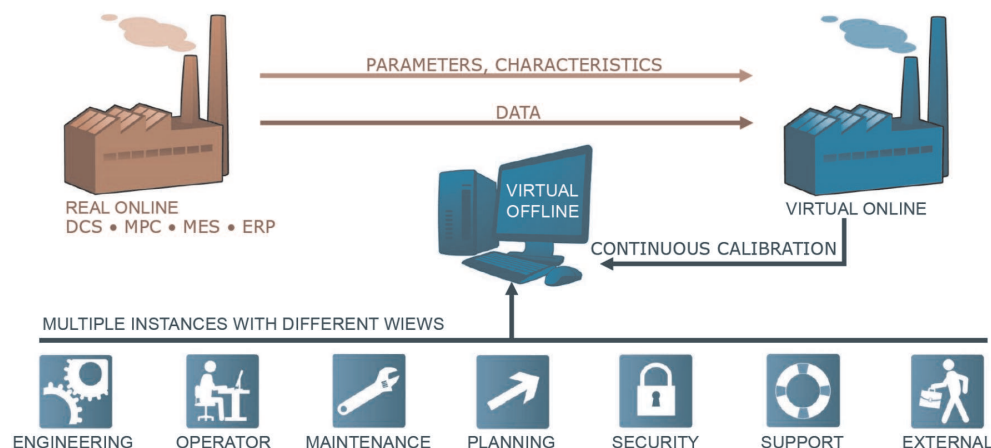
Figure 8: The virtual plant concept as suggested in the road map. Source: [18]

- Low cost measurement devices to enable high levels of process monitoring;

- Understanding and modelling multi-phase and multi-physic phenomena in products and process.

For all of these items, there exist solutions. Unfortunately, those solutions do not interoperate very well and do not target a complete industrial process. In most cases unit processes can be addressed, neglecting the interactions with the industrial process as a whole. According to the road map it is essential to consider both the complexity in the detail, as well as the large scale character on the higher level.

## 4.5  ProcessIT.EU Roadmap

The road map for ProcessIT.EU [18] was formulated at LTU together with contributors from the other scandinavian countries, mainly Finland. ProcessIT.EU is a centre of innovation excellence within Artemis. ProessIT.EU has it primary focus on process automation and ICT for process industries. Thus, the partnership is built up from end users, technology suppliers, academia and public authorities.

The basic idea of the road map is to identify the needs of the process industry, which is the customer for many of the technology suppliers, and map it into goals over time. Since the target is process automation, research results and innovation in automatic control that addresses the needs of the process industry are automatically relevant within the scope of the road map.

Compared to the strategic agenda for FoF PPP [14] and for SPIRE [17], severa´l of the key areas or actions are captured and refined for the process automation perspective. One of the most important aspects of the road map is the so-called *Virtual plant* which is accompanied by a simulation environment, as depicted in Fig. 8.

In this conceptual idea, which is similar to the digital factories concept, the end user and technology supplier make use of the same platform in order to collaborate on the industrial process in question. This has certain similarities with the tele-presence thinking in *Industrie 4.0*. Clearly, this concept has some compelling properties, where not only the industrial process is accessible but can also be used for training and testing purposes prior to action on the real-life industrial process.

From an automatic control perspective, this poses certain challenges for modelling and simulation, but creates opportunities like early testing of research results and innovations on the virtual representation of a real-life process. Moreover, the virtual plant could render the intelligence for the industrial process when supplied with sufficiently enough information, methods and tools.

## 4.6 Robotics Roadmap

The Robotics Research Roadmap [19] was created by representatives of several major US universities. From within that road map the Manufacturing area is of large interest for intelligent industrial processes.

It is stated that *The continued progress in this area relies on further progress in the area of integrated design, integration from design to manufacturing, new methods for cyber-physical systems integration, and a higher degree of computer-mediated manufacturing*

Again, similar to the *Industrie 4.0* strategic agenda, cyber-physical systems are understood as an opportunity and it is important to further intensive their integration. As a result research relating to *Learning and Adaptation*, *Modeling, Analysis, Simulation, and Control* are essential to enable industry processes which can operate in unstructured environments. There the term unstructured environments can also relate to operating conditions which were not perceived during design.

Moreover, perception of an industrial process can be largely enhanced as soon as it is able to be connected to the surrounding environment and can fetch information on a needs basis. Although this creates challenges of it own, the perception capabilities can be largely extended, which in turn improves adaptation and learning. It also means that the industrial process may have a virtual counterpart in the cloud.

Automatic Control research which deals with computational intelligence and learning is directly related to the challenges that are indicated in the road map.

## 4.7 Research and innovation platform

A common denominator that is found in most agendas was the need for a platform that combines a virtual representation of the manufacturing process with methods and tools that can operate on the virtual process in order to create actions in the real world, both in an online and offline sense. This idea is also partially addressed by some of research projects. Still, a more holistic view on the platform is lacking and also making the platform more intelligent in itself, which could yield and intelligent industrial process in combination with the associated real-life process.

Traditionally, the design and operation of a control system for an industrial process can be represented by the chain depicted in Fig. 9. It has to be kept in mind that the physical building process is not part of that chain and here merely the design of the "soft" components is given. There, three different main streams in the work and information flow can be identified. During the design of an industrial process, the control system components, which are accounted for in an component registry, are combined into the industrial process. Thereafter, the process is modeled, simulated and subsequently analyzed in order to design a control system. Having a description for the control system, it can be implemented in the control system hardware and taken into operation. The work and information flow for the design is indicated by the red arrows in Fig. 9.

Already during the design phase and prior to implementation and operation, a virtual representation
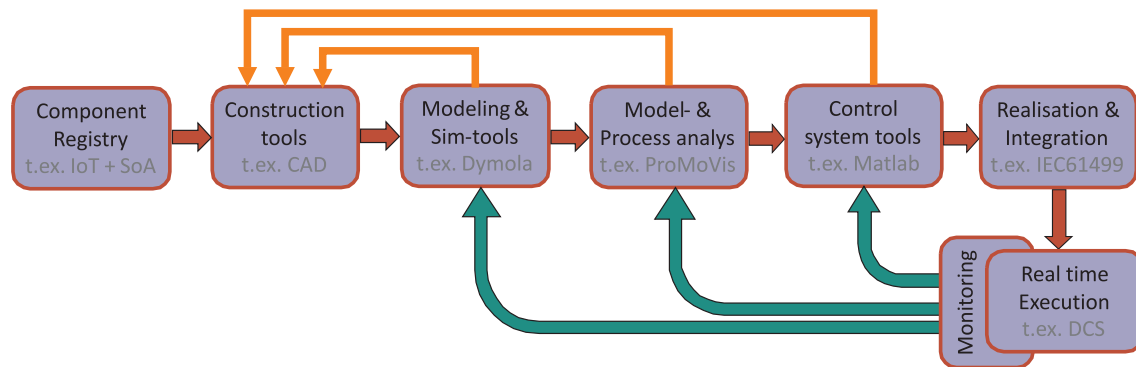
Figure 9: Schematics of a chain of activities for the development and implementation of a control and monitoring system for an industrial plant. Design work flow during construction or due to hardware change (red arrows), Re-design due to insufficiencies of the design (orange arrows) and Re-design due to insufficiencies detected by monitoring (green arrows).

of the physical process is of importance. It gives the designer the possibility to systematically tailor a control system which has predictable performance characteristics. As soon as the industrial process is in operation it will deteriorate and will be affected by wear and hardware failures. Essentially, this invalidates the virtual representation if it is not kept aligned with reality. Here, the re-flow of information (indicated by the green arrows) and its usage is crucial and comes into play.

In the context of Cyber-Physical-Systems, physical systems are interconnected with the virtual world and both information and actuation flows occur in both directions, [20]. As a result, the control system becomes an integral part of the process physics and, due to the communication capabilities, becomes completely accessible from anywhere. Nowadays, the design and construction of the physical and virtual components make use of numerous disjoint software tools with their one tool chains and work flows. Thus, there is not such a long step needed to achieve a virtual plant as depicted in Fig. 8 and proposed in [18].

An important issue that arises in tool chains where disjoint methods and tools are used, is the disjoint storage of information. The information is usually only a means of communication between different components in the chain. Consequently, a large dependency on the components and their interoperability arises. From a user perspective, the components themselves are only a means of creating and providing the information, necessary to take appropriate decisions and actions.

From a research, innovation and development perspective, the chain has some compelling properties, when it is implemented at different stakeholders, like researchers, scientists, service providers, consultancy businesses and industries. First, the interaction and exchange of information is streamlined and research results are easily transferred to product development and exploitation. It often results in a the high degree of specialisation and is tailored to a certain application with large dependency on the involved individuals. These types of constructs do not aim for unattended schemes where the human involvement is reduced.

Combining the idea of a virtual plant with an information centered approach yields a platform which not only implements the numerous disjoint tools, but also combines the disjoint storage of information into an information warehouse. Methods and tools become components in such a platform, that upon execution further enrich the stored information. In Fig. 10, a principal architecture of such a platform is depicted.
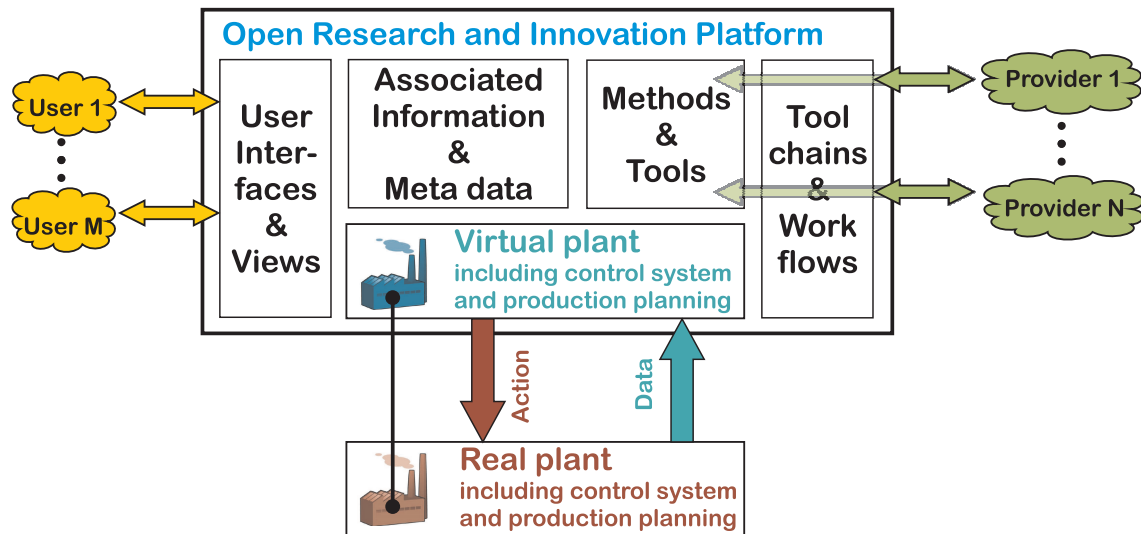
Figure 10: Architecture of the Open Research and Innovation Platform.

Such a platform enables the following principles:

- **Methods and tools** make use of the virtual plant with its stored data and will store the results in the associated information and meta data storage. Thereby, enriching the knowledge of the virtual and real plant.

- **Tool chains and workflows** implement the execution of methods and tools. Thereby, the principles of a tool chain are not lost and the drawbacks are mitigated.

- **Providers** will supply the methods, tools, tool chains and work flows to the platform and further development them including their interaction. Providers can then become both researchers, scientists, specialists and practitioners; any of which can represent an organisation.

- **User interfaces and views** create the interoperability between the user and the platforms information storage. Different user may get different interfaces depending on the user category and context. Most importantly, the user will contribute with actions and conclusions to further enrich the information.

- **Unattended schemes** will be a set of methods and tools that can operate in an unattended manner in the platform and could form an intelligence in conjunction with the real plant, rendering an intelligent industrial process.

Creating an open platform will then enable contributors from different fields of work (industrial engineers, researchers, specialists, etcetera) to participate in the development of such a platform. As a results both research and innovation, including their exploitation is accelerated.

# 5 Stepping stones and partnerships

When the vision and goals of a roadmap are defined, it is important to find feasible starting points and stepping stones towards the goals and the vision.

Using the Open Research and Innovation Platform as a framework to collaborate with other research topics and industry, all research results could find their implementation in the platform. From a timing perspective, the development and implementation of the platform becomes both critical and guiding. It is also important to identify international partnerships which promote the development and usage of the platform on an international level.

Research in Automatic Control often renders results that can be applied on test cases for the purpose of validation. Implementation of the results is therefore a normal part of the research work. Research questions which can be addressed right away and would yield results that could be implemented in the platform at an early stage will make the platform alive early on.

## 5.1   Research starting points

The research question which are of interest at the Control Engineering Group at LTU, do well align with the open issues indicated above. Initial research questions that could be addressed with the given resources at LTU are discussed in the following.

### Large scale interconnected systems

Most industrial processes have a large scale character, which means the number of process variables is large (above 1000), and the usual way of dealing with these processes is to introduce hierarchies. Hierarchies reduces the number of process variables that are simultaneously dealt with on every level in the hierarchy, allowing the application of traditional or classical methods for control design and monitoring schemes.

As a result, the structuring into hierarchies is a critical step and may render a system with unintelligible behavior, when done wrongly. Moreover, the hierarchy which might have been valid at the beginning of a processes life cycle might not be valid later, requiring adaptation of the structure. Such a change is usual very tedious and costly. Methods for structuring have been proposed since the early beginnings of studies in modeling and control of large scale system, and there is a vast bulk of results, see [21] and [22] for a comprehensive summary.

Nevertheless, determining control strategies with hierarchies in mind or not is still a difficult problem and further research and development is needed. The following starting points have been identified:

- Little attention has been paid to the restructuring of hierarchies and reconfiguration of control strategies. Reconfiguration has mostly been addressed in the context of fault tolerant control, but not in the context of reconfiguration for process performance enhancement.

- Decision making on control structures is based on the analysis of processes models, which have to be derived in a previous working step. Methods that can operate on plant data directly are rare and could make the decision making process more efficient.

- Robustness of control structure selection schemes in face of uncertainties has received more attention since 2006, but the methods are still preliminary and would need to be studied more.

- Integration of Control Configuration methods and tools into the Open Research and Innovation Platform. This would require the porting of ProMoVis [23] to the platform.

## Modeling

Software such as Dymola for first principle modeling is now established technology and modeling libraries for standard components such as tanks, pumps, etc. are rapidly evolving. In each branch of process industry there are, however, a set of crucial core processes that are very complex due to some distributed parameter and are not yet handled by modeling software. Examples are the blast furnace and the pulp digester as well as comminution processes in mineral processing. A relevant topic of research is thus

- To develop support for automated modeling of distributed parameter systems in general and these core processes in particular

Lack of knowledge of the parameters and the model uncertainty of a 1st-principle model is often the limiting factor for its applicability in control design, monitoring, etc. Two of the research issues stated in [8] (See Section 3.2) may be thus be highlighted here:

- Integration of first principle modeling with parameter estimation
- Developing model error models from measurement data

## Optimisation

Optimization, intended as the search for the best choice in a set of plausible alternatives, is probably the most widely pervasive concept in the whole set of all the computational sciences. Indeed many practical problems are usually translatable into well-posed optimization problems, e.g., as for learning and decision theory. Distributed optimization, where multitudes of agents collaborate to achieve a common goal, received in the past years a continuously increasing attention. This shift is induced both by the recent development of greater and greater systems (e.g., modern wind and wave farms), and by the quest of developing synergies between cooperators, i.e., coordinated actions that enable total effects that are bigger than the ones achievable without coordination.

Development and study of such algorithms are major research topics in the area of control and system theory [24], [25], and have lead up to now to numerous contributions.

The questions usually addressed by researchers are driven by technological needs. To distributedly solve complex optimization problems, indeed, computations should require minimal coordination efforts, small computational and memory requirements, and do not rely on central processing units. Technologies are thus developed to simultaneously improve the convergence time of these algorithms, while keeping bounded the complexity and frequency of communication among agents. The final aim is eventually to obtain general-purpose fast distributed optimization techniques: the vision is that these optimization algorithms may become a key enabling technology for estimation, reconfiguration and control of networked systems only if combining fast convergence properties with generality.

We then noted that two of the main points that make centralized optimization so pervasive in our industrialized world have not yet been translated to the distributed domain, and forecast that they will become soon important areas of research:

- Distributed Interior Point Methods, where feasibility conditions are encoded using barrier functions.

- Distributed Derivative-Free Optimization Methods, that is, consider the case where the value of the cost function at a given point can not be observed directly (e.g., because of some noise arising as a result of using numerical tools for the evaluation of the cost, as for example in numerical simulations).

Moreover, the optimum point of operation of a process might not be determined a priori due to large uncertainties in the process model. The optimum may also be time-varying due to changing operating conditions. The combination of unknown and time-varying conditions of optimality necessitates on-line optimization and then the concept of Extremum-Seeking Control (ESC) is a potential tool. The downside of ESC is that it induces a disturbance into the plant in the form of a dither signal. Important open research questions are thus

- Minimizing the disturbing influence of ESC control

- Combining ESC control with traditional control schemes

### Control and monitoring

With the rapid development in the are of cyber-physical systems and the systems of systems approaches, major issues are rising with respect to the reconfiguration of processes' components as well as reconfiguration and robustness of process controllers in order to adapt to the concept of flexible and one of a kind production. To address this process, specific research should be conducted on new and unconventional production strategies, with continuous and multidimensional sensory data gathering, even in line in the production cycle, and in full symphony with the concept of internet of things, that will allow the optimal operation of the factory and the easiness in online reconfiguration of the production components based on the current customers' demands.

When it comes to monitoring, A typical problem is the detection and diagnosis of oscillations, e.g. due to malfunctioning actuators, poor controller tuning, etc. that arise and spread due to the complex interconnected nature of a process industry facility. Current techniques for this purpose are mainly data-driven. An interesting research problems aimed at improving detection and diagnosis is

- How to use models of a complex plant in order to predict where oscillations are prone to arise and to combine this with data-driven techniques

### 5.2 Stepping stones towards 2030

From the prior analysis and scanning of available literature, the following intermediate goals (stepping stones) seem to be favorable to achieve until 2030. These goals require collaboration between Automatic Control, other research domains and industry. It also requires a certain level of commitment from all stakeholders and a sustainable funding for the development and maintenance of research and development platform.

The following stepping stones as a time line:

**2015:** First setup of the Open Research and Innovation Platform and its integration into research and education. New methods and tools will be implemented in the platform.

**2015:** Small scale implementation and with a simulated process.

**2017:** Small scale implementation with real lab process.

**2019:** Small scale implementation with a real-life unit process with actuation.

**2021:** Large scale implementation with real-life plant. Solutions for one of the grand challenges are found and published.

**2025:** Increased level of autonomy with effect on the process on lab and small scale implementation.

**2030:** Fully automated decision making and adaptable platform with some implemented unattended schemes. Solutions for both grand challenges are found and published.

In order to achieve these stepping stones it is important to create a collaborative framework which provides leadership, guides activities and embeds the platform goal in both research and education. The framework could be integrated into ProcessIT Innovations at LTU.

Moreover, funding will be a necessity and a certain amount of seed capital would be necessary to establish. Further funding need to be aggregated from regional, national or european funding bodies.

## 5.3   Partnerships

Collaboration is essential to establish the open research and innovation platform on both a national and international level. An analysis of the international research environment and the potential collaborations from an automatic control perspective, reveals several interesting environments. In the analysis it was important that the environment has a clear relationship to research within automatic control.

**Technical University of Munich.** Beside the fact that TUM is on the international university ranking list amongst the best 30 universities world-wide, an excellence center relating to cognition and computational intelligence in technical systems has been established, named *CoTeSys*. The university has also a strong profile in automatic control related research.

**ETH Zurich.** The Automatic Control Laboratory at ETH has a long going history and excellence in control of industrial processes and especially, when it comes to large scale systems. Additionally, the university has a main focus area, which is called *Industrial Processes*.

**International Institute of Applied Systems Analysis:** The institute is situated in Austria and has a long going history in the development of methods and tools for both large scale and complex systems in a diverse range of applications. Most namely, the applications do not relate to industrial needs in the first place but are on a societal level. The research expertise is not directly in automatic control, but has a strong mathematical background.

**Complex systems society:** The society is an international organization and not limited to a certain research expertise. Participating in the society might help to connect to research groups which are of interest for the development of the research and innovation platform.

Collaboration in Automatic Control on a national level is already established and naturally on-going in overlapping thematic areas.

# 6  Concluding remarks

Research in Automatic Control has both a long going history when it comes to industrial processes which enabled the automation of industrial processes and thereby improved overall equipment efficiency.

Current trends in Automatic Control research have a focus on the large scale interconnected world and the optimization of processes within it. Research results in this direction have a huge potential to render industrial processes which are flexible, resource efficient and to some extend self-aware. A prerequisite for this is a multi-disciplinary approach.

The research which is conducted at the Control Engineering Group is very much aligned with these trends and the group is actively contributing by publishing state of the art research and creating innovations with industrial relevance.

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