ABB Research Center Germany
Annual Report 2015

Power and productivity
for a better world™

Content

Dr. Jan-Henning Fabian
Head of the ABB Research Center in Ladenburg

Dear friends and colleagues,

In year 2015 a great moment was the Hanover Fair and the official product release of the YuMi Robot: the first truly collaborative robot with an inherent safety concept, a robot providing a dual arm assembly solution with the ability to feel and sense. As the corporate research organization significantly contributed to this technology innovation, we were delighted to support our business unit colleagues at Hannover to show ABB customers the uniqueness of this robot. YuMi allows fenceless operation and a safe human machine interaction, with these features highly productive semi-automated assembly lines are one target application. However, beside all the technical features, a robot directly collaborating with the worker will change the work environment in our factories with a unique potential shaping the future factory workplace in Industrie 4.0.

With over one hundred employees, the German research center in Ladenburg is a key player within the global structure of the seven corporate research centers of the ABB group. The German research team focus on new technologies for process and factory automation, building automation and solutions for our service business. We in Ladenburg have a particular focus on software research, a technology field within ABB of increasing importance in all our products. Also the technology needs to bring Germanys Energiewende to a success puts our effort on research for energy grids of the future to our focus.

Our annual Technology Press Event 2015 illustrated the transformation of our today's energy systems: in the past with hierarchical structures from producers, transmission and distribution networks with an unidirectional energy flow to the consumer to complex, intelligent automated networks (smart grids) with a high proportion of distributed and intermittent producers and more flexible consumers, including locally installed generation and storage capacities; so with many more active participants in the energy system. This provides a great challenge to automation and energy management solutions, while ensuring the security of supply at all levels. ABB offers already today great technical solutions, plus the recent results of our research work will bring great potential for energy and cost savings to the market ultimately providing the required technologies for energy transition and a sustainable climate protection.

In 2015 the significant change by the introduction of cyber physical systems to industrial automation, using internet communication and scalable cloud computing technologies, offering new services to our customers, was branded by ABB to IoTSP – the Internet of Things, Services and People. With IoTSP we at ABB highlighted beside the technology and the service aspect also the importance of people - for us as researcher extremely interesting to shape with our technology innovations the workplace 4.0. Beside the various ABB internal research activities on IoTSP, the Ladenburg Research Center was also in 2015 an active player in the German Industry 4.0 platform initiative, contributing to several working groups and reports of the Industrie 4.0 platform.

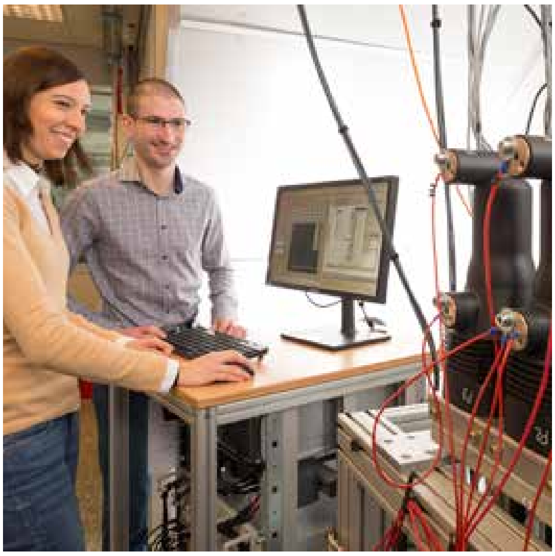
This annual report will give you an overview of our core activities in more detail. I am pleased and honored to present this report as a summary of the valuable work undertaken by the German corporate research team in 2015. I am convinced that it will raise your interest and that you will enjoy reading it. I also would like to thank all our partners at universities and different ABB business units for the constructive productive and successful project work with the common prospect to continue these successful collaborations in 2016.

Finally, I would like to express my sincere thanks to all colleagues who have created all our successful innovations by their dedicated work. I am looking very much forward to continue this successful work.

Jan-Henning Fabian

ABB Corporate Research Center Ladenburg

The German Corporate Research Center in Ladenburg is one of seven local research labs in the global ABB Corporate Research community. It is part of the Global Research Lab, which bundles the competencies and skills of ABB's 700 researchers in eight global research areas. With respect to local organization, the German Research Center is part of the ABB AG in Mannheim.



Global Corporate Research Lab

Activities and resources in Corporate Research worldwide are managed and structured in a Global Research Lab comprising eight Global Research Areas, which are aligned to ABB's core technology areas. The mission of a research area is to maintain world class competence in the respective field and to develop the technologies for future generations of ABB's innovative products, thus ensuring and strengthening ABB's technology leadership.

The German Research Center focusses on the four research areas

- Software
- Control
- Mechanics
- Sensors

During the course of the year 2015 we re-aligned our resources and competences with these research areas, which is reflected in the line organization. Our strongest competences are in the Software research area, where we are the lead center within Corporate Research.

Vision and Mission

"Leadership through Innovation" – this is our vision. Recognized as an excellent industrial Research Center we create sustainable value for ABB business through technical innovations.

Our mission is to deliver R&D project results as a basis for innovations to our business units – effectively and efficiently. In order to achieve this, we have to maintain a high level of competency in our key technology areas.

Customer oriented organization

According to our mission we provide the technologies for future innovative products and solutions to the ABB business units and product groups, who are our internal customers. From the German Research Center we support businesses in all of ABB's four business divisions:

- Process Automation
- Discrete Automation and Motion
- Electrification Products
- Power Grids

Our biggest customer is process automation with focus on process control systems, process instrumentation and production optimization solutions in all industry segments. The second largest customer is electrification products, were we work mainly on products and solutions for smart buildings and sites and on products for medium and low voltage energy distribution networks, both AC and DC.

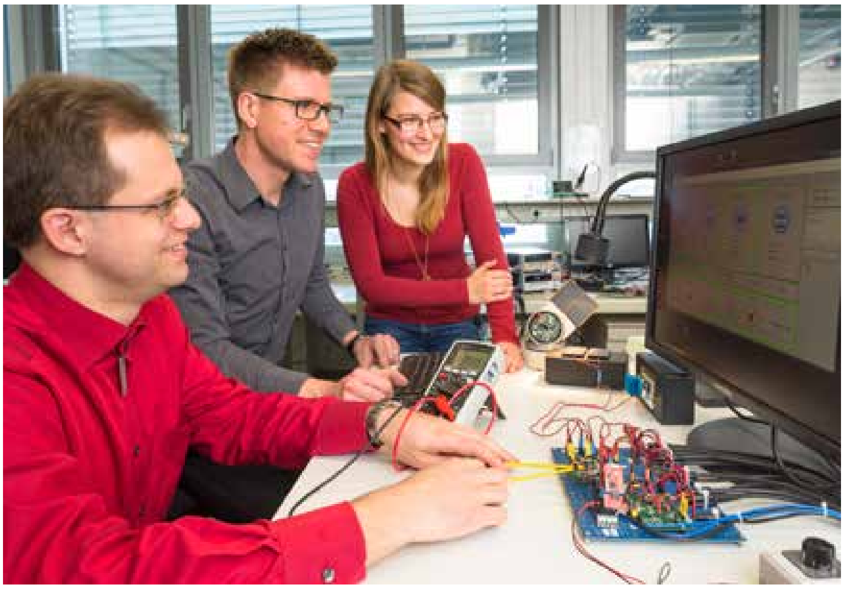
Within the discrete automation and motion division, we focus on future advanced robotics applications, particularly based on safe human-robot collaboration. For the new division power grids, we started in 2015 some activities to support ABB's business for future AC and DC high voltage power transmission networks, which gain increasing importance in the context of the German "Energiewende". These activities will be extended in the coming years.

We have assigned dedicated members of our management team, namely department leaders, to the customer segments. These people act as customer relations managers and are responsible for capturing customer needs, optimizing the project portfolio for their customers and improving customer satisfaction.

Strategic key topics

Across customer segments and research areas, we have selected five strategic key topics, where we will put special focus on in the coming few years. All activities related to such a topic are coordinated by a topic coordinator, in order to facilitate sharing of knowledge and to avoid redundancies. Our strategic key topics are:

- **IoTSP: Internet of Things, Services, and People**
  Rethinking the architecture of automation systems in the context of the fourth industrial revolution
- **Data Analytics**
  Data driven analytics for industry applications and new software based services
- **Human Machine Collaboration**
  Safe collaboration between humans and robots for new manufacturing paradigms.
- **Building Automation**
  Automation systems for operation and energy management in homes, buildings and sites.
- **Future Power Grids**
  Providing technologies for the grid infrastructure to support German "Energiewende"




ABB

Organizational Structure

Resources, competences and infrastructure in the German Research Center are organized in seven research groups, which are aligned with the global research areas in which we are active. Research groups are managed by research group leaders, who are responsible for resource development and operational excellence in project execution in their group. The research groups are structured in two departments, one of which is covering the software and system aspects of our technologies, while the other one is dealing more with hardware aspects and devices. The resulting organizational structure is shown in figure 1.

Department Software Technologies and Applications

Software Systems: Software technologies, future-proof systems architectures as well as sustainable software architectures play a major role in industrial products and systems. They are increasingly contributing to functionality and the creation of added value. The seamless integration of powerful, high-quality software has therefore become a decisive competitive advantage.

Operations Management: Industrial and grid automation systems are at the heart of ABB's business. The group's mission is to create value adding functionality on top of our automation systems based on control, optimization, simulation and analytics methods. The focal applications domains are the processing industries and power grids.

Analytics and SW Applications: The Internet of Things, Services and People significantly impacts automation and power industries. The focus of this research group lies on the development of (big) data analytics to assess and improve the reliability, availability and maintainability of fleets of products and systems. In this context we also work on process- and business model innovation as well as service support by mobile- and wearable devices.

Department Automation Device Technologies

Mechatronics and Actuators: Mechatronic systems are characterized by integrated aspects of mechanical engineering, electrical engineering and information technology. Mechatronics represents an inherently interdisciplinary field, and applies these three subject areas to extend the functionality of conventional components. This interaction of disciplines gives rise to a vast assortment of opportunities for the improvement of existing products and the development of innovative new technologies.

Robotics and Manufacturing: The trend towards flexible production systems puts high demands on the utilized automation solution. As a response, a tighter integration and coordination of intelligent devices, robots and humans is needed. This reaches from low-level control primitives of collaborative robots to the autonomous optimization of the production processes involved.

Industrial Sensor Technology: Sensors provide the relevant information for process control and optimization as well as condition monitoring and service. Electrical and process sensors, which may be stand-alone field devices or value-adding microsystems embedded in ABB products, are helping our customers to operate plants and to increase their productivity.

Intelligent Devices: Devices form the core of automation solutions performing more and more tasks with increasing intelligence, implemented in the form of software as embedded systems. Devices have to meet increasing demands in functionality, usability and system support and so the modelling of information and the integration into systems is a key field of research for the group. Beside that, the group is concerned with the high resource constraints like low footprint and low power.

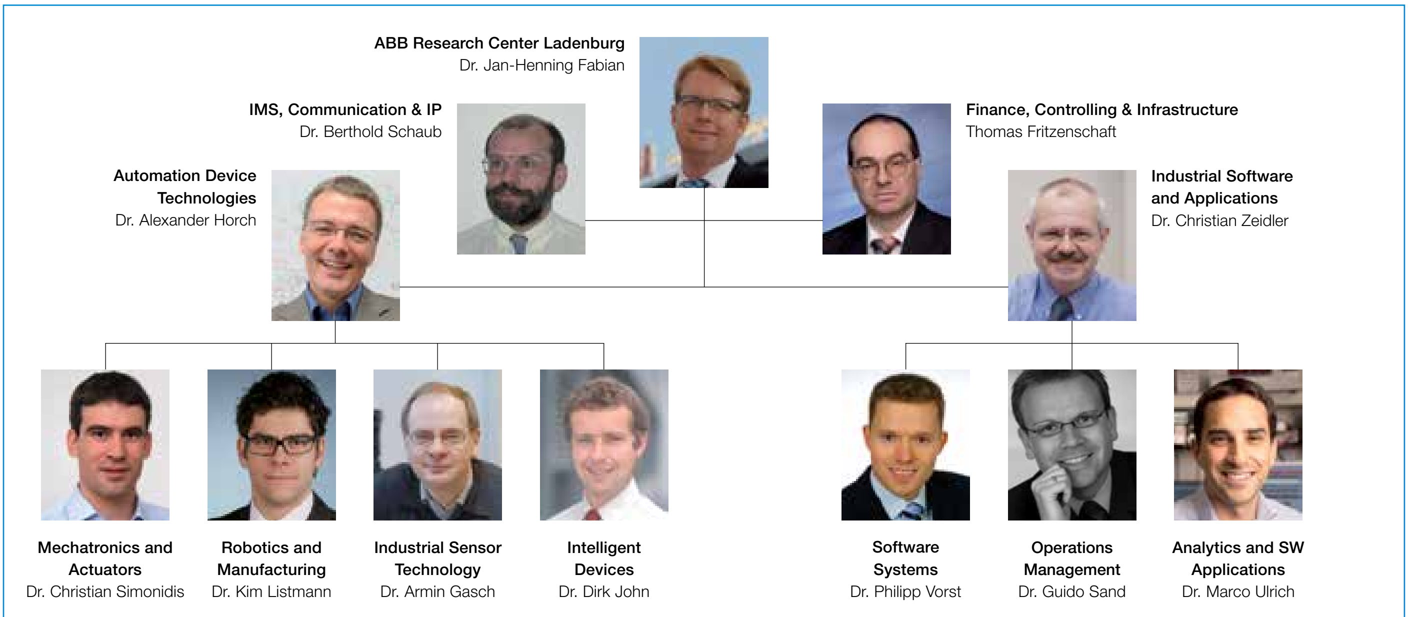
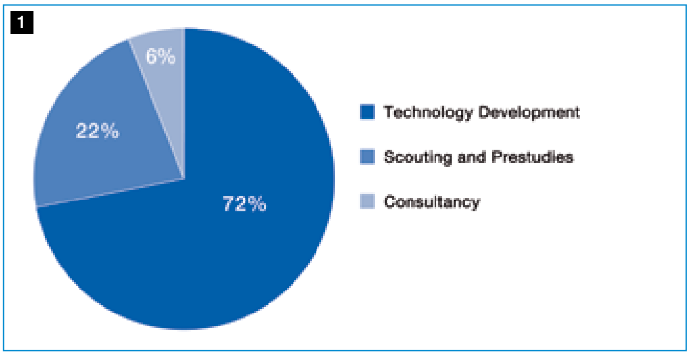
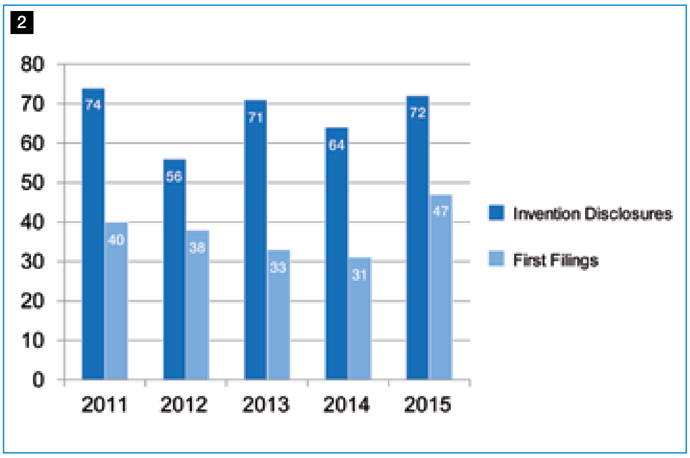


Figure 1: Organizational structure

Facts and Figures

Key Figures	
Employees	98
Temporary employees, Students	88
Inventions	72
Patent Filings	54
Publications	130





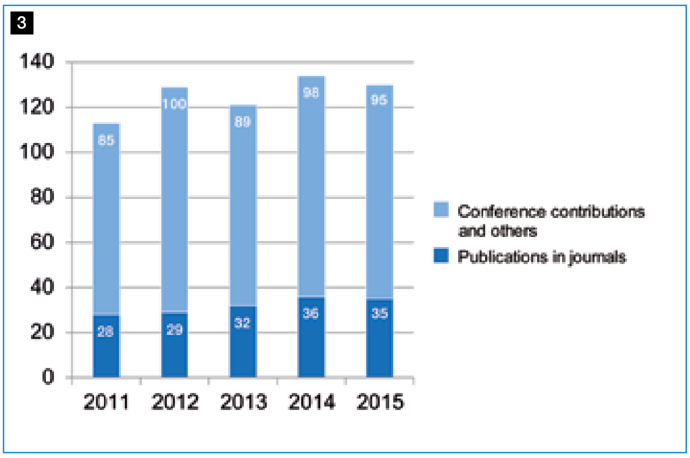


Figure 1: Project revenues by project type | Figure 2: Inventions and First Filings | Figure 3: Publications

Project Portfolio

The project portfolio is continuously adjusted to our current and future strategic key areas, which are the Internet of things, services and people (IoTSP, in Germany referred to as Industrie 4.0), building automation, human machine collaboration, big data analytics, and future power grids in the context of the German "Energiewende". In 2015 already more than 50% of our project volume was related to these areas, and we will further increase this in the coming years. Furthermore, we will put more focus on public funded joint projects in the areas IoTSP, advanced robotics and future power grids, which fit quite well with our strategy. The total project volume is roughly constant, reflecting the available resources in DECRC.

Regarding project type a clear focus remains on the development and transfer of technologies for future ABB products and solutions, which stands for 72% of our project volume (see figure 1). This development is driven by a balance of customer needs and technology trends. The German Research Center is driving some large strategic technology development projects, namely in our key areas, which stand for 40% of the total volume for technology development. The share of prestudies and technology scouting projects is kept on an adequate level (22% in 2015), in order to explore relevant new technologies, create new ideas and develop proposals for larger projects. Furthermore, we support our business units with consultancy projects when required.

All of our research work is performed within the global research areas, with focus on Software (40% of project volume), followed by Control and Mechanics (17% of project volume each). Regarding our customers, 40% of our project work supports Process Automation, followed by Electrification Products with 27%. All technology development projects follow the ABB gate model, a business decision model that helps to steer a project from the project customer's point of view. We continue to monitor the quality and efficiency of project execution based on the Gate Model with a special focus on transferring projects results into business.

Project Results

Project results are new or improved technologies, demonstrators or prototypes, which create value for ABB once they are implemented in new products, solutions or processes by ABB business units. In 2015, we achieved 8 well recognized technology transfers from our projects with a significant impact on ABB's business. Some of these project achievements are described in more detail in the Technical Results section of this report. In addition to project results, we monitor carefully how our results are implemented in new ABB products. In 2015, 7 new products, to which DECRC contributed with key technologies, were released and introduced to the market. The highlight among these products was certainly the collaborative robot YuMi, which was launched during Hannover Fair 2015.

In addition to the primary project results, valuable intellectual property like patents, utility models or trade secrets is created in our projects. In addition to the number of inventions we place a strong emphasis on the filing rate, which is an indicator for the relevance of the inventions to ABB business. In 2015, we could significantly increase the filing rate to 80%, leading to a record number of 47 first filings (see figure 2).

Publications in renowned journals and active contributions to conferences are important to demonstrate ABB's technology leadership. Both the total number of publications and the number of publications in renowned journals could be maintained on the high level we reached in the previous year (see figure 3). This gives our researchers the opportunity to be highly visible in the academic community and to contribute actively to future technology trends.

Human Resources

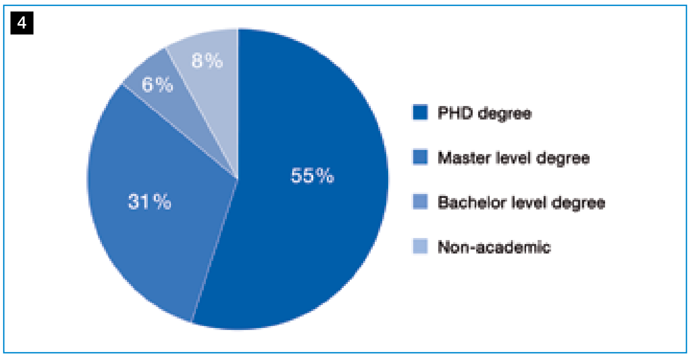
Our employees are the main assets of our Research Center. In addition to our permanent employees, we employed a record number of 88 temporary employees like students or guest scientists, who gain first experience in an industrial research environment during the thesis work or internship. This is a very appropriate measure to increase the visibility of the ABB Research Center as an employer towards students.

The world class competence level of our employees, including technical, social and management skills is a prerequisite for excellent research results. In 2015, 92% of the employees held academic degrees. The majority of these hold a PhD (see figure 4).

It is part of our mission to recruit talented young engineers and scientists, give them the opportunity to work for some years in corporate research and later offer them new career opportunities in ABB units. During 2015, we hired 6 highly qualified new scientists and during the same time period 7 employees could take the next step in their professional career in ABB business units.

The unique academic environment in Germany is still an important source of our new employees. Four of six recruitments in 2015 came from German key universities. In the German Research Center we maintain an interdisciplinary, multinational team with a high educational and cultural diversity. Our Human Resource portfolio currently consists of 16 nationalities. Regarding education the focus is on electrical and mechanical engineering and computer science (see figure 5).

We emphasize strongly on the continuous development and education of our scientists, both by attending seminars and by on-the-job- training or job rotations. On average, we allocate approximately 5% of the revenues for personnel training and development.



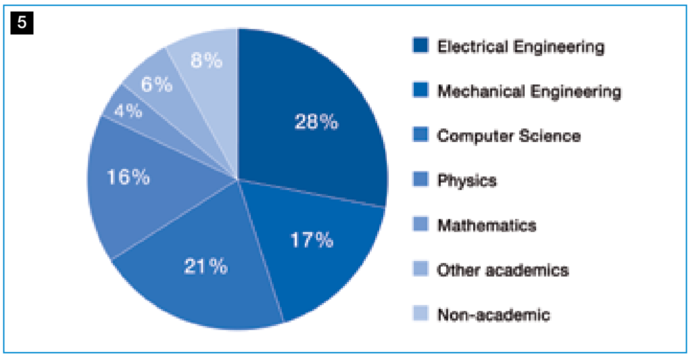
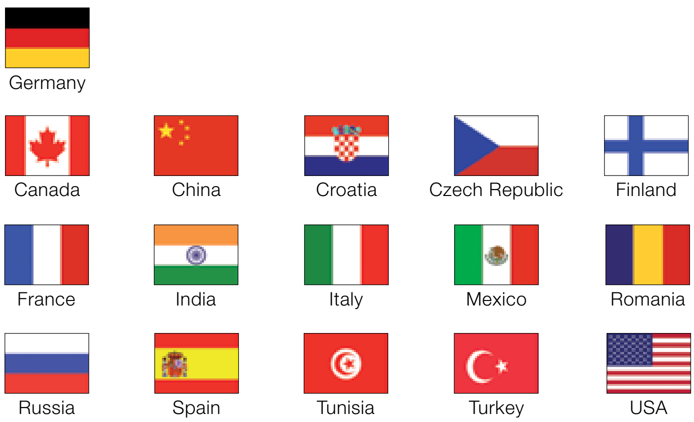


Figure 4: Educational level of employees | Figure 5: Branches of study of DECRC employees

Researcher diversity



Events and Highlights

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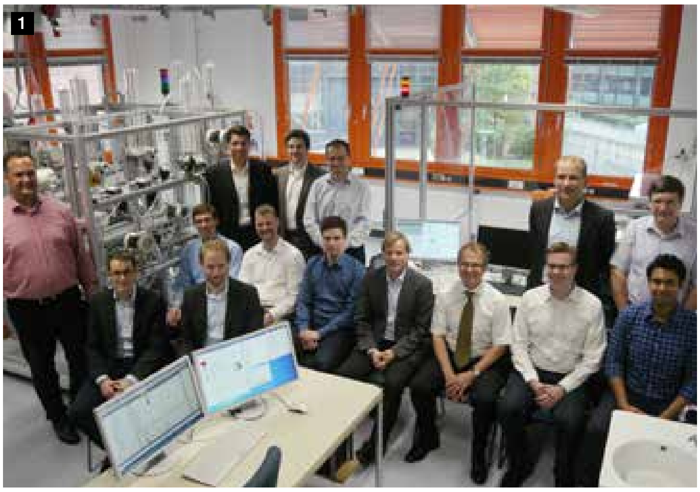

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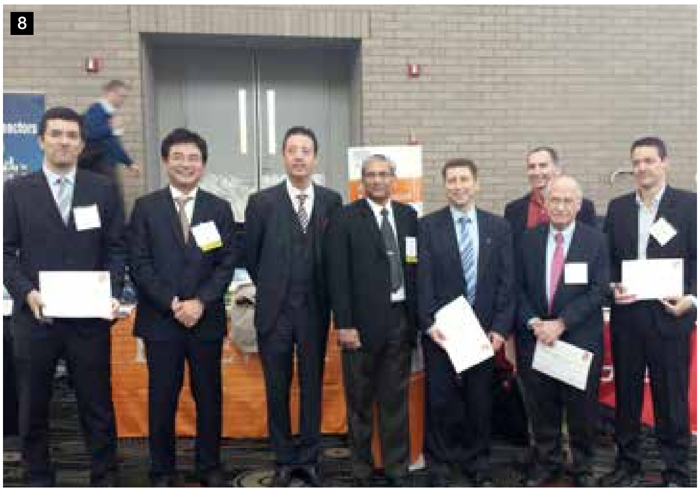
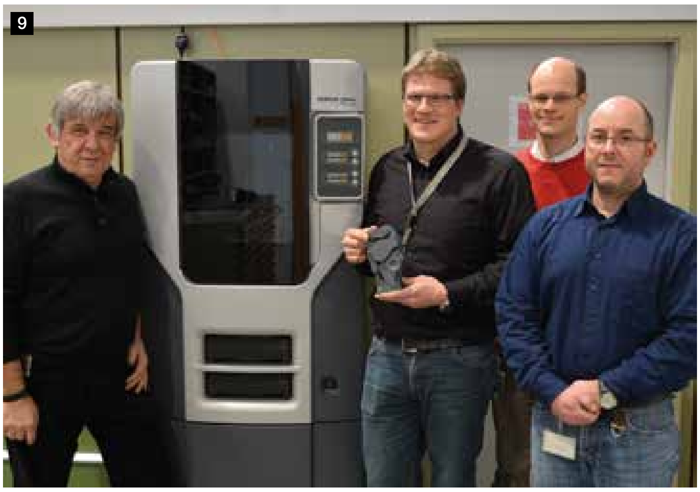
3


4


January	February	March	April	May	June
	1 Consortium Meeting from FEE project in Ladenburg		2 Presentation of first truly collaborative robot at Hannover Fair	3 Eugen Hartmann Award for Arne Wahrburg	4 Technology Day at Corporate Research Ladenburg





July	August	September	October	November	December
5 Annual DECRC Barbecue	6 Successful re-certification of DECRC according to ISO 9001, ISO 14001 and OHSAS 18001 standards	7 Children's Day at Corporate Research Ladenburg		8 Computers & Chemical Engineering (CACE) Best Paper Award for Iiro Harjunkoski et. al.	9 Inauguration of a new 3D printer in mechatronic lab

Cooperations with Universities and Public Research Institutes

Successful innovation requires the combination of a range of competencies ranging from basic research to technology development and productization.

In industrial research, our focus is on applied research with the goal to develop new technologies for future innovative products. In order to ensure the basic research and special skills we need for this development, we maintain a comprehensive network that includes leading universities and research institutes, both in Germany and in other parts of the globe. Particularly in Germany we have unique academic environment with a large number of excellent universities. With many of them we maintain innovation partnerships in bilateral cooperations on project level and in larger, public funded joint projects. Furthermore, our partner universities are valuable sources for the recruiting of world-class scientists.

Bilateral Cooperations

In many of our research and development projects we need competencies and skills as well as results of basic research, which are not available within ABB and where it would not be efficient to build it up specifically for this purpose. In these cases, we enter into bilateral co-operations with universities or public research institutes who are renowned in the academic community for their research in the respective field. Particularly in Germany, we have a large number of excellent institutes, who complement the competencies and resources in our projects in an ideal way. With these cooperations on project level we established a valuable network of academic partners. Furthermore, bilateral cooperations are often a starting point for recruiting excellent scientists who have already worked for some years with ABB people on ABB topics, before they move from the university to industry.

In 2015, we had a total of 38 bilateral co-operations with 30 universities, thereof 20 in Germany, where we focus on strategic key universities such as Karlsruhe Institute of Technology (KIT), Technical University Dortmund, Technical University Dresden or Technical University Darmstadt. With KIT we cooperate on a variety of research topics ranging from energy management in buildings, industrial applications of the internet of things, to industrial services in general. At TU Dortmund we focused so far on collaborative production optimization, while in Darmstadt we have since several years successful cooperations on co-simulations of electro-mechanical systems and on industrial motion control. At TU Dresden we cooperate with several institutes on industrial communications, device integration technologies, automation systems design and data privacy and security.

Outside Germany we have as an example a long tradition of cooperation with Carnegie Mellon University in Pittsburgh, USA, on topics like planning and scheduling methods or demand side management. Other foreign universities with whom we cooperate are for example Politecnico di Milano (DC current measurement, reliability, diagnostics and prognostics), Imperial College in London (plant-wide disturbance analysis), or University of Cambridge (service business development, business model innovation)

Public funded joint projects

In an early, pre-competitive phase of the innovation process, we are participating in larger joint projects where we cooperate with universities and industrial partners inside and outside Germany. These projects are typically partly funded by public institutions like the European Commission or the German Ministry of Education and Research (BMBF) or the German Ministry of Economy and Energy (BMWi).

Currently, we have five active public funded joint projects. Two of them are running under the Initial Training Network program funded by the European Commission, coordinated by Prof. Nina Thornhill from Imperial College in London, with participation of Universities from UK, Switzerland, Poland, Germany, Norway, Spain and USA. The other three are funded by the German Ministries BMBF and BMWi, with cooperation partners from German Universities KIT, Dresden, Kassel, Aachen, and several industrial partners and utilities in Germany. Topics are decision support in future production environments, professional wireless industry LAN and modelling of user interactions in building automation systems. In the coming years, we plan to extend our engagement in this kind if joint projects, particularly on the topic future power grids.

Lectures by DECRC employees

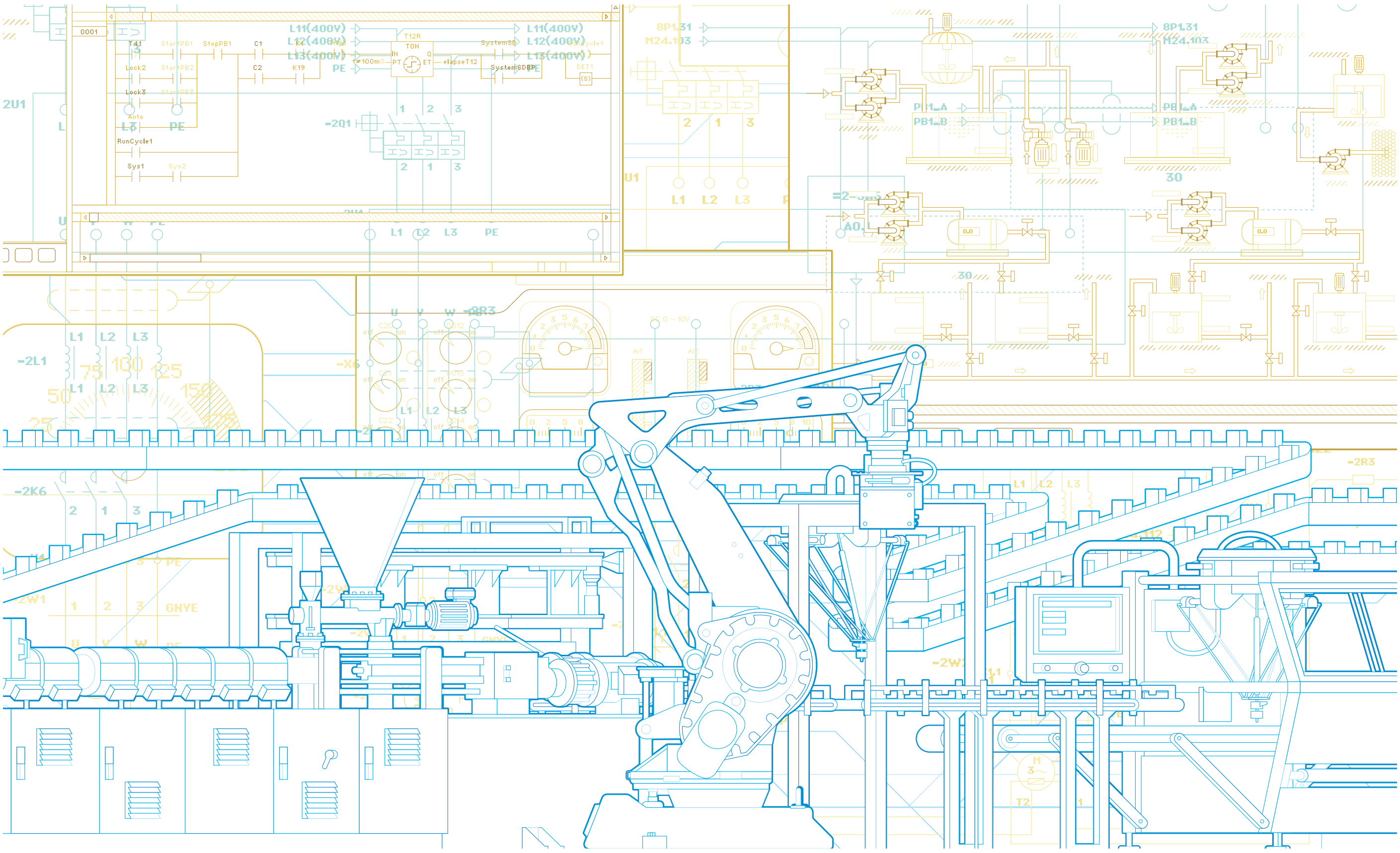
In order in increase ABB's visibility as a technology leader and attractive employer, we encourage interested employees to take opportunities for giving regular lectures at our partner universities. This is also supporting the scientific career of our employees and gives them the opportunity to establish and maintain their personal academic network. During the year 2015, DECRC people gave 18 lectures at 12 universities, mainly in the closer environment of Ladenburg like Mannheim, Karlsruhe, Darmstadt or Stuttgart.

Other academic Activities

Beside cooperations and lectures we maintain a number of other academic activities of our employees. During 2015, we had more than 10 such activities, including memberships in technical and scientific committees, PHD committees, advisory boards, or academic visits.

Technical Results

The following technical papers describe the technical results and status of our research activities in more detail. As examples of major projects and research topics, they provide a good overview of the work in our research groups during the year 2015 to the technically interested reader. In particular, the topics are:



Automation Internet: Shaping Industrie 4.0 and the Internet of Things, Services and People

Dr. Thomas Goldschmidt, Dr. Philipp Vorst, Dr. Zoya Alexeeva Durdik, Dr. Heiko Koziolek, Dr. Martin Krüger, Dr. Dirk Schulz

ABB is on the way to an Internet of Things, Services and People (IoTSP). In this article we summarize a number of contributions, particularly in the context of the German federal initiative Industrie 4.0: We have supported the collection of high-potential use cases of Industrie 4.0, driven the architectures of the future by contributing to a widely accepted reference architecture model, paved the way for making sustainable technology choices in our business units, and shaped Industrie 4.0 on the business side with convincing business models.

Introduction

ABB is committed to the vision of an Internet of Things, Services and People (IoTSP): Interconnecting things, services and people via the Internet enables new insights by data analysis, boosts productivity, enhances reliability, saves energy and costs, and generates new revenue opportunities through innovative business models [1]. The proper choice of standards, technologies and ways how to run business are important building blocks on the way to the IoTSP. At the German Corporate Research Center, we have therefore run a research project, described in this article, that helps shaping ABB's activities around IoTSP and Industrie 4.0 (I4.0) [2]. The latter is the name of the broad German initiative for Internet of Things in industry, similarly as the Industrial Internet Consortium (IIC) drives ideas of the Industrial Internet in the US [3].

For the German initiative I4.0, the year 2015 was coined by gaining a common understanding of Industrie 4.0. As one example, the Platform Industrie 4.0 called for I4.0 use cases in action. ABB is contributing ten of them. Another sample outcome from German I4.0 committees in 2015 was the establishment of RAMI 4.0 [4], the Reference Architecture Model for Industrie 4.0. This model provides the basis for a common technical notion of I4.0. It paves the way, e.g., for mapping I4.0 use cases, norms and standards, and for fostering further standardization. Project team members contributed to deliverables such as RAMI 4.0 in the relevant I4.0 bodies.

In our project, we have selected two further, complementary demo scenarios – currently under elaboration – which help us to explore future I4.0 opportunities together with ABB business units, understand technical capabilities and limitations, and interface with the important committee work in Germany. One scenario is from the area of process automation, the second one from factory automation. These scenarios underline ABB's understanding that IoT has disruptive potential for most parts of automation. For instance, standardization and interoperability as pursued in Industrie 4.0 will change the prerequisites for data analytics also in process automation, which is the theme of one of the selected two case studies.

The selected demo scenarios drive the investigation and assessment of relevant technologies in the IoTSP technology landscape. Additionally, Industrie 4.0 use cases and technologies raise the question how business will look like in an I4.0 ecosystem, with technology providers, service providers, and users/consumers which we also analyzed.

ABB Use Cases for the Industrie 4.0 Platform Initiative

One of the activities of the Platform I4.0 initiative is to provide an overview of already available Industrie 4.0 products and solutions on the German market. The German Research Center (DECRC) coordinated the collection of already implemented ABB I4.0 use cases, and ten of these were acknowledged and adopted by the Platform I4.0. The submitted use cases are listed in Table 1.

Use Case	Summary
Enclosure-free Assembly Station	YuMi® is a collaborative small parts assembly robot solution enabling people and robots to work hand-in-hand on the same tasks.
Robot Remote Monitoring	Patented wireless remote service solution for robot condition monitoring and diagnosis.
Service-Platform with Remote Access Possibility	ServicePort™ is a secure, remote-enabled service delivery platform for monitoring of KPIs of equipment and processes.
Intelligent Energy Distribution	Fail-safe, energy efficient production based on ABB's intelligent low voltage components.
EMMA Advisory Suite	Advisory Systems is a product portfolio for performance management in marine operations of a vessel or a fleet of vessels.
Decathlon Services	Decathlon software combines plant operations data from control systems, ERP, and other data sources into actionable information.
ABB 800xA Simulator	800xA Simulator offers a safe and realistic lifecycle simulator for ABB's distributed control, electrical and safety system 800xA.
Field Device Integration (FDI) for I4.0 Field Level	Field Information Manager is the first FDI-based SW for improved configuration, commissioning and maintenance of fieldbus instruments.
Intelligent Alarm Management	Cloud computing and advanced data analytics services combined to improve enterprise alarm management.
ABB Hierarchical Safety Control	Hierarchical Safety Control concept allows for increase of efficiency in production, while maintaining the personal safety.

Table 1: 10 Industrie 4.0 Use Cases from ABB.

Figure 1: German-wide online map "Industrie 4.0" showing 207 submitted Use Cases

These ten use cases are now available on the first German-wide online map "Industrie 4.0" and were presented at the national IT summit of the federal government of Germany in November 2015 in front of the highest-rank German politicians, including Chancellor Angela Merkel.

Alongside with ABB, about 100 companies, research institutes and universities with altogether 208 use cases are represented on the map. The majority of these come from providers, such as ABB and Siemens, closely followed by IT and engineering companies. Most of the submissions are mature I4.0 application examples, focusing on application of I4.0 possibilities in own companies. While the focus of ABB is rather on process industry, most others focus on production. Among the top represented topics are Factory I4.0, predictive maintenance and virtual reality, with the ABB use cases covering the former two.

As the next step, Platform I4.0 is currently working on definition of I4.0 long term research topics relevant in Germany. ABB, and DECRC in particular, is actively participating in the related activities and committee work.

Reference Architecture Model Industrie 4.0 (RAMI 4.0)

In a broad initiative such as Industrie 4.0, there is the need to categorize existing standards in alignment with case studies such as in the previous section. In addition, it must be possible to identify standardization gaps. The Industrie 4.0 Platform hence released the Reference Architecture Model Industrie 4.0 (RAMI 4.0 [4]) at Hanover Fair 2015. Researchers from ABB participated in the creation of this structuring model.

Figure 2 shows a three-dimensional illustration of the model. The x-axis represents four life-cycle stages reflecting the development and usage of a product type and product

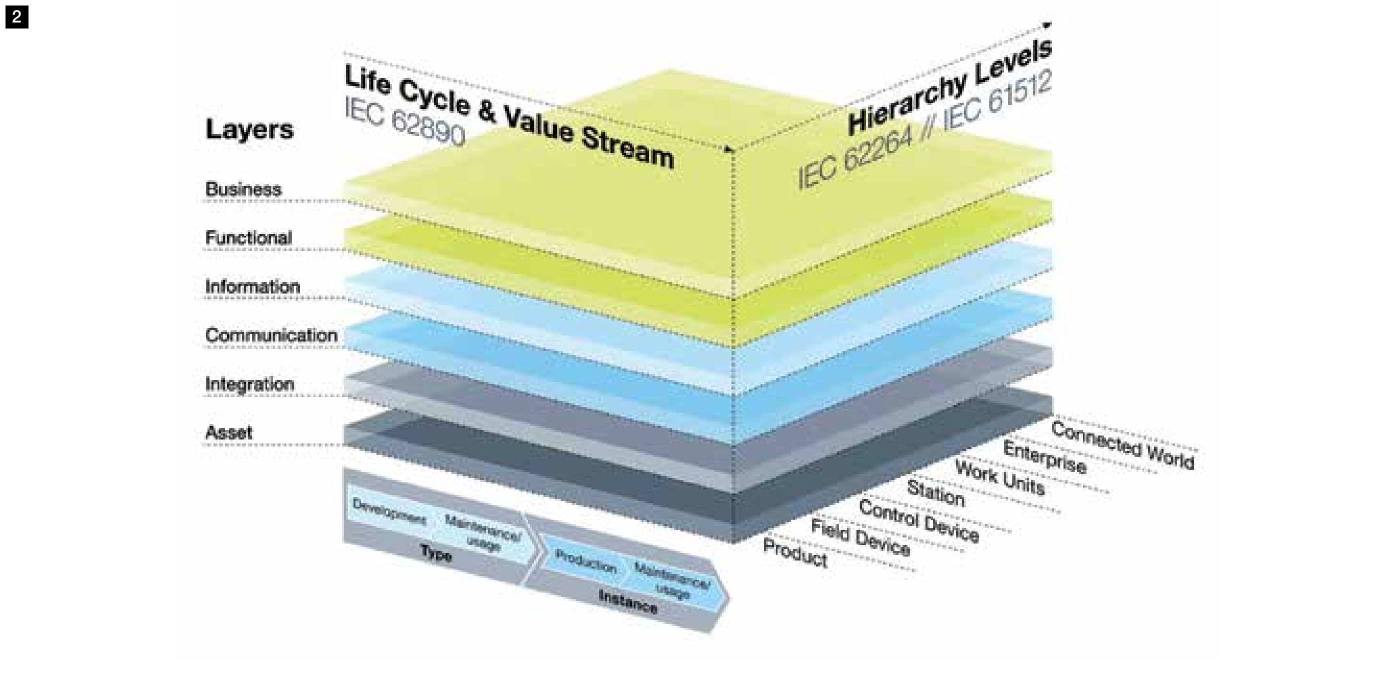


Figure 2: Reference Architecture Model Industrie 4.0 (RAMI 4.0) [4]

instances and is based on IEC 62890. The y-axis shows six viewpoints on the production process ranging from the business viewpoint down to the asset viewpoint. Many standards relevant for Industrie 4.0 application scenarios reside on the viewpoints "Information" and "Communication", e.g., OPC UA or AutomationML. The z-axis was inspired by hierarchy levels from IEC 62264 and IEC 61512 adding "Product" and "Connected World" as new levels required for Industrie 4.0 applications.

The purpose of the model is to scope discussions on standards and to identify standardization gaps. The Plattform Industrie 4.0 has defined seven application scenarios representative for various Industrie 4.0-related topics. These scenarios are now being analyzed using the RAMI model. Individual cubes in the three-dimensional shape can be isolated for each application scenario. Findings about relevant standards for each scenario, gaps in existing standards or missing standards will be communicated to the appropriate standardization organizations, so that the vision of standards-based interoperability between Industrie 4.0 components for versatile industrial production can be realized.

Industrie 4.0 Service Architecture

One of the targeted core capabilities of Industrie 4.0, the self-organization of the production, will be made possible by a system of standardized services. To achieve true plug and produce scenarios a certain degree of interoperability between the service system participants is required. Important mechanisms to achieve these capabilities are easy discoverability as well as semantic descriptions of services. Even though OPC UA has been mentioned as being the main candidate for implementing such as service system, the services themselves should be transferable to other technologies as well.

Within the context of the GMA 7.21 committee, a service architecture has been defined that intends to cover these aspects. As depicted in Figure 3, the one of the results is a layered architecture that supports the definition and composition of Industrie 4.0 services. Starting from the service participant the two bottom layers hold the technology (e.g., OPC UA) specific services of the actual components.

The actual Industrie 4.0 services then start with a layer of "Basic Services" (or "Data Access Services") that encompass the necessary service atoms that are required to build the higher-level services. This includes reading, writing data as well as calling functions and browsing information models. In contrast to the lower levels, these basic services are technology agnostic and create the basic layer of interoperability on the information layer of RAMI (cf. Figure 2).

On top of these atomic services there is a layer of "Platform Services" (or "Administration Services") which serve the self-organization of the resources within the Industrie 4.0 system. Examples here are service registries (used for service discovery)

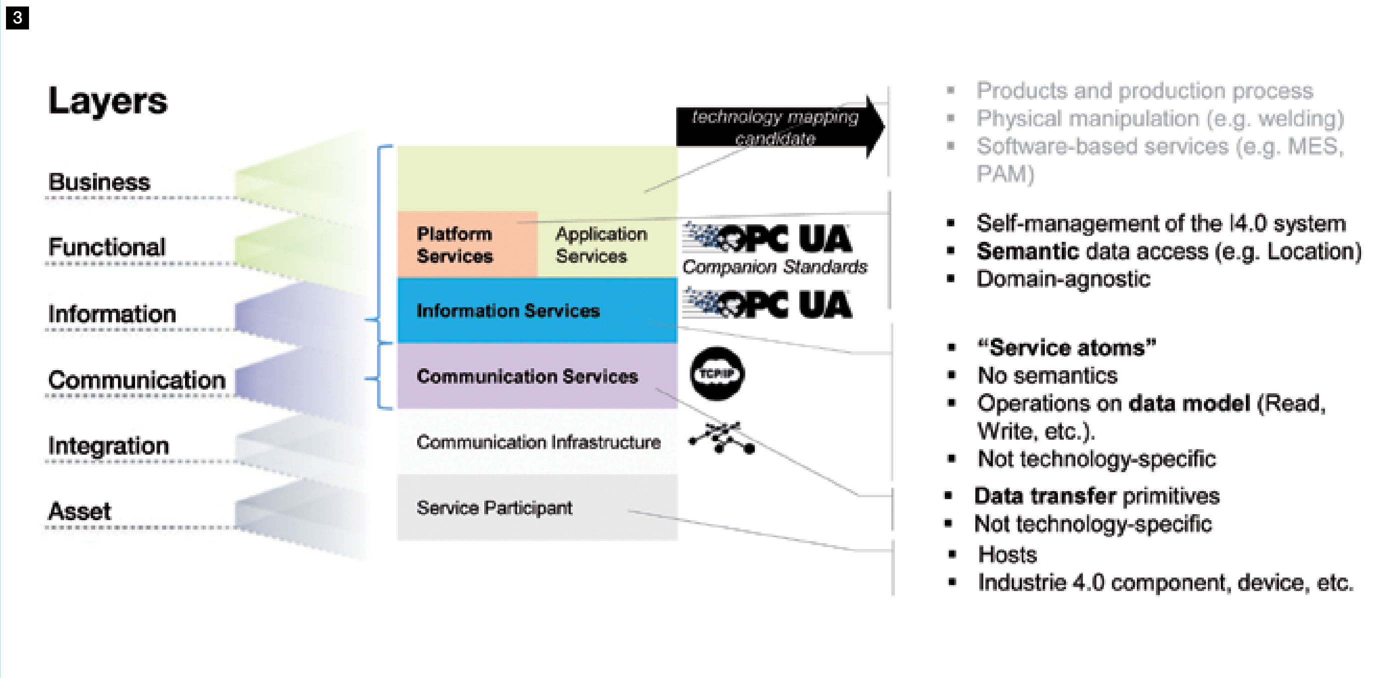


Figure 3: The Industrie 4.0 Service Architecture and mapping to RAMI 4.0 layers

or access to semantic data (e.g., localization services). The platform services are domain independent and are therefore uniform across all Industrie 4.0 systems. This allows the interoperability between the various hierarchy levels along the RAMI.

Finally, higher-level services that organize the actual application specific production, called "Application Services", are built on top of this infrastructure and are therefore out of scope of the standardization activities. Examples for services on this level are actual production services such as "Welding", "Transportation" or "Production Scheduling".

With the standardization of the these services in the Industrie 4.0 committees and the technology abstraction included in this architecture it is ensured that higher level services can be executed in an interoperable and self-organized way. This is the basis for the realization of the main targets of Industrie 4.0 namely a highly flexible and efficient production.

Technology Example: Indoor Localization

One key challenge in any mobile indoor service, from guided maintenance to site/installed base survey, still is the precise localization of the worker and their point of operation. Contrary to outdoor scenarios, we do not have the luxury of using GPS for localization; triangulating wireless signals (if available) is not very precise. With devices like the Google Tango consumer tablet, we see indoor localization become possible at a precision of up to 10cm without having to deploy a specific infrastructure. Furthermore, we would also like to offer simple and easy integration of the mobile device with our Industrie 4.0 enabled automation system. ABB already provides a series of device apps supporting the worker on their mobile devices. However, toward supporting Industrie 4.0 applications out of the box, a new challenge is the seamless integration of the information provided out of the mobile device, independent of app, service, or user.

To meet these challenges, we have implemented an OPC UA server on the Tango tablet, exposing:

- Survey records, where users trigger the recording of raw position data along with artifacts like photographs (e.g. of device tags or hazardous situations), which are then time-stamped and stored for later processing by another software-based service.
- Live raw sensor data, including traditional GPS data, temperature, etc. along with the novel indoor positioning data

This means that the survey capabilities of the mobile device are exposed as Industrie 4.0 services – instantly and permanently, as long as the device is online on the local wireless network. In the Industrie 4.0 service architecture, interested consumers of survey information can simply discover such location servers and subscribe to changes on the OPC UA model to learn about newly found devices. No explicit

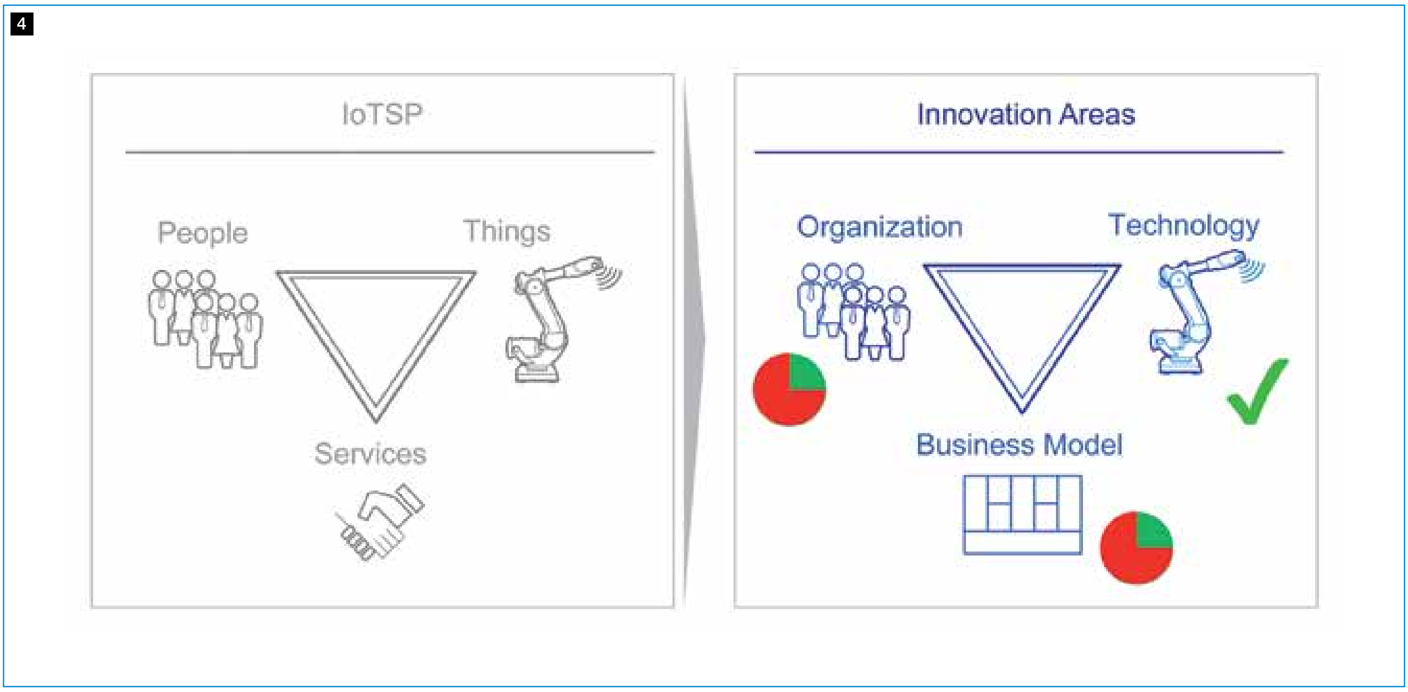


Figure 4: Areas of Innovation

synchronization of the device to the system is required, no need to pre-configure data consumers and push available data to them.

By combining the data from several such devices or less precise localization systems based on e.g. WiFi technology, other services can turn raw location data into global coordinates, account for drift on the mobile device sensors, etc. Other services can subscribe to such refined information to obtain approve coordinates during installed base survey.

With this approach, we use OPC UA technology services to actually tie mobile device, automation system, mobile worker, and installed base services into a true Industrial IoTSP with "localization as a service".

Industrie 4.0 Business Models

From ABB's IoTSP interpretation of Industrie 4.0 three areas (cf. Figure 4) of required innovation can be derived: technology (things), organization (people) and business models (services). Thereby technology has driven innovations in the field of Industrie 4.0 – and organizational adaptation and business model innovation are lacking behind. However, only the co-innovation of all three areas will create successful Industrie 4.0 business.

Services are the basis for new business in the Industrie 4.0 future. They can easily be found to be essential parts of the use cases listed above (e.g., Decathlon Services, Robot Remote Monitoring). Services require new systematics of making business. Instead of linear value chains, where value is created by products, new business ecosystems will emerge in which several members partner to co-create value through services [5]. This requires a change of the way our customers and we ourselves think about making business. In data-driven services, for example, we need a partnership with customers, as the value is co-created by the customer providing access to various data sources (e.g. condition data, process data, maintenance logs, etc.) and ABB providing access to data in ABB assets and providing access to expert knowledge about the asset. So, both parties need to open up, and this can only be enabled by a trustful relationship.

In the Industrie 4.0 business ecosystems, members can take several roles:

- Suppliers, e.g. providing a service
- Enablers, e.g. providing the infrastructure and platforms to access, organize and store data
- Users, e.g. consuming a service

It is important to note that ABB can take all of these roles, as we provide products for Industrie 4.0, have our own production facilities and more and more also provide advanced services. However to prepare the organization and business model of a unit in such large and heterogeneous corporation, each unit has to identify which role it will take in the ecosystem, and focus the innovation processes on this.

DECRC collected and sorted the ideas around the topic of Industrie 4.0 Business Models and supported various business units in transforming their business from products to product-service-systems. DECRC also actively shapes the respective committee work and exploits university collaborations to learn from the experience from other partners and tried to raise awareness through publications [5] and public presentations to not forgetting the organizational adaptation and business model innovation for Industrie 4.0 in our own organization and with our customers.

Conclusions and Outlook

In summary, Industrie 4.0 is two things: First, Industrie 4.0 is an initiative today that aims at shaping the future of Industry by learning from relevant use cases, of which we provided examples above. Shaping includes consensus, focus, and reduced uncertainty, which is supported by public and industrial R&D. Second, Iindustrie 4.0 is the future stage of industrial automation in which technologies and business models will be alive as shown in this article. This stage, envisioned in ABB as the IoTSP, will involve things such as robots and sensors, services such as remote monitoring, and the people behind and consuming these services. It will take industry several years to broadly reach a level of an "Industrie 4.0", but the year 2015 has made that stage much more tangible.

Customer / Internal Customer

Divisions: Process Automation, Discrete Automation and Motion

Acknowledgments

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Contact

Dr. Philipp Vorst
Phone: +49 (0) 6203 71 6280
Email: philipp.vorst@de.abb.com

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Figure 1: Collaborative robot YuMi (ABB)

The internet of things, services and people – the impact of Industrie 4.0 on the human being

Dr. Rainer Drath, Dr. Björn Matthias

Industrie 4.0 predicts the introduction of internet technologies into production, with promising potentials and complex interaction. The consequences are hard to guess. One of the key questions is: will the methods and concepts to manage complexity grow faster than the complexity in our industry? A major concern with respect to Industrie 4.0 is the role of human workers in a future production environment. By example of the robot YuMi, which is especially characterized by its ability to collaborate with people, the authors discuss the potentials and consequences of Industrie 4.0 achievable by the clever combination of devices, software and people.

The collaborative robot YuMi

YuMi® is a dual-arm robot, developed by ABB, driven by the vision of partially automating the assembly of electronic consumer products such as cell phones and personal computers. Central goal of YuMi is the productive interaction with humans, hence its technical characteristics are: human-like dimensions, light-weight design, moderate payload, speed and force, as well as rounded and padded surfaces, rendering it both harmless and productive. The most important property its ability for flexible redeployment to variable tasks in mixed human-robot environments.

This enables a variable degree of automation in production, with people and robots in collaboration, focusing on their respective strengths. While robots contribute repeatable quality and endurance in specific steps, the human skills of complex manipulation, system overview and problem solving remain superior. Also, YuMi's human-like design leads to its acceptance on the factory floor: people like YuMi, a non-technical aspect of high value.

Applications with variable tasks, frequent relocation of the robot as well as fenceless operation are particularly well-suited for YuMi. Assuming that end-effector, work pieces and other items in the working environment pose no additional hazards, one has a highly flexible, scalable partial automation solution. For the first time, this provides an economical approach to increasing productivity in small-lot, high-variant production by automation.

YuMi and IoTSP

YuMi as such addresses current market needs for high-variant assembly. Combining human skills with those of a robot in the context of industrial production is a promising perspective, compounded by the inherent ergonomic properties of the design and behavior of this robot. It addresses the challenges of an aging work force. But, as we know for all automation devices, without connectivity to the environment of resources in a modern manufacturing facility, YuMi remains isolated and restricted to repeated execution of its tasks until explicitly reprogrammed. Integrating YuMi into the information context of the entire production system opens up a variety of new possibilities for productivity increases.

With IoTSP, YuMi would be embedded into a network of resources that can deliver new functions, like explorability of the network, storage and retrieval of data in a production cloud, self-driven interaction with other manufacturing resources in the production system, thus gaining information on the overall context as well as providing information on its own role in this context. But especially for YuMi, this enables novel higher level functions of interest.

Learning and Teaching

IoTSP and YuMi together can offer new ways of sharing and disseminating knowledge of assembly steps and tasks in a way that is not available today (Fig. 2). Simplifying instruction and programming of industrial robots is a perpetual topic for research and development. Recent approaches for collaborative robots have employed lead-through and demonstration elements. Demonstration and imitation are old and powerful elements of learning and dissemination among humans - and the new approaches seek to extend this to the world of human-machine instruction (step 1).

Once robots such as YuMi have acquired certain skills relevant for manufacturing tasks, it becomes possible via IoTSP to store these capabilities in a cloud (step 2). From here, other robots of the same type or even of a different type with appropriate characteristics can access this knowledge (step 3). Thus, the network awareness of production resources can support the dissemination of manufacturing capabilities among machines. A query to similar resources for a particular skill can lead to a download and activation of this skill to a robot, which then no longer requires explicit programming for this capability. Robot skills automatically become re-usable within the connectivity horizon of the production cloud. With cloud connection, the value of YuMi's capabilities and experiences scales with the size of the connected ecosystem.

Finally, this concept allows closing the loop from human to human. We envision that manufacturing tasks can be demonstrated by YuMi to a new employee (step 4). Knowledge-flow across steps 1 to 4 through the cloud increases the value of experiences and adaptations from human workers or from YuMi whenever they feed their improvements into the cloud, making them available to all relevant production resources.

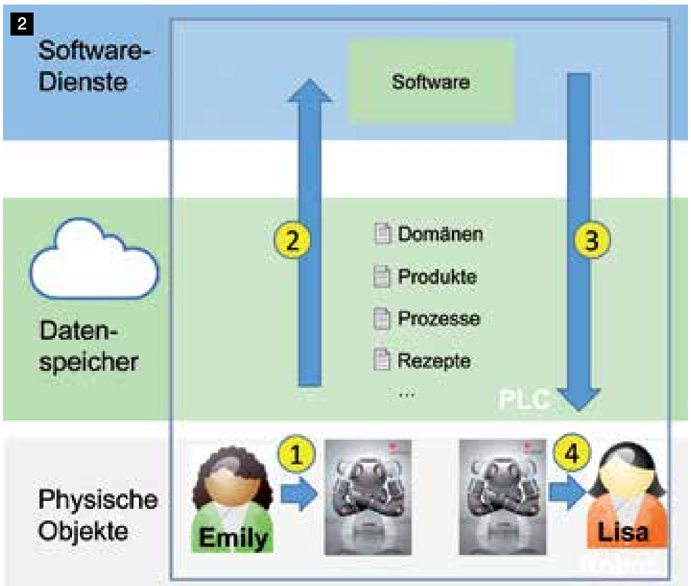


Figure 2: Remote knowledge transfer from person to machine and back mediated by the IoTSP

While such approaches have been discussed in the research community, their practical applicability has never been evaluated in an industrial environment. However, we see IoTSP as an enabler for the idea of experience-based learning and improvement.

Collaborative production strategy

Given the IoTSP connection of resources within the overall production system, YuMi is aware of the neighboring manufacturing resources and their respective status. As a result, the robot can auto-nomously adapt its behavior according to the status of these neighbors. YuMi again informs its neighbor YuMi. The neighbors again inform their neighbors, this idea is valid across all automation devices. This leads to an overall adaptation of the production system to particular events or to changing production targets. This is reminiscent of intelligent swarm behavior known in nature. Hence, the production system collaboratively pursues a production strategy and optimizes itself to achieve this.

In any case, this requires real-time interconnection between the participants, which is one of the pillars of IoTSP. The information exchange can include simple status information such as "production", "maintenance", "suspended", or "error condition", but could be extended to more complex information, such as the number of remaining units in a production lot, the need for replenishing consumables at a particular station, etc. When YuMi makes available its own information, the awareness of its status can propagate as needed and neighboring resources then can adapt as needed. Participation in the exchange of status information can be extended easily to the people working in production.

The combined awareness of the overall production target paired with the access to real-time in-formation of participating production resources thus becomes a platform for robust operation of the production system. Disturbances can be resolved in new ways, given that the overall system is situation-aware and has the necessary resources or redundancy to react. This may be as simple as informing an employee that a particular machine needs servicing, but can be as sophisticated as dynamic rerouting of the production flow through machinery.

Mobility

YuMi can be combined with an autonomous mobile platform. This will allow the robot to navigate independently through the production facility, for example supporting wherever needed. Situations can include replacing a defective robot, complementing a manufacturing station with additional capacity, or serving as an assistant robot to personnel. Business opportunities arise in the area of leasing or renting complete and self-contained robot systems.

Automatic Programming

Today, robot programs are mostly created and tested manually and remain static. They define fixed production tasks that can react to changes in the production environment only in a predefined and limited manner. With IoTSP, design and assembly information for a product are accessible in the cloud. Using this, YuMi can in principle automatically create the required robot motion program for the step it is assigned to. Together with the other manufacturing resources, whether persons or machines, a collaborative production landscape emerges that is capable of executing individualized manufacturing tasks in a highly flexible manner, realizing the partially automated small-lot production vision.

Additional Aspects

Beyond the above, the YuMi concept offers a multitude of other applications when integrated into an IoTSP network. Examples are:

- the automatic detection of ergonomic needs of a particular person and suitable adaptation of the workstation,
- dynamic re-planning of production lots for improved distribution of machinery loads,
- in-process parameter measurements by robots can be communicated and used for quality assurance, documentation and improvement and
- more complex subassemblies comprising their own network connectivity can broadcast their further assembly needs and parameters, for example torque values for tightening bolts or similar specifications.

Conclusions and Perspective

More demanding market requirements and growing technological capabilities are driving the complexity of industrial production. We are moving beyond the simplicity of fixed processes and equipment set up towards a future characterized by both flexibility in the manufacturing task and adaptivity of the equipment and resource configuration.

The key questions are: Will our methods to manage complexity grow faster than the complexity of industrial production? How can we embed the human's talent for penetrating complexity and gaining a view of the essential?

The good news is: only such complexity that is manageable will survive. Other technologies will disappear, as economic viability is the paramount criterion. YuMi can take the role of a "missing link" between this more complex future and the production worker in that context. Its sophisticated capabilities combine talents of robots and humans. The IoTSP can significantly enhance the applicability of YuMi and at the same time provide the foundation for managing complex production systems.

Basis for all this is the development of suitable standards, especially for communication and storage infrastructure as well as for communication interfaces and semantics. This is a major challenge. Without standards, we remain in a world of isolated vendor-specific islands. The value of internet technologies is the interoperability of hardware and software from different suppliers, and similarly, the key prerequisite of IoTSP is the availability of information across the overall production system.

Contact

Dr.-Ing. Rainer Drath
Phone: +49 (0) 6203 71 6471
Email: rainer.drath@de.abb.com

Dr.-Ing. Björn Matthias
Phone: +49 (0) 6203 71 6145
Email: bjoern.matthias@de.abb.com

FDI and the Industrial Internet of Things

Dr. Dirk Schulz

The Field Device Integration (FDI) standard represents an industry-wide consensus on device integration for the process industry. Following the release of IEC 62769, first products have been released at Hannover Fair 2015. Backward-compatibility to EDDL, interoperability between vendors, and vertical integration based on OPC UA ensure protection of investment and lower life-cycle costs.

With Industrie 4.0, the fourth industrial revolution is set on merging automation and information domains into the industrial internet of things, services, and people. Self-configuring and -maintaining systems proclaim the dissolution of the automation pyramid.

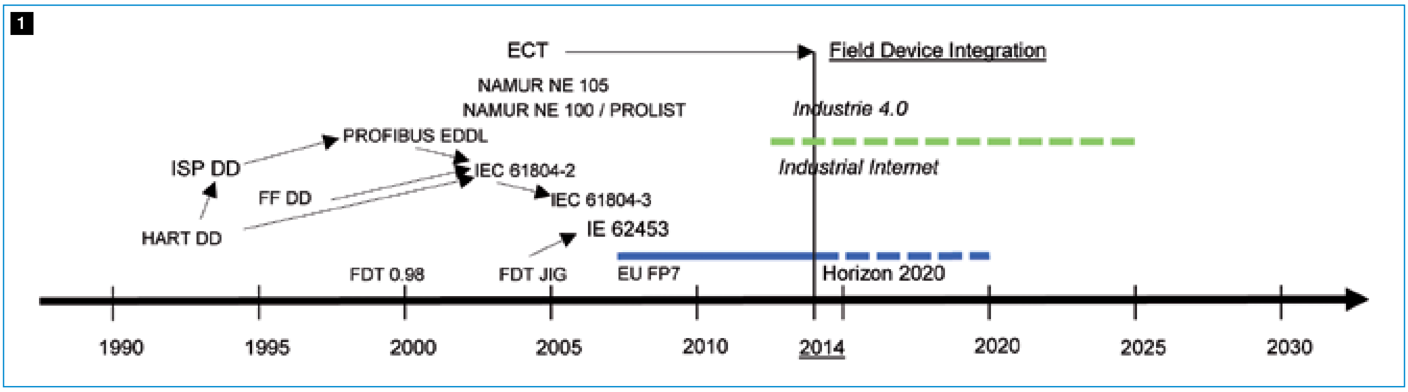
In this situation, FDI can become the bridge between the protection of past investment and the future of automation, moving from asset- to service-oriented automation, while keeping plant owners in control of their processes.

Introduction

Any new technology is measured against the current state of the art. The FDDI predecessor standards Field Device Tool (FDT) and Electronic Device Description Language (EDDL) have been established in the market for over 10 and 20 years, respectively. Any new, even superior technology needs to address the cost and risk of migration.

Given these considerations, FDI already enjoys very broad support since its first conception. This holds for both the suppliers of automation systems and the fieldbus organizations. In fact, FDI is backward-compatible to existing EDD files from the last 20 years, which are available for an installed base of over 50 million field devices with HART, PROFIBUS, or FOUNDATION Fieldbus protocols .

Industrie 4.0 is an ambitious undertaking, subscribing to the purpose of connecting industrial IT with all aspects of industrial production, across all layers of automation systems, along material flow and supply chains. Its goal is perfectly flexible and self-organizing production, reducing resource consumption and time to market, making even smallest lot sizes feasible.



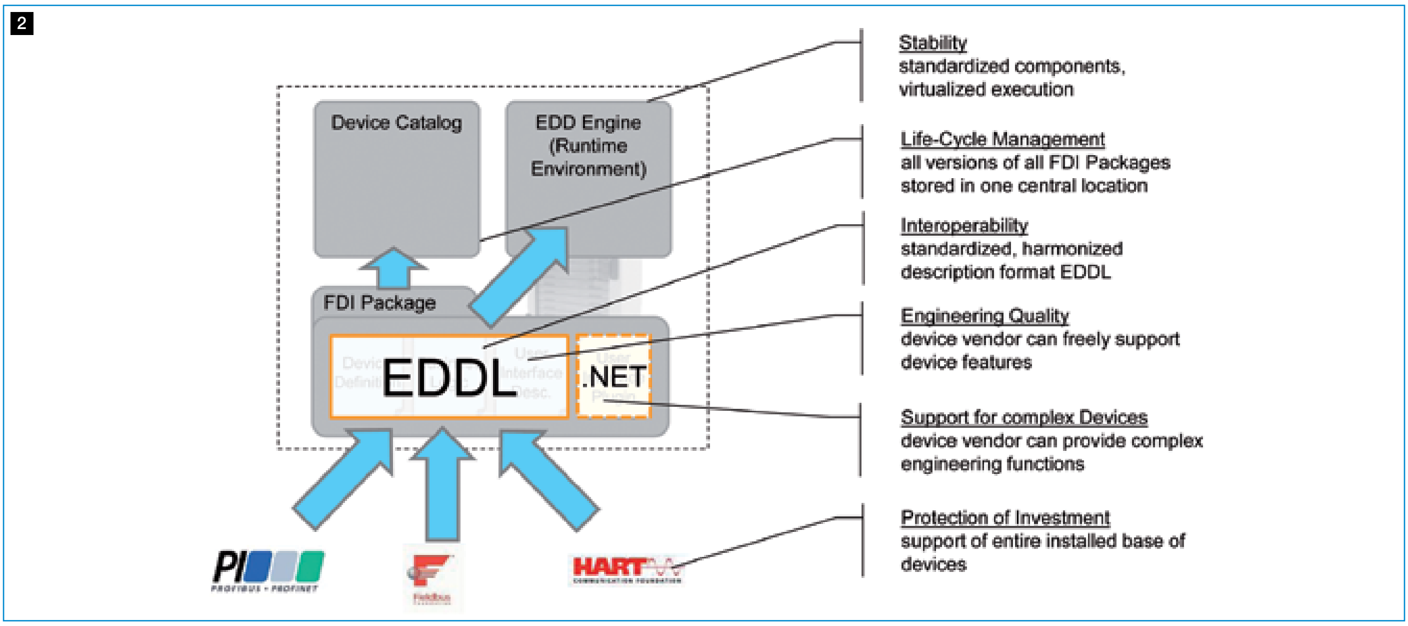


Figure 1: Past and future developments concerning Field Device Integration (FDI), see for reference | Figure 2: Server-internal Mechanisms and Advantages

Given this ambition level, it is indispensable to scrutinize specific standards like FDI in the context of an infant Industrie 4.0. We therefore present the key features of FDI which leverage the requirements of Industrie 4.0 and protect customer investment along the way.

Field Device Integration – Key Features

With FDI, each device comes with a so-called FDI package acting as a kind of device driver. Using this package, a user can parameterize, commission, and monitor a device. To this end, the package contains an EDD file compliant with the latest version of the EDDL language specification.

This allows the simple migration of the entire installed base of devices in customer sites from existing EDD files to FDI.

Within an FDI host system, an existing FDI package is loaded into the so-called EDD Engine, which interprets the EDD file at runtime. This leads to higher system stability compared to stand-alone tools or FDT DTMs. The EDD Engine is developed by the members of the FDI Cooperation as a re-usable software component. It is part of the FDI reference host system, which in turn is part of the official FDI development and certification environment. System vendors are encouraged to directly embed this component into their own device management systems to guarantee standard-compliance. These aspects are illustrated in Figure 2.

For integrating FDI with other systems in the automation hierarchy, the FDI OPC UA information model plays a central role. Based upon the OPC UA companion standard for devices, this model defines a device type catalog, the instances of the field devices, and the communication paths for accessing online data through a fieldbus hierarchy. Even user interfaces are deployed through OPC UA. To support a new device type, no installation is needed on any of the FDI Clients.

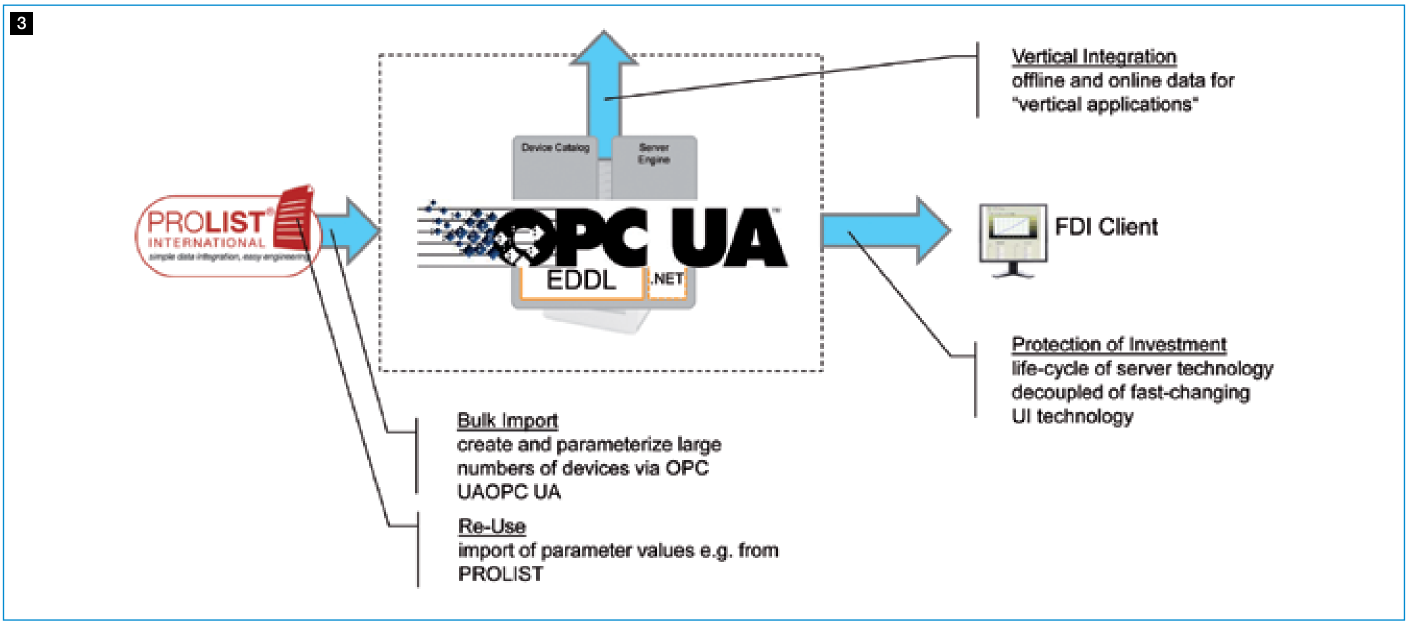


Figure 3: Benefits of the external FDI OPC UA information model

The OPC UA information model also permits bulk data import so we can re-use the information from IO lists or device descriptions according to the eCl@ss classification standard. Lastly, it is also possible to expose the health condition of device assets via OPC UA, following NAMUR recommendation NE107. While implementing the OPC UA information model is not mandatory for an FDI Host System, we see that there are many advantages in engineering, commissioning, condition monitoring, and better vertical integration. These aspects are illustrate in Figure 3.

Industrie 4.0 – Connectivity and Confidentiality

The Internet of Things (IoT) is mostly synonymous with a plethora of data to which all nodes in the network have direct access. The industrial IoT can be regarded as the source for industrial big data analysis. Seamless access to any data is taken for granted due to the existence of the Internet.

In an industrial context, this assumption may prove wrong for two main reasons:

1) The majority of today's installed base of devices does not support IP communication: typically, controllers, electrical devices and robots are connected via Ethernet, but the vast number of sensors are not.

2) The inside of an industrial site has high protection requirements, starting from data confidentiality, the protection of production assets, uninterrupted production, to functional safety and the protection of human lives.

Next to safety and confidentiality, the main customer interest lies with uninterrupted production. It is often claimed that the automation pyramid will dissolve with Industrie 4.0. In our view, this dissolution of the automation pyramid does not to imply loss of hierarchical control over the production process, but rather making hierarchical connections between ERP, MES, and control levels more flexible. In other words, also self-organization systems require a certain chain of command to protect stakeholder interests. Strict (hierarchical) control over data access is more important than ever before.

There already are different access rights e.g. for engineers and operators. Engineers typically can change any aspect of the system, operators in the worst case can only shut down the production process. Engineers are to make sure that operators can never violate system integrity. Still, on engineering level, authorization is the only protection that the system has. Considering remote on-demand reconfiguration of the process is not even conceivable by just setting access rights on data.

Moving toward Industrie 4.0 we therefore expect to need a finer granularity of such zones of trust and more meaningful protection of the system integrity. There are numerous examples for third parties who might legitimately expect access to internal data upon deeper horizontal and vertical integration:

- Additional systems from the DCS vendor (e.g. condition monitoring, production optimization, data analytics)
- Service providers outside of the company (running locally or remotely)

– Device vendors (interested in their installed-base)
– Suppliers (interested in product parts)
– End customers (interested in the finished product).
– Government agencies (interested in audit trails)

It is an open question for Industrie 4.0 how to formalize legitimate interest in the system architecture.

IP convergence and standardized information models are already provided by FDI. In the following section, we discuss how FDI contributes to other key requirements such as

1) Confidentiality of data to protect trade secrets

2) Functional integrity to protect human lives, production, and production assets

3) Seamless data access in the Internet of Services and People.

Migrating the Installed Base to Industrie 4.0

The requirements introduced above lead to a number of techno-economic challenges for research and (re)development of field devices.

Considering the installed base of field devices in production the foremost priority. How can we turn the entire spectrum of field devices, from a proximity sensor to a motor control center into a part of the Industrial IoT?

We also expect that classic fieldbus devices will still be developed in the years to come. Where is the break-even point of a native Industrial IoT device, outclassing a classic 4-20mA device?

Especially for security, the challenges in brown- and green-field scenarios will differ. Will the development and production of new Industrial IoT devices be able to rely on a proven brown-field security infrastructure – and can we just focus on integration, cost, and footprint?

Seamless data access in Industrie 4.0 is basically enabled by two properties:

1) IP communication

2) Explorable, semantic information models (enabled by OPC UA, a core part of FDI)

Migration on device level can be achieved by combining the different options given in Table I.

	Approach	Scope	Restrictions
1	Firmware Update	Ethernet and WiFi devices	No central access control
2	Evolution Kits	All existing devices	No central access control, added cost for physical components
3	Gateways	all existing devices	No central access control, devices are not actually updated
4	IP Convergence	newly developed devices	Re-development of devices needed
5	Data Aggregation	all IoT components	In itself not a migration path, but allows combining any of 1-4

Table 1: Options for Device Integration in Industrie 4.0

We previously indicated how the process is wrapped for operation purposes, essentially making it impossible to do harm out of operation. To also make the system configuration subject to negotiation between service participants, we require a kind of semantic protection to ensure the functional integrity of the system. Semantic protection requires that it is possible to assess the meaning of individual changes on the entire system according to defined objectives like safety or confidentiality. Authentication and authorization are a necessary but on their own not sufficient ingredients.

We propose to realize the needed protection layer on the intermediate levels of the automation system where all information from the field level is aggregated – like e.g. an FDI server as illustrated in Figure 4. Such a single point of data access is ideally suited to ensure confidentiality for data access to the installed base of devices. Defining the details of such a protection layer is a key challenge on the way to a connected world. We see the responsibility with the Industrie 4.0 platform committees on reference architecture and security.

Conclusions and Outlook

FDI implements requirements coming from the automation domain, not from IT companies. It considers the experience of DCS vendors, manufacturers of field devices, and their customers from the last 20 years. It reconciles its predecessor technologies FDT and EDDL. Since FDI is able to re-use existing EDD files, it protects the investment that process companies have made in the installed base of devices when migrating to the new, superior technology. Regarding the integration depth that Industrie 4.0 aims for, this is an absolute necessity.

Especially the FDI OPC UA information provides important benefits:

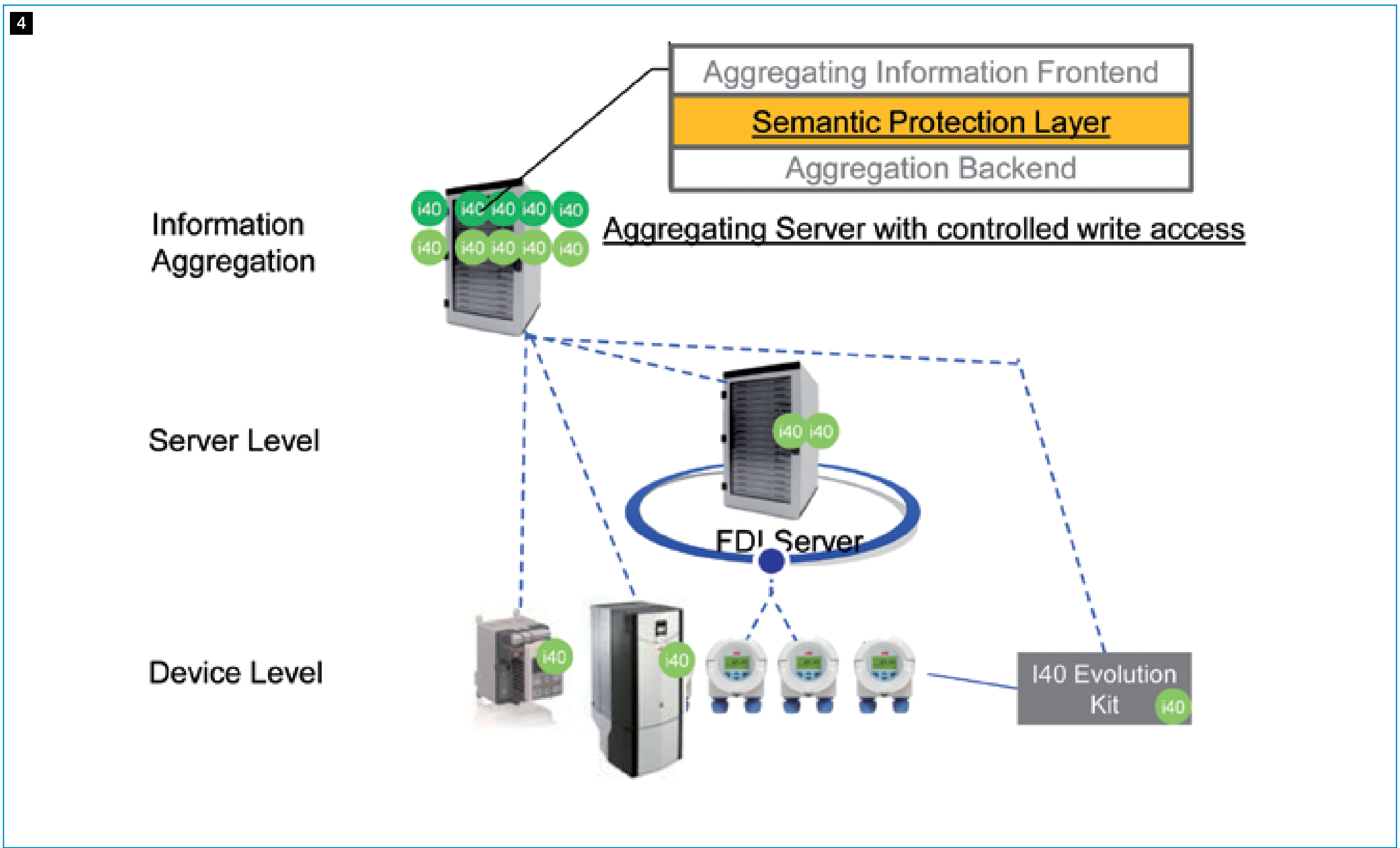


Figure 4: Aggregation architecture with semantic protection layer

– A common, protocol-independent perspective on devices
– Explorable online data models
– Access control, authentication, and encryption (features of OPC UA)
– IP-enabling of any field device (by acting as protocol gateway)

In conclusion, an FDI Server or any aggregating OPC UA server represent a controlled point of entry for seamless information access to all field devices of a plant. The level of information aggregation is the natural place to focus our efforts on when protecting investments and the integrity of self-configuring automation systems of plants, factories, and smart buildings.

Customer / Internal Customer

Division: Process Automation

Contact

Name: Dr. Dirk Schulz
Phone: +49 (0) 6203 71 6267
Email: dirk.schulz@de.abb.com

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Condition monitoring of electric motors based on low-cost MEMS sensors

Dr. Stephan Wildermuth, Dr. Ulf Ahrend, Christoph Byner

Using micro-sensors in industrial applications is of great interest due to their small size, low-cost and little power consumption. They could pave the way for widespread condition monitoring of industrial machinery as well as enable internet of things, services and people (IoTSP) and the implementation of fleet management at acceptable cost. However, the harsh environmental conditions encountered in an industrial environment have so far hindered the large scale deployments of, for example, MEMS-based sensors. In our work we use a miniature triaxial geomagnetic sensor for condition monitoring of low voltage motors. The performance of the magnetometer is studied under conditions encountered in industry. Furthermore the magnetometer is used to measure magnetic fields of an electric motor in a healthy state and in case of a broken rotor bar. By frequency analysis of this data it is demonstrated that the magnetometer measurements can be employed to distinguish between these motor conditions.

Introduction

Condition monitoring of electric motors is becoming more and more important as operators try to avoid any downtime in modern production facilities. Several techniques of monitoring the condition of a motor have been investigated during the last decades, e.g. based on vibration analysis as well as temperature or current monitoring. Many of these are routinely applied today. One promising condition monitoring approach is based on magnetic flux detection. This non-intrusive and easily deployable method could strongly benefit from the rapid development of micro-fabricated magnetometers. For example, the method may serve as a low-cost and easy-to-use condition monitoring solution for initial diagnosis of electric motors.

The diagnostic capability may even be enhanced if a number of motors are equipped with smart sensor tags (see cover picture) which contain sensors to deduce e.g. vibrations, temperature or overload conditions. Proper connectivity ensures that this data can be collected and aggregated to run statistical analysis on a whole fleet of motors or even do a benchmarking and efficiency monitoring of all motors in a plant. This additional intelligence may reside on cloud based servers and diagnostic or efficiency information can be easily made accessible to operators as well as service technicians. The vehicle to these vast opportunities for new services is in the end the local sensing and communication capability on the motor.

To allow for widespread application of such monitoring equipment two parameters are of great importance: low-cost of the sensor combined with small size. Today's MEMS-fabricated magnetometers for e.g. automotive or consumer applications are miniature (range of a few millimeters), cheap (less than 1 USD per sensor) and measure magnetic fields in three axes. Traditionally, leakage flux of electric motors has been measured by flux coil sensors. These sensors are relatively bulky, expensive equipment and allow for measurement of magnetic flux in one direction only.

Characterization of a MEMS magnetometer

We have selected a BMC050 eCompass sensor from Bosch Sensortec (Figure 1) which is a typical integrated 3-axis compass solution for consumer market applications providing a direct digital output signal. This sensor was readout by a non-real-time NI-System (Figure 2). The magnetometer has been characterized with respect to its frequency response as well as accuracy and reproducibility.

Frequency response

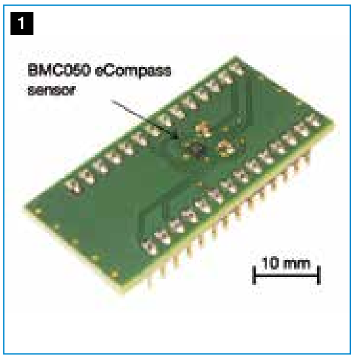
The BMC050 can be operated either internally triggered at an output rate of 30 Hz or with an external trigger at a sampling rate of up to 615 Hz. In the process of magnetometer-based monitoring of electric motors, the response of the magnetometer to ac magnetic fields in the range from a few Hz to approximately 120 Hz is of the greatest interest. The frequency response has been measured at a data rate of 500 Hz (Figure 3). The relative measurement deviation from the nominal amplitude of 300 μT was found to be less than 3.5% over frequencies ranging from 1 Hz to 200 Hz. This data can be used to calibrate the frequency response during later measurements of the magnetic field generated by an electric motor.

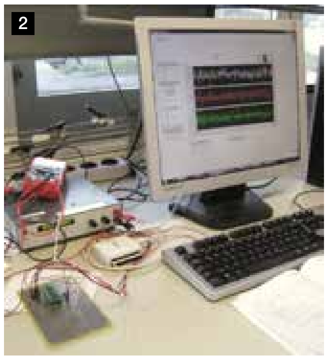
Measurement stability

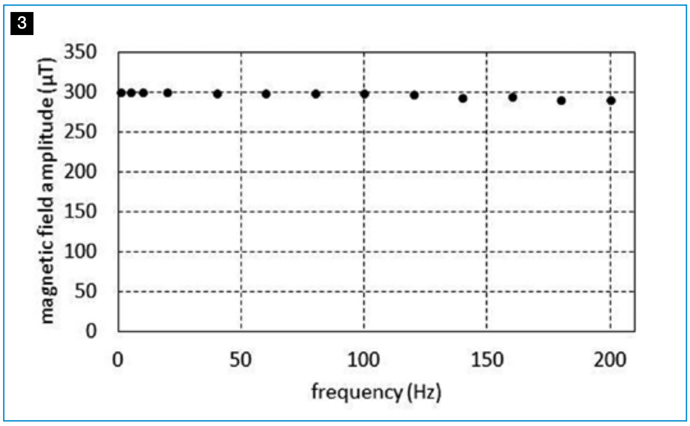
In addition to the previous validation also the temperature dependence of the magnetometer has been checked experimentally. The magnetometer including a magnetic field generating wire has been mounted in a climatic chamber. The temperature has been varied from -40°C to 85°C. The temperature has been held at a constant level for at least 1 h before each measurement to allow for thermal gradients to equilibrate. As expected, the output of the magnetometer is dependent on the ambient temperature (Figure 4). A linear fit yields a temperature dependence of $8.7 \cdot 10^{-4}$/°C. This calibration curve may be used to compensate for measurement uncertainties resulting from changing environmental temperature encountered during operation of the magnetometer in a factory environment.

Leakage flux analysis of a low voltage motor

Magnetic flux leakage in axial and radial direction is expected from a motor running under both nominally healthy as well as faulty conditions. The axial field is coplanar with the motor axis; it is generated by the currents in the stator end windings







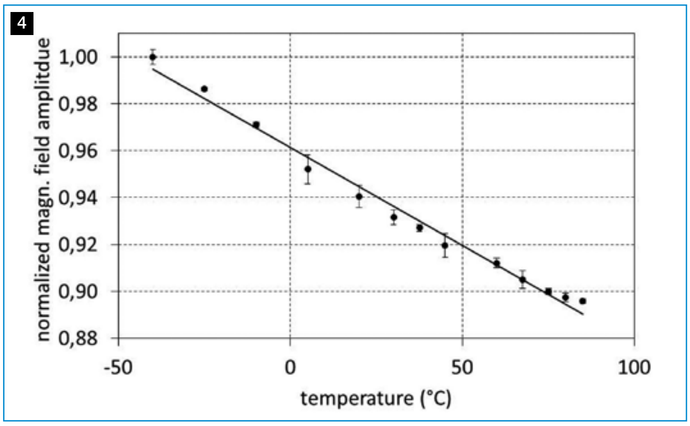
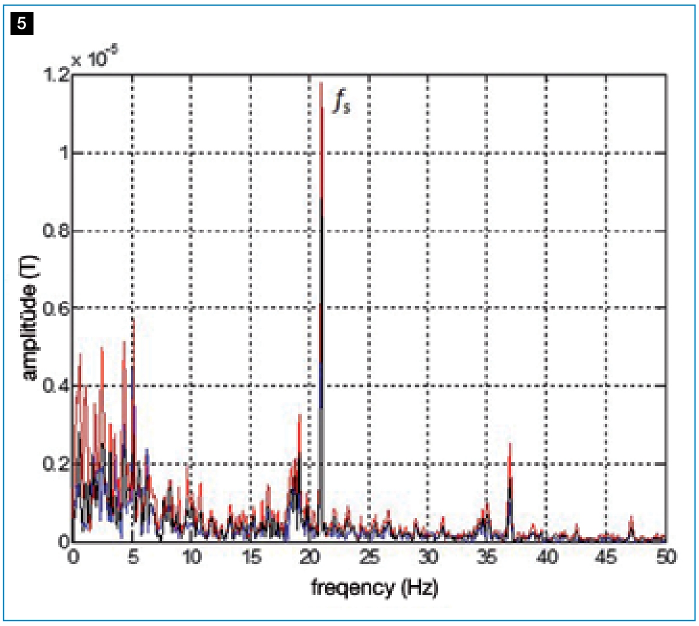


Figure 1: Magnetometer BMC050 from Bosch Sensortec mounted on a shuttle board for easy access to pins. | Figure 2: Experimental setup with NI-Hardware for sensor readout. | Figure 3: Response of the magnetometer to ac magnetic fields at different frequencies. The measured magnetic field amplitude shows a slight drop at high frequencies. | Figure 4: Output signal of the magnetometer has been recorded for varying ambient temperature. For a typical operating temperature range in industry applications the output signal of the magnetometer can be well approximated by a linear behavior.

or in the rotor cage end ring. The radial field is located in the planes perpendicular to the machine axis. It is an image of the air-gap flux density which is attenuated by the stator magnetic circuit (package of laminations) and by the external machine frame. Both fields can be measured separately by placing a magnetic field sensor in an appropriate location. Since the



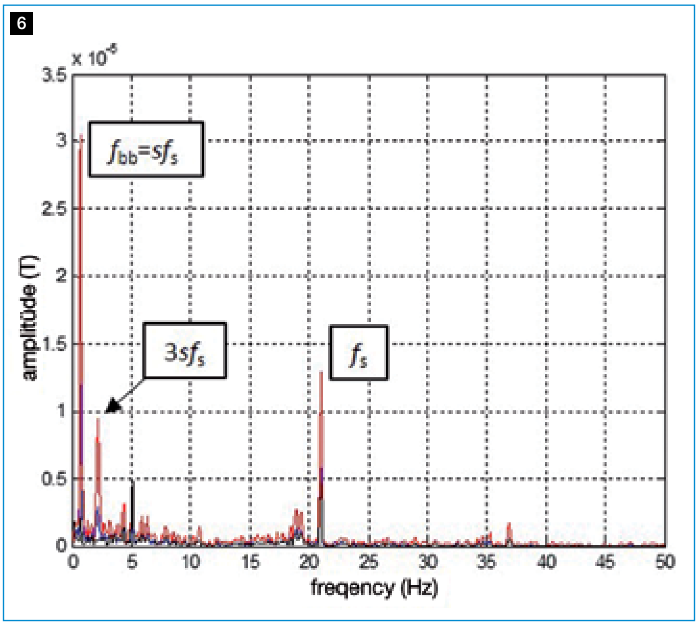


Figure 5: Spectrum of the magnetic field amplitude of the motor prepared in a healthy state. Sensor direction of the 3-axis magnetometer is indicated by colors red, black and blue. | Figure 6: Spectrum of the three-directional magnetic field measurement in case of the broken rotor bar. Sensor direction of the 3-axis magnetometer is indicated by colors red, black and blue.

magnetic field sensor used for these measurements is three-directional, precise orientation of the sensor while making measurements is not critical.

In order to detect any deviations from nominal operating conditions it is essential to look at the low frequency region of the magnetic field spectrum. In the specific case of a broken rotor bar fault the induction motor slip $s=(f_s-f_r)/f_s$ is of great interest, where f_s is the actual operating synchronous supply frequency (line frequency divided by number of motor pole pairs) and f_r is the actual running speed. Slip estimation is critical for identification of many different fault types. Therefore estimation of the actual running speed as well as the line frequency – both required to derive the slip – based on magnetic field measurements or other measurement types is a topic of many publications and will not be discussed in this article.

The presence of a broken rotor bar or broken end ring causes an unbalance to the rotor magnetic flux, as the current cannot flow through the broken or cracked bar/end-ring. The unbalanced rotor flux can be considered as the combination of positive- and negative-sequence rotor flux, rotating at a slip frequency into the opposite directions. It is known that the presence of a broken bar causes the appearance of an additional frequency in the magnetic field spectrum: the broken bar frequency f_{bb} can be described by $f_{bb}=sf_s$.

In the following subsections two motors of the same type have been analyzed. The machines have been operated under the same conditions but in different states: one has been in a healthy state while the other has been seeded with a broken bar fault. For the experiments, an induction motor supplied by a variable-frequency-drive (VFD) was used. During these tests the sampling frequency of the magnetic field sensor was set to 100 Hz and the signals were recorded for the length of 10 seconds. Since the motor was supplied by the VFD its operating conditions were different from a nominal operation (direct grid connection). The actual line frequency was set to 21 Hz and the running speed was 20.69 Hz which corresponds to 1241.4 rpm.

Magnetic field analysis of a healthy motor

The amplitude of the magnetic field of the healthy motor has been simultaneously measured in all three axes (Figure 5). The direction has been marked by colors red, black and blue for x, y and z direction, respectively. It can be clearly seen that the line frequency (in this case 21 Hz) has a dominant character in the spectrum and is apparent in all three axis. This is a typical frequency response of a healthy motor.

Magnetic field analysis in case of a broken rotor bar

The magnetic field amplitude of the motor in the broken rotor bar case has also been measured with the same 3-axis magnetometer (Figure 6), spectral data shown in red, black and blue color corresponding to x, y and z direction, respectively. The line frequency f_s equal to 21 Hz is clearly visible in both motor cases. However, in the case of the healthy motor the line frequency dominates the entire spectrum, while in the case of the broken bar it is noticeable that the lower frequencies contain the most energy.

Based on the magnetic field data analysis the value of slip s was estimated to 0.0345 and the line frequency f_s was estimated to 20.99 Hz. Using the equation mentioned above the value of the characteristic frequency f_{bb} for a broken rotor bar can be calculated to be 0.724 Hz. What is also worth to mention is that there is an additional peak related to the broken rotor bar visible at $3sf_s$. This component can also be taken into account as an additional indication when suspecting this type of fault. The ratio of the amplitude of frequency f_{bb} and the amplitude of the RMS of the entire signal can potentially be used as an indicator of the broken rotor bar presence.

Conclusion and Outlook

Magnetic field measurements with a magnetometer based on MEMS-fabrication technology have been used to detect the characteristic signature of a broken motor bar in the frequency spectrum of the magnetic field of a low voltage motor. The sensors were characterized in detail to check if they meet the criteria for the application in motor diagnosis, the focus being on achieving sufficient frequency response. Furthermore the stability of the sensor output to changes of the environmental temperature has been evaluated. Long term robustness of the sensors has been qualitatively tested and has been found to be sufficient for operation in an industrial environment.

MEMS-based sensors are used in many of today's consumer products and therefore benefit from low-cost, small size and high flexibility. Such miniature sensors enable to set up cost efficient measurement systems, paving the way for several applications in the industrial domain, in particular condition monitoring of industrial assets such as electric motors and further components in the drive-train of industrial plants. In combination with wireless communication a quick and simple integration seems possible. This way monitoring of a larger fleet of assets may become feasible and commercially attractive. As an important step towards an Internet of Things, Services and People (IoTSP) a smart motor tag (see cover picture) has been presented at the Hannover Messe by ABB.

Customer

BU DMMG (Discrete Automation and Motion - Motors and Generators)

Contact

Dr. Stephan Wildermuth
Phone: +49 (0) 6203 71 6409
Email: stephan.wildermuth@de.abb.com

Absolut zero invasion – Noninvasive temperature measurement keeps things tight

Dr. Andreas Decker, Tilo Merlin, Dr. Jörg Gebhardt

The majority of measurements made in the process industry are of temperature and pressure. Around half of the temperature measurements are used for monitoring purposes to secure product quality, increase process efficiency and ensure plant safety. Suitable conventional temperature measurement instruments are widely available and the cost of these has decreased over time due to high volumes, technological progress and competition. However, these devices are mostly intrusive in nature. ABB's noninvasive, wireless and energy-autonomous temperature sensor is now changing the face of industrial temperature sensing, as has been illustrated in a recent pilot installation in The Absolut Company's vodka distillery in Sweden.

The heyday of technological advancement in temperature measurement was in the 19th century. Thomas Johann Seebeck (thermoelectric effect, 1820) and Carl Wilhelm Siemens (platinum resistance thermometer, 1871) were two of the most prominent pioneers. ABB's activities in industrial temperature measurements date back to 1881 when Wilhelm Siebert melted platinum in his family's cigar-rolling factory in Hanau, Germany and mechanically worked the material into wires. Though subjected to continuous improvement, the main design – with a measuring inset, protected from the process medium by a strong thermowell and a connection head – changed little over the years and many of today's devices are based on these early discoveries. A game changer was introduced in 1978 by ABB (Degussa at that time) with the implementation of an electronic transmitter inside the connection head (Fig. 1).

This allowed the measuring circuit and the sensor element to be combined even in harsh environments – thus reducing the need for long sensor wires, which tend to be sensitive to electromagnetic interference that affects sensor accuracy and introduces signal noise. This major innovation paved the way for today's distributed smart sensors that deliver standardized and linearized measurement values to a central control system [1].

Almost 40 years later, ABB has transformed the temperature sensor once more, making it autonomous by introducing wireless communication as well as an energy-harvesting power supply that feeds the instrument from the temperature gradient between the process and its surroundings (Fig. 2). ABB has integrated these two technologies into the fully autonomous

Figure 1: First transmitter for mounting inside the sensor head (TR01)
Figure 2: First autonomous temperature instrument TSP331-W
Figure 3: Typical thermowell designs

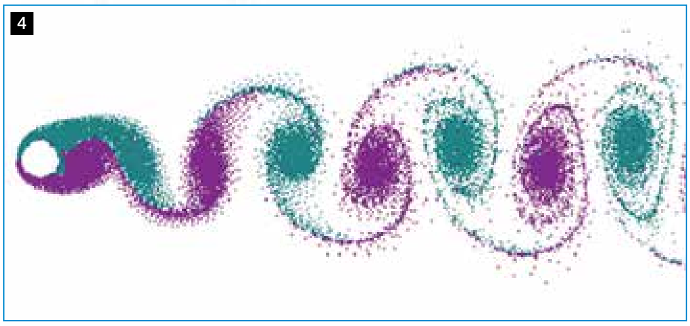


Figure 4: Alternating vortex shedding. The effect is also seen in a flag waving in the wind.

temperature instrument TSP300-W series. This ABB innovation was a major milestone in temperature sensing and an enabler for wireless communication in process automation.

One remaining shortcoming of industrial temperature measurement devices, however, was the thermowell.

Thermowells

The thermowell protects the sensitive measuring inset from the hot, chemically aggressive, abrasive or pressurized flow inside pipes, boilers and vessels (Fig. 3). However, the thermowell obstructs flow, leading to a pressure drop, and creates low-pressure vortices downstream of the thermowell (Fig. 4). Vortex shedding causes the thermowell to vibrate, and if the vortex shedding rate matches the eigenfrequency of the assembly, resonance occurs and dynamic bending stress increases substantially.

In terms of plant safety, thermowells are the most critical part of a temperature instrument, as they can easily burst if they are not designed properly, especially at high flow speeds and pressures. Accordingly, standards have been developed by organizations such as ASME to assist engineers in selecting suitable designs. However, for applications not covered by the standards, the engineer is fully responsible for the proper design of shape, length, diameter, coating and interface type. Altogether, this leads to a greatly enlarged number of variants – resulting in higher cost, stock levels and logistic effort.

Besides the safety issues, a thermowell is a nuisance to the process: It reduces the effective pipe cross-section and the pressure drop it causes generally results in higher pump power consumption. It also forms an obstacle to pipe cleaning, thus food, beverage and pharmaceutical plants are reluctant to use thermowells due to increased risk of contamination. In brown-field installations, the plant has to be shut down and the pipes emptied prior to replacement installation. Thermowells also have a detrimental effect on the measurement itself as they introduce a temperature drop between medium and sensor and increase the response time. Last but not least, they are often the most difficult and expensive part to install as they frequently require welding.

In 2010, in response to some these challenges, ASME updated its basic standard for thermowell calculation [2], resulting in more robust thermowells with larger diameters, stronger materials and shorter lengths. These changes merely amplified the measurement disadvantages mentioned above.

Figure 5: TSP341-W noninvasive temperature measurement

Noninvasive methods

Thermowells can be eliminated by using a noninvasive temperature measurement. Noninvasive instruments leave pipes and vessels unaffected, with many advantages:

- The shells of pipes and vessels are not penetrated.
- The possibility of contamination is eliminated.
- There is no need to empty the pipe for installation.
- No welding is required on site and no special permission for hazardous areas is needed.

These advantages have considerable implications: Measurement points are now easy to install and can thus be used on a temporary basis – e.g., during setup and test of a new process or, if there are issues in production, for root-cause analysis. As soon as a satisfactory situation is reached, the number of measurement locations can be reduced to an economically and technically appropriate long-term value.

Why have noninvasive methods not been used before?

There are good reasons why noninvasive technology has not been used in the majority of temperature measurement installations so far.

The easiest way to obtain a noninvasive temperature measurement would be to attach an existing instrument to the surface of a pipe or vessel instead of introducing it into a thermowell. However, the temperature sensor is then further away from the process medium so that the response time would be impaired, and ambient conditions would have a bigger influence on the measurement.

A good noninvasive temperature instrument, therefore, has to have an appropriate design of the thermal pathway from the process to the sensor, which includes all materials and all interfaces through which the heat has to be transferred. In addition, reuse of as many components of the existing (thermowell design) instrument is beneficial in order to reduce the development effort, keep the number of variants and additional parts low, and make it easy for the customer in terms of familiarity and certification retention.

A challenging case

Two autonomous [3], noninvasive temperature instruments were given to The Absolut Company in Nöbbelöv, Sweden so they could explore the device's capabilities without having to interrupt the processes in their vodka distillery (Fig. 5). To keep the effort on ABB's side low, adapters were manufactured to mount existing (thermowell design) instruments with adjusted inset length to the pipes.

After installation, the automation engineers from The Absolut reported that the energy harvesting functionality, as well as the wireless communication to ABBs System 800xA DCS, were working well. However, measurement accuracy and the response time of the instruments failed to meet their expectations.

Improving the measurement

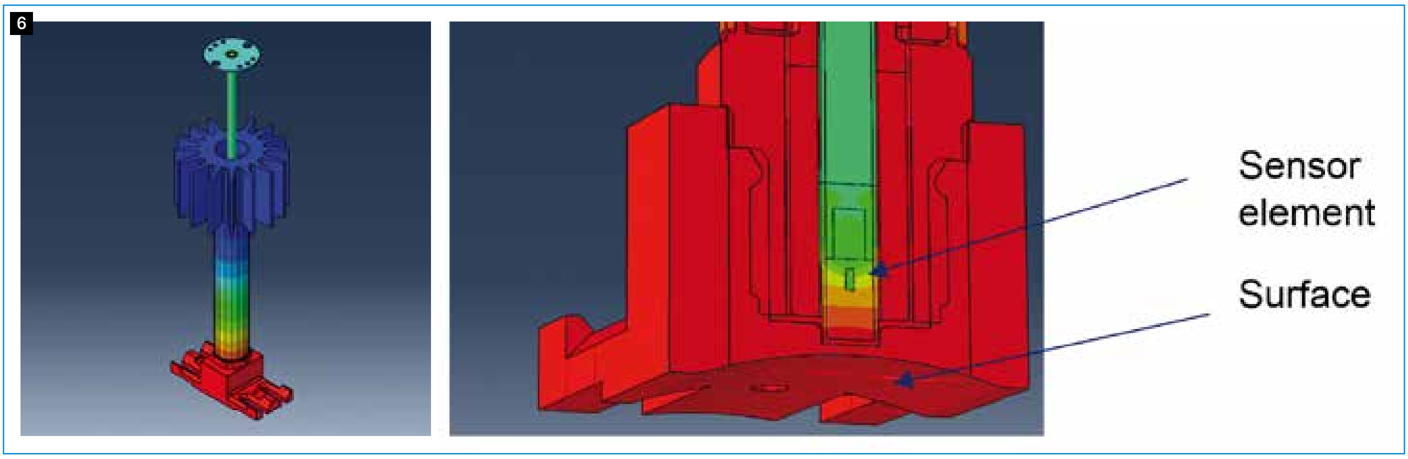
A series of measurements at The Absolut revealed a detailed picture of the thermal situation at and around the instrument as well as at the adapter that connects the instrument to the pipe. After determining the cause of the measurement issues, the design of the adapter was improved and tested. The measurement inset and thermal interface materials were also modified. In the final configuration, measurement error was reduced to approximately 1 K (from several degrees Kelvin). At the same time, response time was decreased by 75 percent, such that both performance parameters were close to those of an invasive (thermowell design) instrument.

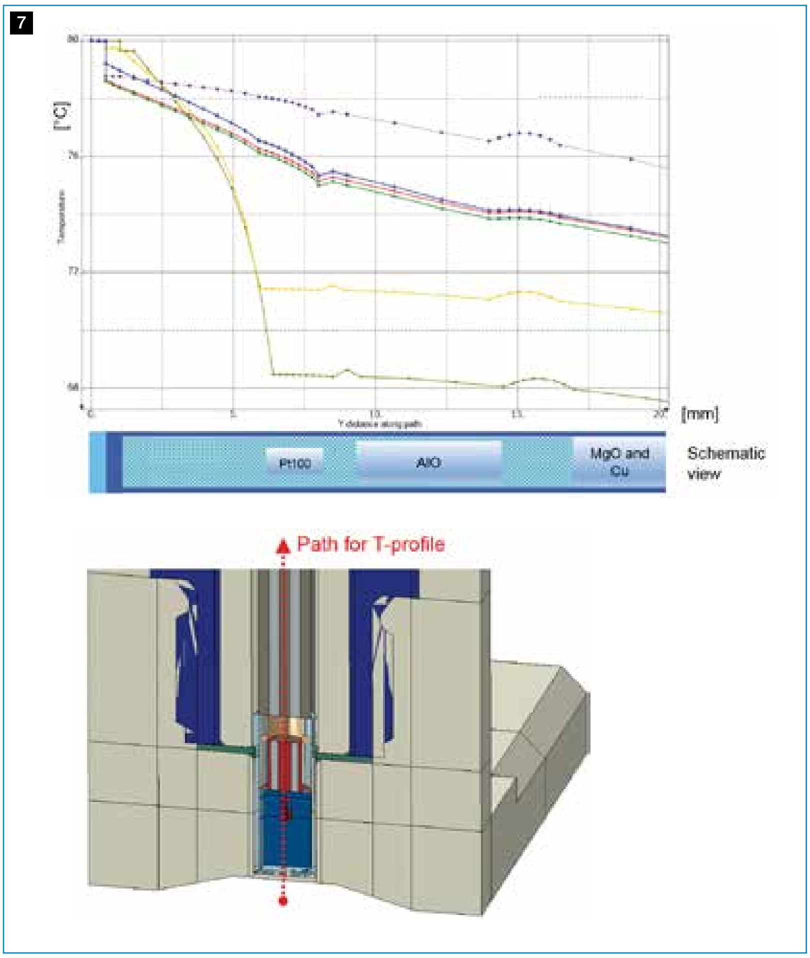
Modeling

Physical understanding of the measurement point and subsequent modeling and simulation of the thermal situation were important for arriving at a good design. Finite-element simulations and extensive automatic model-tuning [4] were used to identify the relevant design parameters (Fig. 6). Geometry, materials and interface properties could be effectively represented in the models (Fig. 7).

Furthermore, it was important to understand how the sensor temperature can be affected by details of the measurement situation, e.g. by different insulation types, flow conditions, and the measurement device itself.

An understanding of these influences was generated via conjugate heat transfer calculations in which a hot or cold fluid is modeled, flowing along a pipe where the instrument is mounted. The calculations are carried out as co-simulations of structural





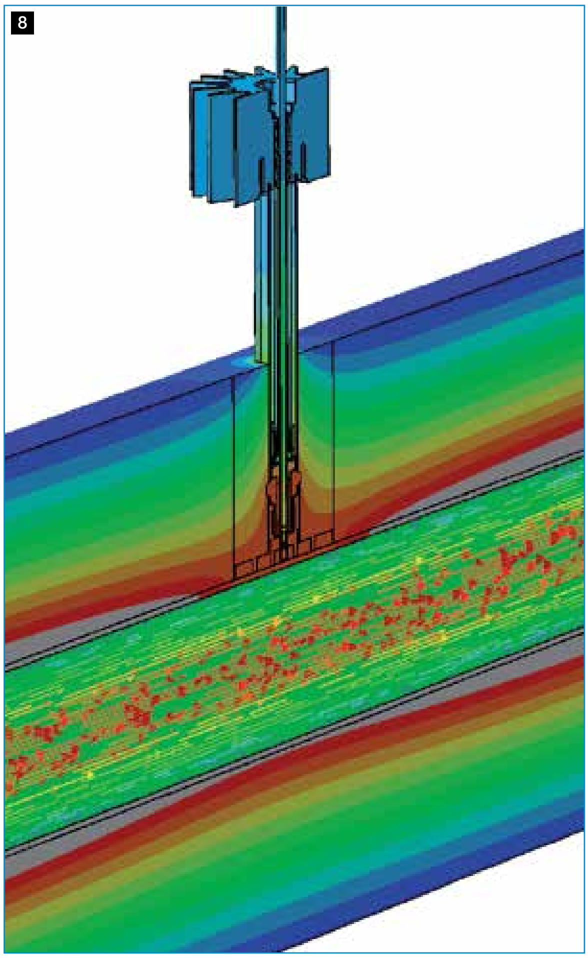


Figure 6: Finite-element result for the temperature field in a typical setup before optimization (a: Entire device; b: Interface to target surface).
Figure 7: Systematic search for relevant design parameters. The temperature field is plotted along a path through the device for various design iterations.
Figure 8: Conjugate heat transfer has been analyzed in cosimulations of coupled finite-element and fluid-dynamic calculations.

finite element models coupled to computational fluid dynamics models. A typical temperature field generated in such a situation is shown in Fig. 8. The result can be directly used to estimate the measurement accuracy.

Easy installation

The newly designed adapter can be mounted onto a wide variety of pipe diameters; only the length of the clamps (simple steel bands) has to be adjusted, thus greatly reducing the

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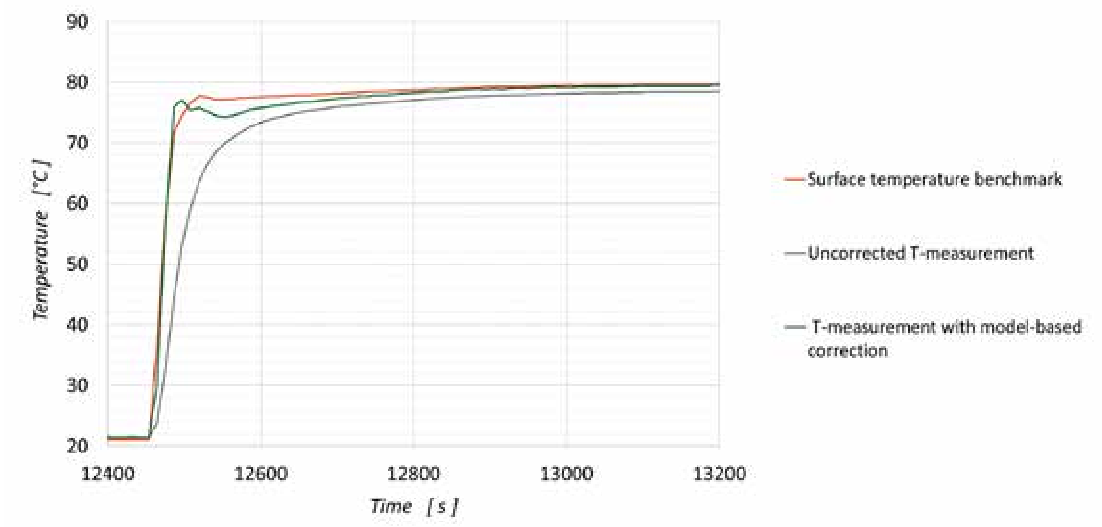

Figure 9: Response of the measurement system to a strong step in temperature, e.g. by switching on a hot pipe flow. Through model-based correction, the deviation from the benchmark values is strongly reduced. So, accuracy and response time of the measurement are improved.

number of variants and increasing flexibility. The design's lower complexity compared to the initial adapter requires less machining and allows simpler installation, which is especially beneficial in hard-to-reach locations. The installation does not require calibration or extensive parameterization.

Following this optimization, The Absolut Company installed four TSP341-W units and the predicted improvements in measurement accuracy and response time were confirmed.

Conclusions

Noninvasive, wireless and energy-autonomous temperature measurement ushers in a new era of flexibility. With temperature measurement and the job of engineering it into a System 800xA DCS now made so easy, applications that add a high value – but traditionally have been difficult to justify from a cost perspective – are now well within reach. A good example of such an application is short-term instrumentation of processes during optimization and continuous improvement exercises or energy efficiency initiatives. Another example is to supply ABB's System 800xA heat exchanger asset monitor (HXAM) – a condition monitoring tool that identifies heat exchanger performance changes and operational degradation – with the temperature inputs it requires to guarantee more energy-efficient operation and reduced maintenance costs. In large facilities, improved heat exchanger performance delivers substantial energy savings.

Only applications with extreme spatial or temporal temperature gradients pose a challenge to the complete closure of the gap between the performances of the noninvasive sensor and its invasive counterpart – both in terms of measurement accuracy as well as response time.

At a certain point, for physical reasons, passive thermo-mechanical design changes will not lead to further improvement. Nevertheless, additional progress can be made if modeling know-how is converted into simplified system representations which can be used for measurement value correction. Free parameters of the reduced modelare identifid by algorithmically tuning the model to reproduce experimental results. Fig. 9 shows the improved step response behavior of the measurement after inclusion of such model-based knowledge in the signal processing.

Internal Customer

Division: Process Automation
Business Unit: Measurement & Analytics

Contact

Dr. Jörg Gebhardt
Phone: +49 (0) 6203 71 6473
Email: joerg.gebhardt@de.abb.com

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Analytics – From Data to Actions: For the Fleets, by the fleets and Of the Fleets

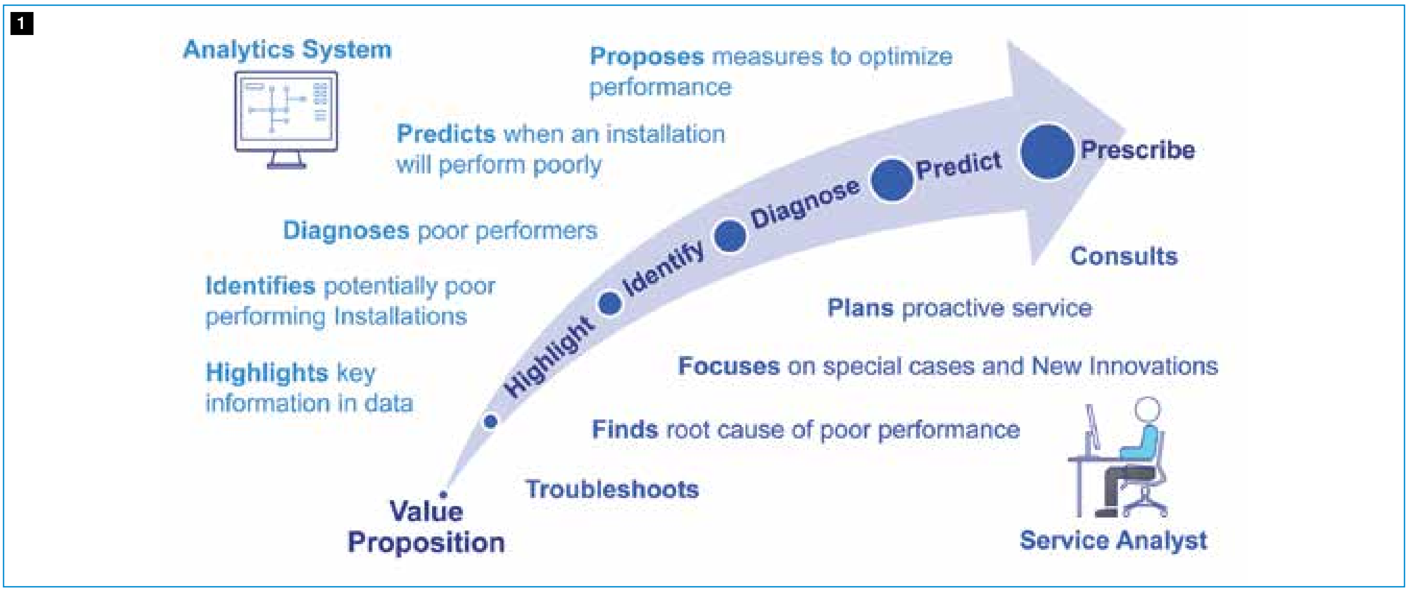
Dr. Subanatarajan Subbiah, Dr. Ralf Gitzel, Dr. Benjamin Klöpper, Dr. Simone Turrin, Dr. Benedikt Schmidt

Advances in communications technology, processing power and low-cost sensors indicate that devices will soon be providing us with more information than ever before. With data obtained from such sensors in addition to data streams from design, operations, maintenance, and processes collectively from fleets of devices/systems, through analytics, better decisions and actions can be taken by ABB to satisfy our customers, and can also support our customers to take better decisions effectively. This article describes how we might analyze the foreseen wealth of incoming data from fleets of devices/systems in order to generate additional value to ABB and to our customers. Currently, the extensive utilization of fleet-wide analytics is still unrevealed. At the German Corporate Research Center (DECRC) we have explored this area to present an overview of what fleet analytics are (compared to the alternative of performing analytics at component, system and plant levels), what are the advantages of fleet analytics and what questions might fleet-wide data be used to answer. DECRC has also rigorously investigated and proposed an idealized process for developing a fleet analytics solution.

Introduction

Fleet analytics is the analysis of data collected from a set (fleet) of many, more or less homogenous, technical installations in order to gain valuable insights about the behaviors of such installations [1]. These insights should lead to actions regarding single technical installations or the whole set of installations. Thus, fleet analytics does not focus on analyzing and gaining insights for one single unit, for example using the service and operation history of one motor to gain insights into this unit rather multitudes of motors. Fleet analytics uses data from a fleet of installations and combines data like the service and operation history to gain insights relevant for each single unit as well as for the fleet as a whole.

Benefits from performing analytics at fleet level are enormous. It is evident that large amounts of data collected from a fleet of devices or systems might be used to create transparency, to enable experimentation in order to discover needs, to expose variability and to improve performance, to segment populations and to customize actions, to replace/support human decision making with automated algorithms and to innovate new business models, products, and services [2].



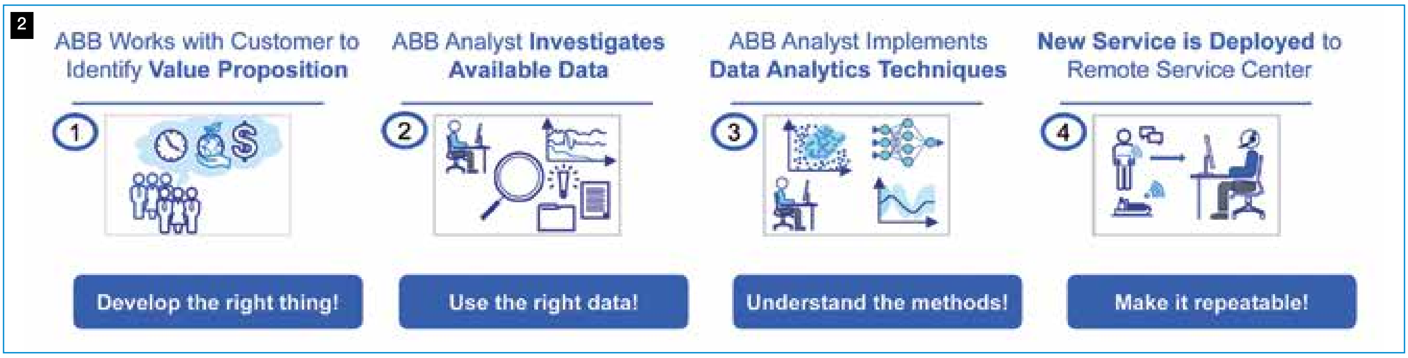


Figure 1: Fleet Analytics Road Map | Figure 2: Summary of the Process for Developing a Data-Driven Solution

Approach to fleet analytics development

As a foundation for a systematic approach to developing fleet analytics solutions a roadmap to match the possible offerings with the availability of data is sketched. The key lies on increasing the access to installation data (and increasing analytical capabilities), thus enabling more complex analytical questions to be solved. Figure 1 shows the fleet analytics road map that can be realized with increasing data availability. The left hand side of the figure indicates the capabilities of the analytics systems, whilst the right hand side shows what types of associated service a human can offer with the support of the system. The arrow denotes the different types of fleet analytics with increasing size indicating increasing quantity of available data. This is also equivalent to a measure of time (as it will take time to acquire large quantities of relevant data). The different types of fleet-related services that might be developed include:

- **Highlight**: Indication of relevant information about the installed base in service and operation data bases.
- **Identify**: Detection of installations with an operation which deviates from the operation of other installations in the fleet.
- **Diagnose**: Root cause analysis of deviations in the operations of an installation.
- **Predict**: Calculation of failure probabilities for the near future.
- **Prescribe**: Suggestions of how to improve the situation or how to avoid future problems.

Fundamentally, the process to develop a fleet analytics solution should execute in the following structure: (i) identifying a value proposition; (ii) investigating the available data; (iii) implementing data analytics techniques and (iv) deploying the new product offering. Taking fleet analytics to the customer breaks down into four key tasks (see Figure 2). Initially, value propositions are identified together with the customer (Task 1). Next, available data is investigated (Task 2) and an analytics technique is implemented (Task 3). These two steps often require expert knowledge from a data analyst who is familiar with the domain the data originates from. The analyst needs to take care of the data collection process. Furthermore, the data quality needs to be guaranteed, requiring initial exploration, pre-processing and data cleaning. The implementation of the analytics requires a detailed investigation of possible techniques and evaluation of the quality of the created solution. In the last step (Task 4), the fleet analytics solution is offered as a service or as a part of the product-service system, one scenario is to deploy it to the remote service center. In Figure 2, a summarized version of the development approach, condensed into four key tasks is shown.

While all of the steps above are important, not all of them are supported equally well by the state of the art in data analytics research. In fact, the assessment of data quality was identified as an important white spot. The following section discusses our research work conducted to close this important gap.

Data Quality Assessment

It should be no surprise that data quality plays a pivotal role in data analysis. The reason is that analytical algorithms take data at face value, so even obviously wrong values (e.g. an electrical motor aged 2000 years because the year 2014 was written as '14') will be included in the calculations without warning. What constitutes good data quality depends on both the algorithm and the domain. In our data quality research project SARA, we have analyzed data quality issues in the context of reliability analysis.

Manufacturers and maintainers of industrial equipment need to understand the failure behavior of their equipment for different purposes such as maintenance planning, failure forecasting (time-to-failure-data-based prognostics [3]), warranty planning [4], reliability optimization/improvement ([5], [6]), or to help R&D [7]. A common metric to represent the failure behavior is the reliability function *R(t)*, which describes the probability for a product to still be working at a given time *t*. For example, *R*(3400*h*)=0.95 means that a product of the given type has a probability of 95% of still working after 3400 hours of operation. The failure function *F(t)* is the exact opposite of the reliability function, i.e. *F*(3400*h*)=0.05 means that the probability of a product of a given type to fail at some point before 3400 hours of operation is 5%.

F(t) and *R(t)* are cumulative probability distribution functions whose parameters can be estimated from field data. But how good is such an estimate? A goodness of fit test can be performed to determine how well the distribution fits the empirical failure data. A typical example is Pearson's chi-square test, which can be used to test whether the frequency distribution of failures observed in a sample is consistent with a particular theoretical failure distribution. However, there are limitations

Figure 3: Data Quality Issues in Reliability Analysis

to what the test can tell us about the accuracy of our failure distribution. The test can only be used to determine how well the distribution function represents the data recorded (i.e. what we think happened) and not how well it represents the actual events which took place (what really happened). For example, if some early failure events have not been recorded (possibly because the database was not in place yet), we will underestimate the probability of failure in the early phase of product life. However, our estimated parameters might still have a pretty good fit to the recorded data. This means there are two major sources of inaccuracy in modeling the failure behavior. First of all, the estimated failure distribution might not fit the recorded points of failure well (poor fit). Second, the recorded points might not reflect reality well (data quality problems).

In order to assess the data quality problems and to point out the required remedies to the user, we have developed a prototypical data quality dashboard. The quality metrics shown in Figure 3 is designed to recognize data quality problems in the context of reliability analysis as explained above. We will briefly explain some of these metrics to give you an idea about the approach.

The classical data quality metric for statistics is the sample size. Low sample size means that odd random events have a greater influence on the values than in large fleets. For example, a fair flip of an unbiased coin twice can still lead to the result of two heads. But as the number of flips increases, it becomes more and more obvious that the probability of getting heads is 50% not 100%.

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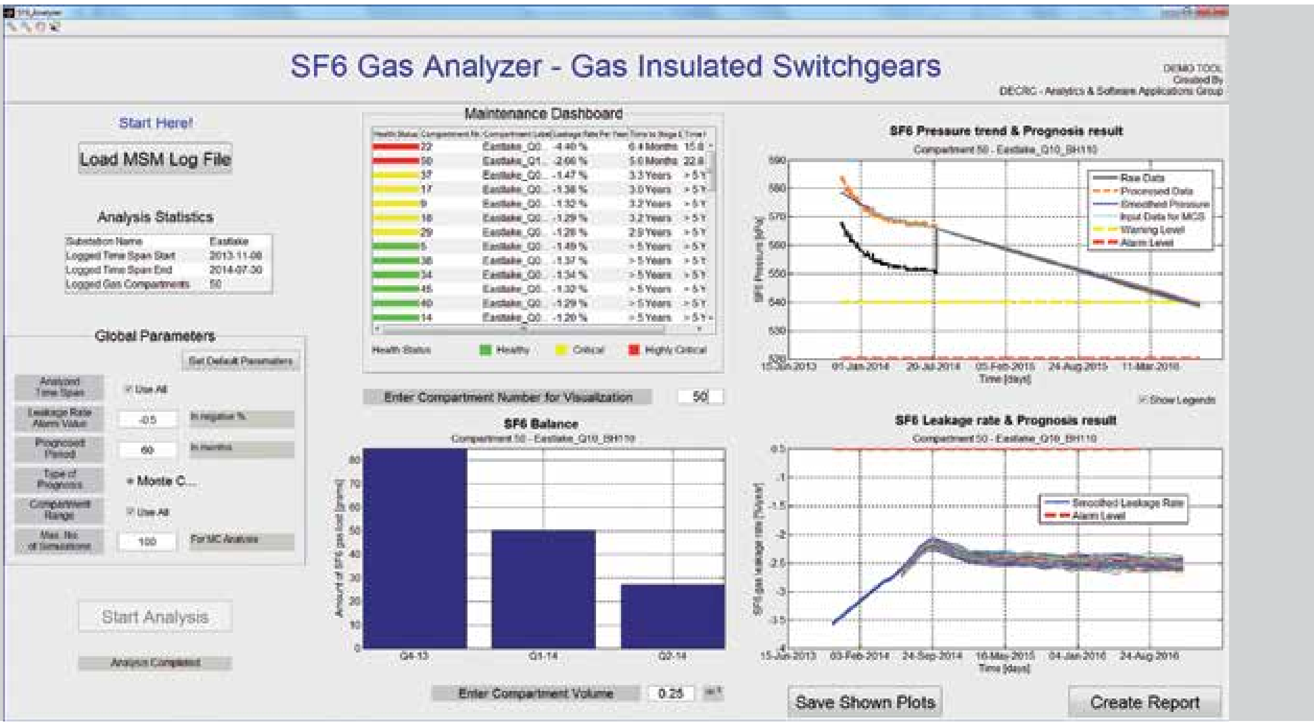

Figure 4: Screenshot of the GUI for SF6 Leak Analysis

Completeness and free-of-error are two key data quality metrics not typically considered. If data is missing (e.g. an empty serial number) or obviously wrong (e.g. a failure date in the future), that particular data set cannot be used for the calculation. Thus, the sample size is effectively reduced. However, the impact of the reliability calculation depends on which data fields are wrong/missing. In our dashboard, we focus on those fields which are critical for the calculation.

Warranty Bias occurs if the majority of data comes from the warranty period. Extrapolating this data to make statements about the whole life cycle is problematic if the failure behavior changes over time. One example for that is wear-out of parts which is not common during the warranty period and changes the failure rates significantly as a product ages.

Besides out research on data quality, we also ran projects covering all steps of the fleet analytics process. An instantiation of the proposed process on building fleet analytics solution is explained below for an application case in high voltage products.

Example Case: SF6 Leakage Analysis

Background: High voltage products such as Gas Insulated Switchgears (GIS) and Generator Circuit Breakers (GCB) use sulfur hexafluoride (SF6) due to its very high insulation capability to extinguish the arc created between the contacts during switching. Since SF6 is a potent greenhouse gas a limit on maximum permissible leakage rate is defined (0.5% per year) on the amount of gas stored inside a gas compartment. Hence it is important to identify the leak and to predict it well in advance.

Value proposition: As a first step of the process the customer's pain is recognized; which in this case is the identification and prediction of the SF6 leak in order to ensure reliable operation of the GIS. The above statement is then transformed into an analytical question – "How to predict the time available to refill the SF6 gas in the compartments before the alarm level is reached?"

Available data investigation: The next step is to collect and investigate the relevant data to answer the analytical question. The gas pressure values which is monitored and logged with the condition monitoring system – Modular Switchgear Monitoring System (MSM) is used. The SF6 gas pressure data is pre-processed to impute any missing values. In addition the noise due to temperature variations is filtered for seasonal corrections with a suitable filter thus preparing the data to apply predictive analytics.

Data analytics techniques: First using the pre-processed gas pressure values and statistical approaches any leakage is identified. From the individual pressure profiles of compart-ments of the fleet and using suitable clustering methods the pressure profiles are clustered to extract insights on the leakage trends and are classified. With the insights on the leakage trends and the gradients as the basis a Monte-Carlo based predictor is used to predict the leakage rate of SF6 gas of a particular compartment of interest.

Potential new service: The developed analytics is then bundled as a tool which can be used by technicians and development engineers to identify and predict SF6 gas leak in GIS. A snapshot of the interactive tool can be seen in Figure 4.

Conclusions

Whilst analytics may be performed at the component, system and plant levels, the great advantage of performing analytics at a fleet-wide level is that it allows large numbers of similar elements to be compared allowing subtle underlying patterns or trends to be extracted with greater confidence. A crucial necessity for fleet analytics is that it should be based on clear value propositions, business understanding, problem understanding, access to relevant data with the overarching requirement for good quality, and suitable approaches to solve the analytical problem. In addition to these, to ensure an efficient and optimal development processes it is crucial that the quality of data is assured. Furthermore data analysts require a broad and deeper understanding on the reasons why a particular method works, beyond simply knowing how to apply different methods. Another crucial point is that a strong understanding of the underlying application (domain knowledge) is highly beneficial in any data analytics activity. Fleet analytics can act as an enabler for a wide range of more advanced products potentially of great value for ABB and its customers. We thank our colleagues from the Polish Corporate Research Center who provided insight and expertise that greatly assisted the research on fleet analytics.

Internal customer

Division Power Grids, BU High Voltage Products
Division Discrete Automation and Motion, BU Motors and Generators

Contact
Dr. Subanatarajan Subbiah
Phone: +49 (0) 6203 71 6112
Email: subanatarajan.subbiah@de.abb.com

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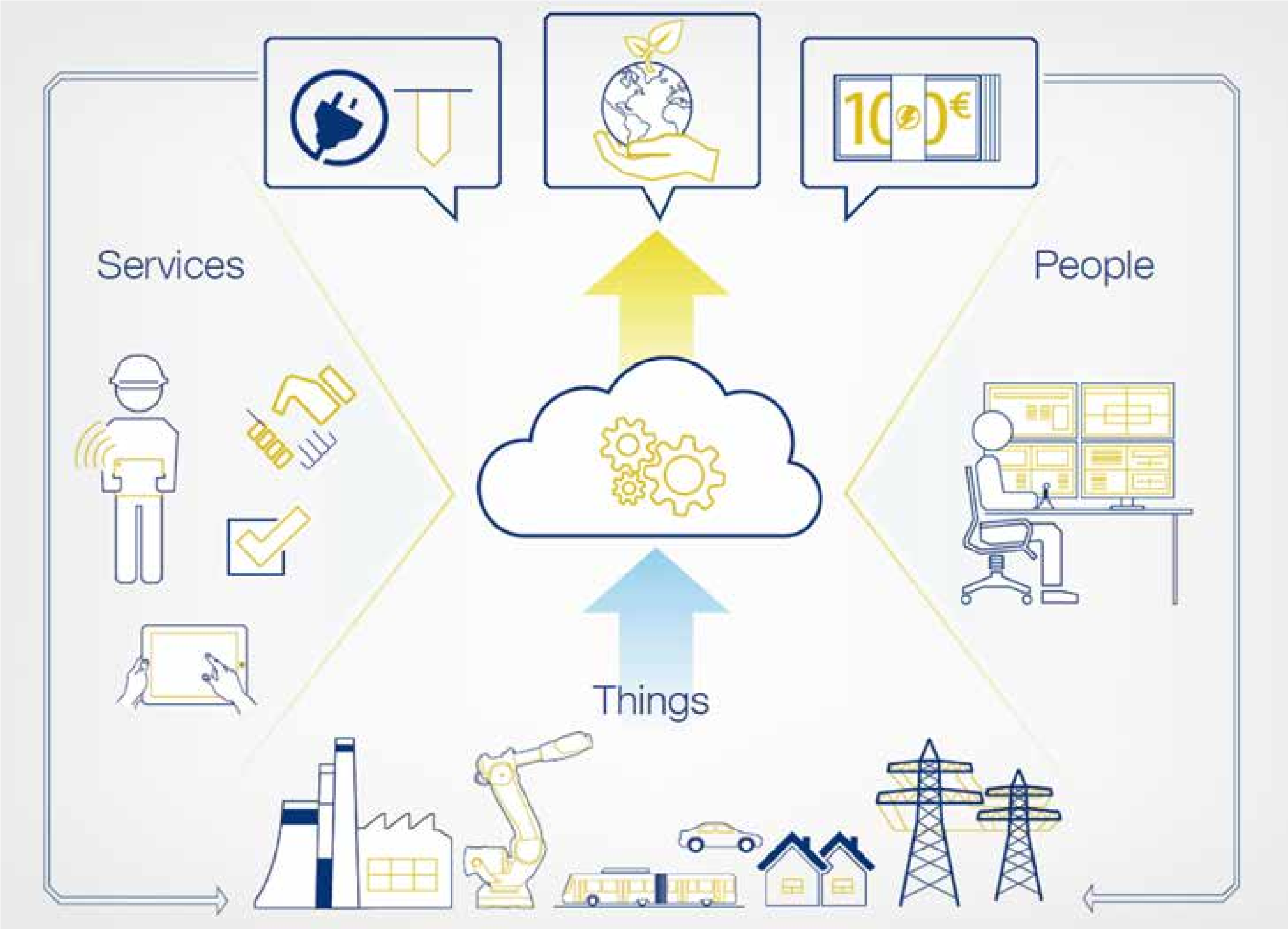


Service Delivery Simulation: a Quest for Excellence

Dr. Zied Ouertani

A major managerial challenge for product-service providers during their servitization journey is to transform their business models in terms of organizational principles, structures, and processes, their capabilities, the relationships with customers and the supplier network. This new paradigm is what is referred to in ABB as the journey towards IoTSP[1]. It entails a cultural shift that should be thoroughly understood by product-service providers. To succeed in this transition, the ServSim[2] project proposes the SErvice Engineerng Metholdology (SEEM) based on Service Engineering discipline to assess the performance of service delivery at local business units. Service Engineering has emerged as a discipline calling for the design and the development of an integrated product-service offering adding value to customers.

The SEEM methodology

SEEM as represented in Figure 1 is composed of two main areas: the customer area and the ABB area. The former addresses customer analysis while the latter aims at defining the service delivery process with the aim to optimize the trade-off between customer satisfaction and ABB internal performances.

SEEM encompasses the four most common phases in SE models namely as: offering identification and analysis, customer needs analysis, process prototyping, and process validation. As shown in Figure 1, the first two phases belong to the customer area, while the remaining two belong to the ABB area. In addition, some of these phases are further decomposed into tasks, and for each of them, one or more methods have been suggested.

An overview of the four phases is provided in the following considering the engineering of an IoTSP offering, with a particular focus on the service Side and People elements.

[1] IoTSP – Internet of Things, Service and People
[2] ServSim – CRID40049 Service Delivery Simulation: Quest for Excellence

Customer Area – Offering identification and analysis

This phase of the SEEM refers to the analysis of the current offering portfolio of the respective business units and/or generally of the market. The aim is to have a clear understanding of how ABB is actually satisfying the customer needs using its current service offering portfolio. This phase is run as a workshop with the business unit in order to align with their strategic targets and uses the catalogue of service offering portfolio[3].

Customer Area – Needs analysis

The purpose is to obtain a clear understanding of the customers' needs and requirements in terms of products, service, and expected performance. This analysis can also lead to the segmentation of customers in several, homogeneous classes in terms of main requirements and needs. This phase is also run as a workshop with the business unit using the value map tool for customer segmentation[4].

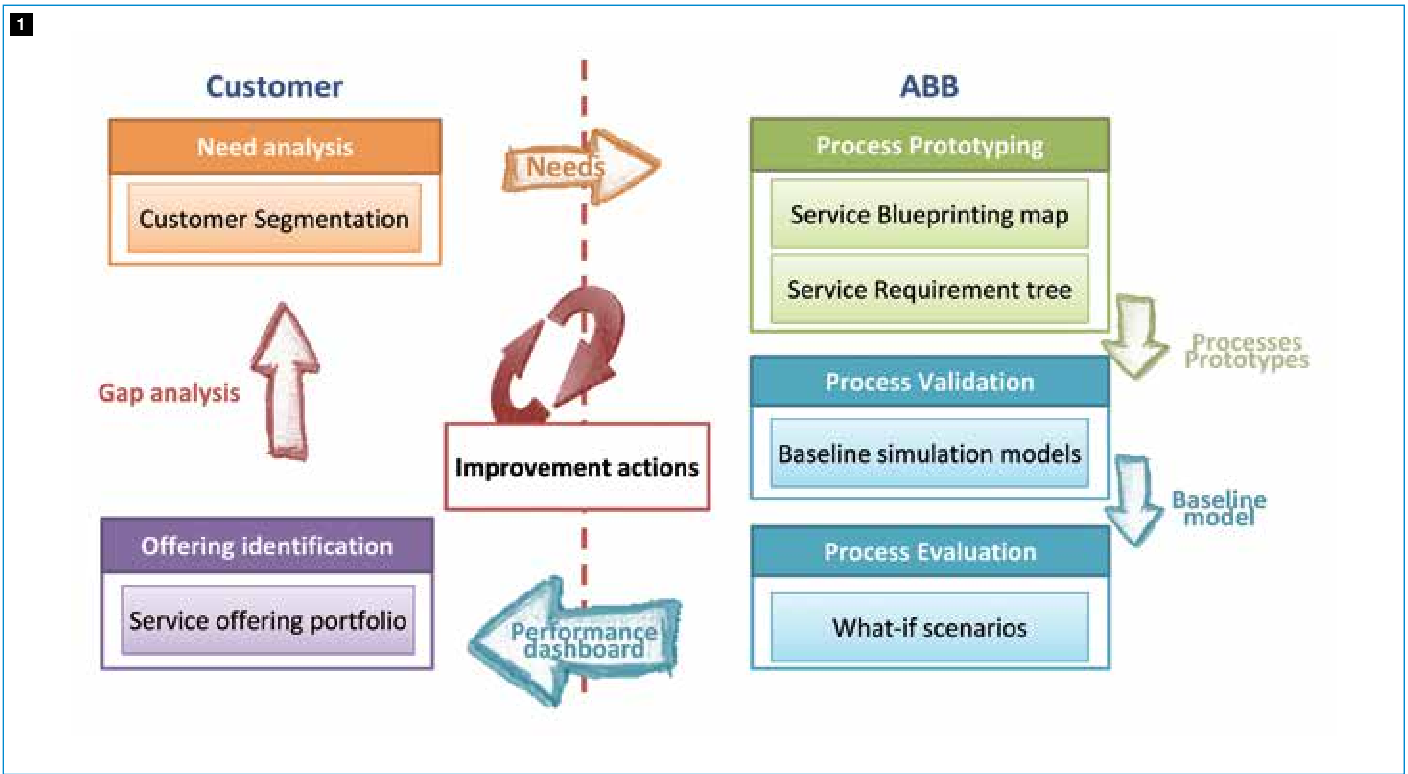
ABB Area – Process prototyping

The phase of process prototyping aims at identifying and mapping the internal processes of service delivery. There are usually several processes for service delivery in each local unit according to the scope of supply of the service product considerer. This phase is run as a workshop with the local units and is based on the service blueprinting technique[5,6]. A reference process[7] is used as a baseline to map the actual delivery process.

ABB Area – Process validation

The result of the previous phase consists in the definition of one or more alternative service delivery processes. Nonetheless, this is a static result meaning that nothing can be inferred about the performance of the process(es) from internal and external point of views. Therefore, the aim of the third phase of the SEEM it to set-up the baseline for the service delivery processes. It involves the validation of the dynamics of the service blueprints based on the analysis of previous years' data. To this end, SEEM adopts a process simulation approach as it allows for the dynamic analysis of the service delivery process by learning from previous years data. Considering that service delivery processes at ABB could be fairly well defined discrete the methodology suggests the adoption of Discrete Event Simulation (DES). Such approach offers great potential as a means of describing, analyzing, and optimizing service and service systems of many types.

Figure 1: The SErvice Engineering Methodology (SEEM)



[3] How to Win Initiative Service Offering Portfolio
[4] How to Win Initiative Service Specific Marketing
[5] This technique is based on Bitner, M. J., Ostrom, A. & Morgani, F., (2008). Service Blueprinting: a practical technique for service innovation. California Management Review, 50(3), pp. 66 – 94
[6] Blueprinting technique is recognized as Best Practice for How to Win Initiative Service R&D
[7] The reference process has been developed together with How to Win Initiative Processes & Applications

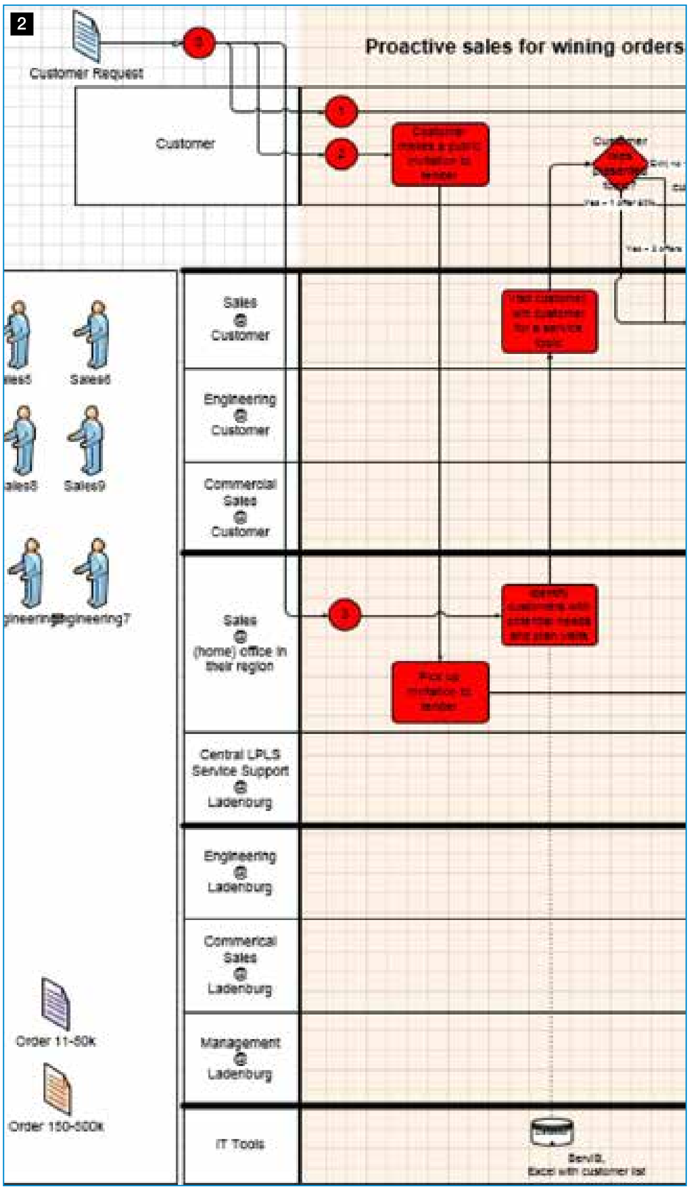


Figure 2: Snapshot of a Service Blueprint "System Extension delivery" at Low Voltage System Germany

ABB Area – Process evaluation

Having established a baseline for the delivery processes of ABB processes at local BU, the purpose of the final phase is to evaluate the performance of such processes. We use a simulation approach to develop what-if scenarios. Those scenarios are defined in collaboration with the local BUs according to their strategies and the purpose of the simulation is therefore to: i) assess the performance of a service under different conditions (what-if analysis), ii) evaluate the effectiveness of possible changes in the service system organization, iii) support the selection of the process configuration with the best trade-off between internal performance and value for customer, and finally iv) provide insights about the service delivery process dynamics and bottlenecks.

The SEEM simulation tool

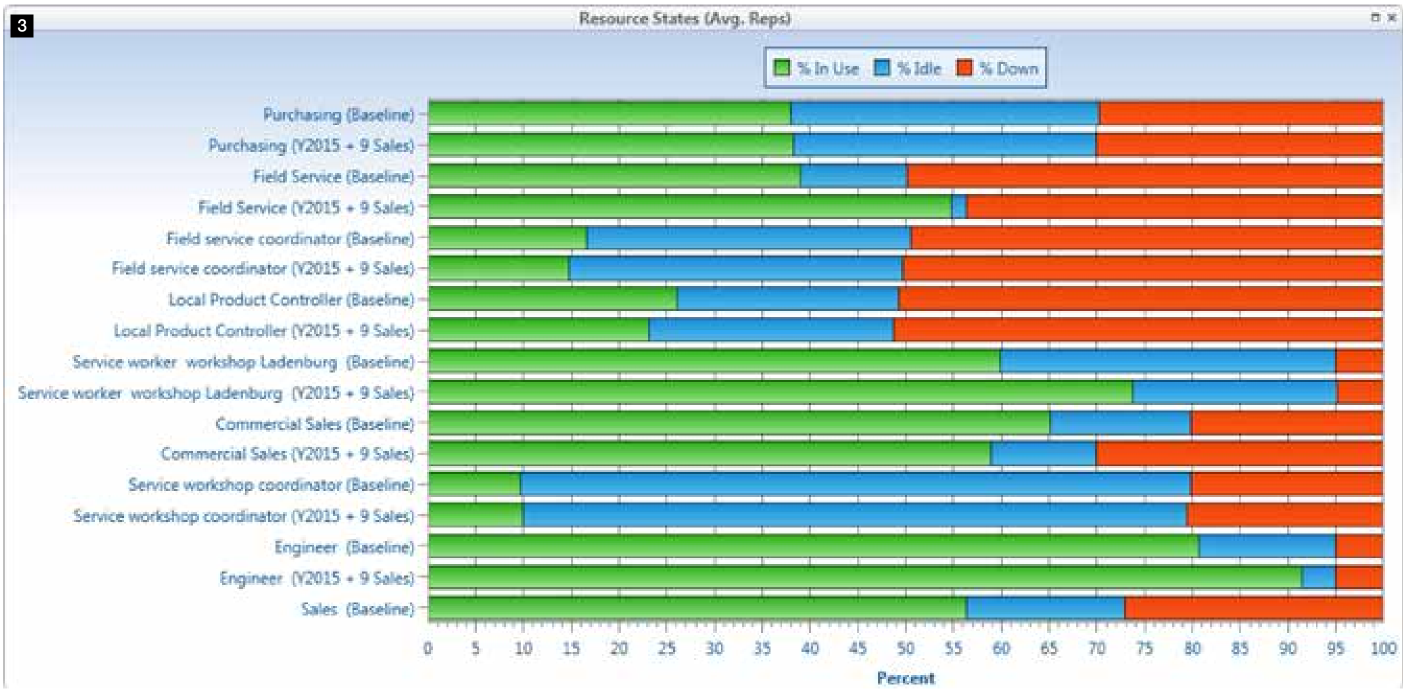
SEEM simulation tool is composed of two main components. The first component is Microsoft Visio Professional to map the service blueprints. The second component is the discrete even simulation engine that could be plugged as an add-on to Microsoft Visio. The simulation engine plug.in comes also with a performance visualization dashboard. This dashboard could then be customized according to the Key Performance Indicators (KPIs) to be assessed.

SEEM application at ABB

This section shows examples of the results from the project. For this purpose we will focus on the delivery of a specific service product (System Extension) in a particular local business unit (LPLS Germany). The choice to focus on this particular service product has been discussed and confirmed with the local managers. System Extension is a strategic offering for the local business unit and has great potential of growth. Figure 2 shows a snapshot of the service blueprint describing the service delivery of system extension. As could be seen, the customer involvement is also mapped in the blueprint. A key characteristic of the service blueprinting is the capability to map customer interaction with ABB. Moreover, the blueprint allows to differentiate between the front stage and back stage offices of ABB as well as the IT tools and processes that have been applied.

Once the blueprinting have been validated, a baseline has been generated based on previous years data and confirmed by the business unit managers involved in the study. A set of scenarios to be tested has therefore been defined in collaboration with the service delivery team. Among such scenarios is to test the hypothesis of "WHAT is the impact on the LPLS Germany organization IF it hires new resources to support the service sales team?" The KPIs considered for this what-if scenario are among others:

– Resource States (see Figure 3): this KPIs describes the utilization rate of each resources involved in the delivery of System Extension at LPLS Germany. Green: resource is working, Blue: resource waiting for job, Red: resource assigned to another task than "System Extension"
– Scoreboard (see Figure 4): this KPIs reports on the number of finished jobs and the time spent to be delivered to customers. Total exits: number of jobs delivered to customer. Average Time in System: the average time an order spends from customer contact until it is delivered to the customer. Average Time in System: the average time an order is effectively being worked on until it is delivered to the customer



4 Scoreboard (Avg. Reps)

Scenario	Name	Total Exits	Average Time In System (Day)	Average Time In Operation (Day)
Baseline	Customer Request	445,00	162,82	39,90
Y2015 + 9 Sales	Customer Request	459,00	114,39	39,99
Baseline	Order 1 10k	215,50	69,19	2,83
Y2015 + 9 Sales	Order 1 10k	148,00	88,48	2,91
Baseline	Order 11 50k	99,50	79,18	12,03
Y2015 + 9 Sales	Order 11 50k	85,00	106,64	11,59
Baseline	Order 150 500k	0,50	67,47	35,51
Y2015 + 9 Sales	Order 150 500k	9,00	157,18	60,29
Baseline	Order 50 150k	17,00	92,11	22,09
Y2015 + 9 Sales	Order 50 150k	25,00	109,63	21,38

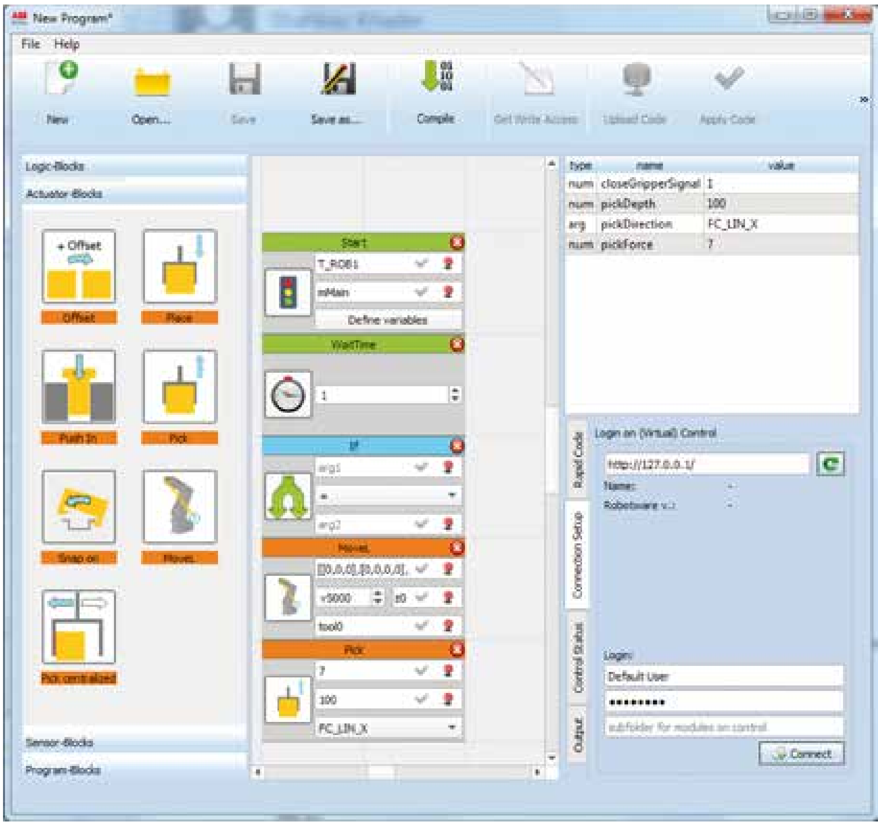
Figure 3: Resources Utilization at LPLS Germany to deliver System Extension (Simulation results)
Figure 4: Scoreboard of finished jobs and time spent until delivery to customer (Simulation results)

Internal Customers

This project has been conducted in collaboration with the University of Bergamo funded by the Research Area Control and with internal customers from 4 different business units and one group function (LPBS; LPLS; DMMG; DMRO; GF-GS) distributed in 3 different countries (DE, IT, EA) and 2 different regions (Europe and AMEA)

Contact

Dr. Zied Ouertani
Phone: +49 (0) 6203 71 6041
Email: mohamed-zied.ouertani@de.abb.com



Robot Assembly Skills Based on Compliant Motion Control

Dr. Fan Dai, Dr. Arne Wahrburg, Björn Matthias PhD, Dr. Hao Ding

Up to now, industrial robots are mostly programmed with procedural programming languages that support the specification of robot motion sequences. Still, creating a robot application requires relatively deep robot programming knowledge, and is time consuming. For decades, the robotics community has been working on approaches for supporting robot programming on a task-oriented level thus defining the robot tasks rather than motion. One of them is introducing robot skills, which are robot functions representing robot capabilities to perform certain tasks. However, existing robot skill models involve knowledge and control policies that are usually complex and hard to implement, as well as not easy to use by application engineers.

To achieve practically usable results, we focused on assembly applications and introduced a relatively simple control policy for robotic skills utilizing compliant motion control. Furthermore, we proposed a software concept for application programming based on such robot skills and demonstrated its feasibility with test implementations.

Introduction

Traditionally, industrial robots are designed to execute motion instructions that command them to move to a defined position or to follow a defined motion trajectory. For decades, the robotics research community has been working on more intuitive, application-oriented (task-level) methods for robot programming. In order to perform task-level actions without explicitly programming corresponding robot motions, the robot system must provide higher level functions, which are often called "skills" – the ability to perform actions on task-level. There are research works on the acquisition of robot skills by demonstration [3], on frameworks for skill-based robot programming [4], and on robot manipulation utilizing force-feedback control [5]. However, there is still a gap between theoretical formalism and its applicability for industrial usage. One of the challenges is to provide robotic skills that can be easily implemented and also easily used by application engineers.

In order to develop practically applicable robot skills, we therefore focused explicitly on a selected type of application, namely robotic assembly, and analysed the requirements on robot manipulation skills. While analysing manual assembly, we found out, that we humans largely rely on our capability of compliant motion. Furthermore, we do not try to follow any precise motion path, neither any force profiles or force values. This led us to the idea to develop a simplified compliant motion control policy with a minimal number of parameters. Combined with a software tool supporting drag & drop composition of task sequences using such skill functions, it enables application engineers to program a robot assembly application without dealing with traditional robot programming languages.

Assembly skills

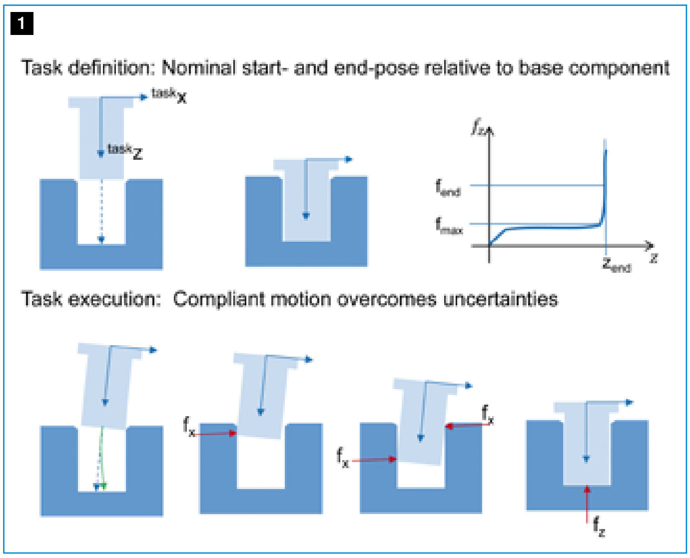
An assembly task basically establishes a geometrical relationship between two objects, where typically one of them is considered as the base component, and the other one is the part that is to be moved to a desired relative position on or inside of the base component. For any elementary assembly task, there is a desired motion path that is to be followed. However, precise positional motion control is not needed because the motion will be constraint automatically by the geometry of the parts, if the robot has appropriate compliance. In fact, this can be achieved with the minimization of force components perpendicular to the desired motion direction, allowing rotational and linear compliance in all coordinate axes other than the desired motion direction. In addition, this desired motion direction is allowed to change because of the rotational compliance. This is due to the fact that compliance is defined in the time-varying tool coordinate frame instead of the fixed base-frame.

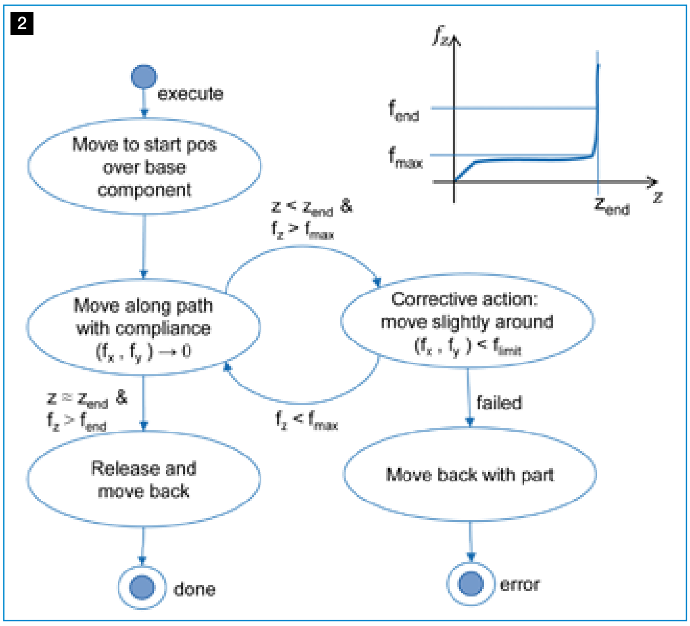
Figure 1 shows the definition of an insertion task with corresponding theoretical force/motion profile, and how the insertion task would be performed based on compliance. Here, the actual force/motion profile is not important. It is sufficient to observe the force thresholds in order to complete the task.

If we assume the desired motion direction is along the positive z-axis, the control policy is reduced to the minimization of force components in x- and y-direction. This can be achieved by defining a reference coordinate system – the task frame with z pointing to the desired motion direction. The force component along z-axis, f_z, is observed, but there is no need to maintain a certain force level. Instead, we move with a desired maximum speed towards the desired end pose, executing corrective actions whenever the threshold on f_z is exceeded. The force f_z is thus kept below the defined limit f_{max}. For the compliance control in x- and y-directions (including rotation), there is also no need to reach a certain minimum force level. Here, a maximum force level (f_{limit}) can be defined to detect exceptional situations like jamming. It also prevents damaging the parts. This results in the basic logic pattern shown in Figure 2.

In general, compliance can either be passive (e.g. mechanical compliance) or active (achieved by robot motion control) [1], [2], [6], [7], and we rely on the latter. Figure 3 shows the theoretical hybrid position and force control scheme we applied, while the implementation was done in consideration of the actual software architecture of our robot controller.

Thus, our approach utilizes hybrid force and position control, on top of which an elementary skill of compliant motion is implemented. The corresponding program instructions provide reference values for motion control on the task level, i.e. the desired positions and force references in the task frame. The





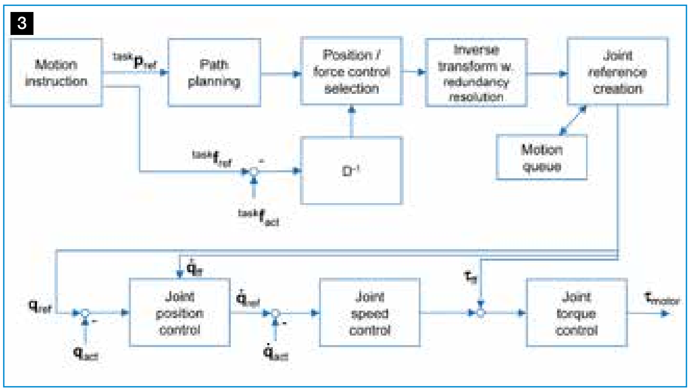
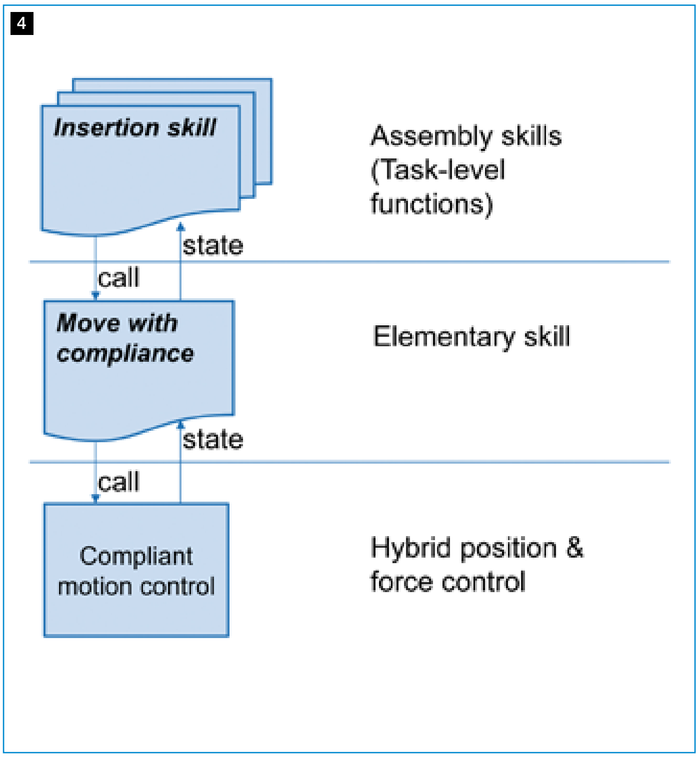


Figure 1: Push-insert task definition, corresponding force-wrench profile, and its execution with compliant motion | Figure 2: Basic control policy for assembly skills | Figure 3: Theoretical hybrid position and force control scheme



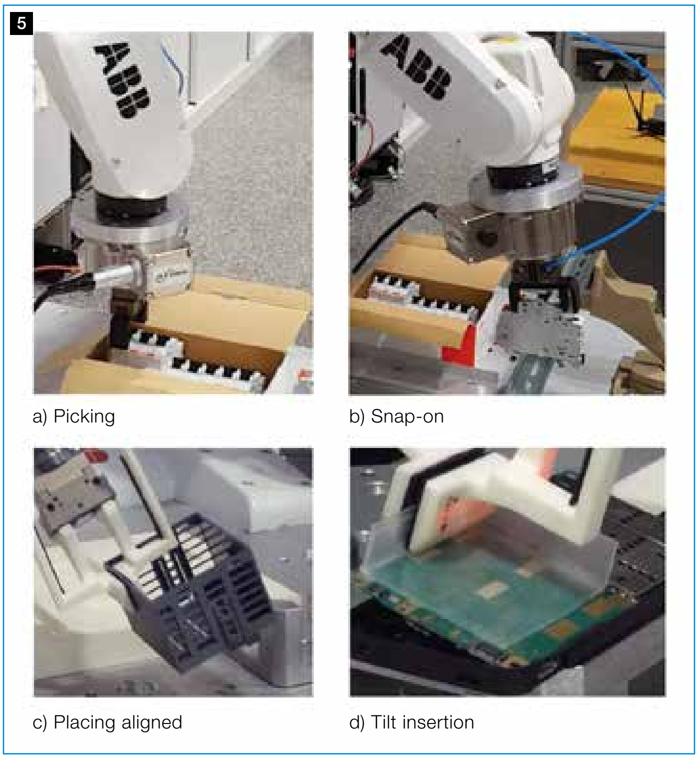


Figure 4: Levels of robot control functions for assembly skills based on compliant motion control | Figure 5: Sample scenarios for robot assembly skills

compliance is based on force feedback control with a damping factor, which yields a correction of the velocity reference, and implicitly of the position reference. The selection of position or force control is also done in the task frame. After inverse transformation into joint space, the corresponding joint reference values are created under consideration of the robot dynamics.

This compliant motion control functionality acts as an elementary skill of our robot system. To make use of it, a calling interface for the robot programming language RAPID is provided which allows selection of the DoFs (degrees of freedom) for position and/or force control, the definition of damping and optional stiffness factors, and the specification of reference and threshold values. As illustrated in Figure 4, task-level functions, i.e. assembly skills using the aforementioned logic pattern can be then implemented and made available as RAPID functions.

These RAPID functions can be used in the usual way within any robot programming environment.

In order to enable application engineers to program assembly applications without the need to learn RAPID language, we proposed a software tool like shown on the title image. The robot skill functions, among other build-in robot functions, are shown as graphic icons. One can compose a robot task sequence by dragging & dropping these graphic icons into the task pane, which then appear as graphic blocks, which can be parameterized. Because of our simplified control policy for assembly skills, only very limited number of parameters are to be defined. The resulting task sequence can be "compiled" to a RAPID program, tested with a virtual robot controller or real installation, and then deployed to run.

Test implementation

For the purpose of concept evaluation and demonstration, two test implementations are done, one with an IRB120 equipped with a force sensor, another one with a YuMi prototype utilizing Cartesian contact force estimation without force sensing, based on motor currents [8]. Our test implementations have shown that the simple skills scheme performs well with the selected sample skills.

To show the Picking skill, miniature circuit breakers are picked up from a box (a), where the exact z-coordinate of the pick-up position are not known a-priori. Closing the gripper is triggered upon reaching a specified force threshold.

With "Snap-on" skill (b), the breaker is snapped onto a rail. Position is controlled in the direction parallel to the rail, whereas rotational compliance is employed for completing the operation.

For the “Placing aligned” skill (c), the TCP is position controlled in z-direction and active rotational and translational compliance ensures that the box is properly aligned to both table and fixture.

For “Tilt-insert” (d), the PCB in the gripper is aligned to an edge of the housing and then folded down to complete the assembly. Position in z-direction is controlled, while position in x-direction and TCP orientation are force controlled.

We demonstrated herewith that assembly skills can be implemented with a very simple control policy, which requires just a few parameters to be specified by the user.

Outlook

With the principal feasibility of our concepts thus demonstrated, we are now extending our work with additional robot skills and more sample assembly scenarios. Work is also ongoing on an easy-to-use method for determining the parameters of the skills, which will further reduce the programming effort for the application engineers. A heuristic approach using application-specific data will determine initial values for the skills used in a particular application. These parameter values will subsequently be corrected and optimized either by user intervention or by automatic optimization during repetitive execution of the application under the supervision of a machine learning approach.

Exception handling for more robust operation is another important issue to be considered. A detailed analysis of potential exceptions during the commissioning and operation phase is necessary. Appropriate methods for exception handling are to be developed, which may require multi-channel sensing.

Internal Customer / Product

Division Discrete Automation and Motion, BU Robotics

Contact Person

Dr. Fan Dai
Phone: +49 (0) 6203 71 6265
Email: fan.dai@de.abb.com

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Scenario-based Requirements Engineering for Building Automation

Dr. Thomas Gamer, Dr. Zoya Alexeeva Durdik

Building automation is a tangible example for industrial domains that are – and will be – changing significantly with the advent of Internet of Things (IoT). Such change will create various opportunities for new products, solutions, and services. It will also require industrial offerings to adapt continuously to the new possibilities and services opportunities. Therefore, it is important to have a common clear view on the field of building automation in order to take informed decisions on new offerings such as additional features or new products. Such common view should be based on a suitable requirements engineering approach – in our case, a scenario-based approach starting from business motivation and then iteratively prioritizing and refining down to features and requirements. In our article, we provide insights into our scenario-based solution approach and the underlying methodology used as well as into stakeholder feedback and lessons learned specific to this approach. As a short summary, the process was a good match to our goals resulting in nine business goals that were further refined into 35 scenarios, 200 use cases, finally providing 180 requirements and 40 features just for our top-priority scenarios and use cases. While the process received very good stakeholder feedback, we also identified some potential for process improvement for the future.

Goals and Motivation

The Internet of Things (IoT), as well as related technologies and initiatives, such as Cyber Physical Systems (CPS), the Industrial Internet / Industrie 4.0 or Smart Grids, have already started to transform various industrial domains. Examples are process automation, power generation and distribution, or building automation. Especially in Living Space® - building automation for residential buildings – we are already seeing many products and solution aiming at making your home smarter, more comfortable and easier to control. In Building Space® – building automation for commercial buildings – such transformation might be less visible and less vigorous but it has nevertheless started already.

One example is smart heating control that adapts to outside temperature or daily routine of the inhabitants in order to increase comfort as well as to save energy cost. Another example are smart home solutions that can be fully monitored and managed by mobile phone apps, either locally or remotely. Beyond, solutions are emerging that provide open service platforms across providers and technology. Mozaiq, for instance, is a joint venture founded by Bosch, Cisco, and ABB, creating such an open B2B (business-to-business) software platform allowing secure remote connections as well as service offerings by various service providers.

In order to be well prepared for future market demands and new business opportunities, it is important to have a common clear view on the field of building automation. Such view helps to take informed decisions on new offerings, additional features or new products. In order to create this common view, we employed requirements engineering techniques. Key questions to be addressed by the requirements engineering process were

- How to manage the complexity of requirements engineering for such broad scope?
- How to integrate various stakeholders with different background, expertise and responsibilities?
- How to assure that no important business cases, scenarios or requirements were missed?
- How to iteratively reach a commonly agreed prioritization?

Solution Approach

In the following, we first provide some details on the requirements engineering process that we actually applied in order to address the previously mentioned questions. Then we also give some insights into the tooling used in order implement the defined process.

Requirements Engineering Process

In order to answer the questions of the previous section, we first had to define a suitable requirements engineering process. Therefore, we analyzed existing processes and frameworks and rated them according to their suitability for our goals. Figure 1 shows a brief overview of our final decision, documented based on the Y approach [1]. As it can be seen, we decided to (1) use a scenario-based approach as it best addresses the need to integrate various stakeholders, and (2) reuse the SGAM (Smart Grid Architecture Model) approach, as it provides proven guideline for scenario-based, iterative requirements engineering addressing a broad scope (the entire domain of Smart Grids). However, we also decided to adapt the SGAM approach to focus on our specific goals only, i.e., to extend the SGAM Meta Model [2, Figure 3] based on our specific needs and previous experience in requirements engineering. The original SGAM Meta Model is available as in Enterprise Architect from the SGAM Toolbox [3].

Figure 1: Y approach [1] for documenting the decision on which requirements engineering process to follow

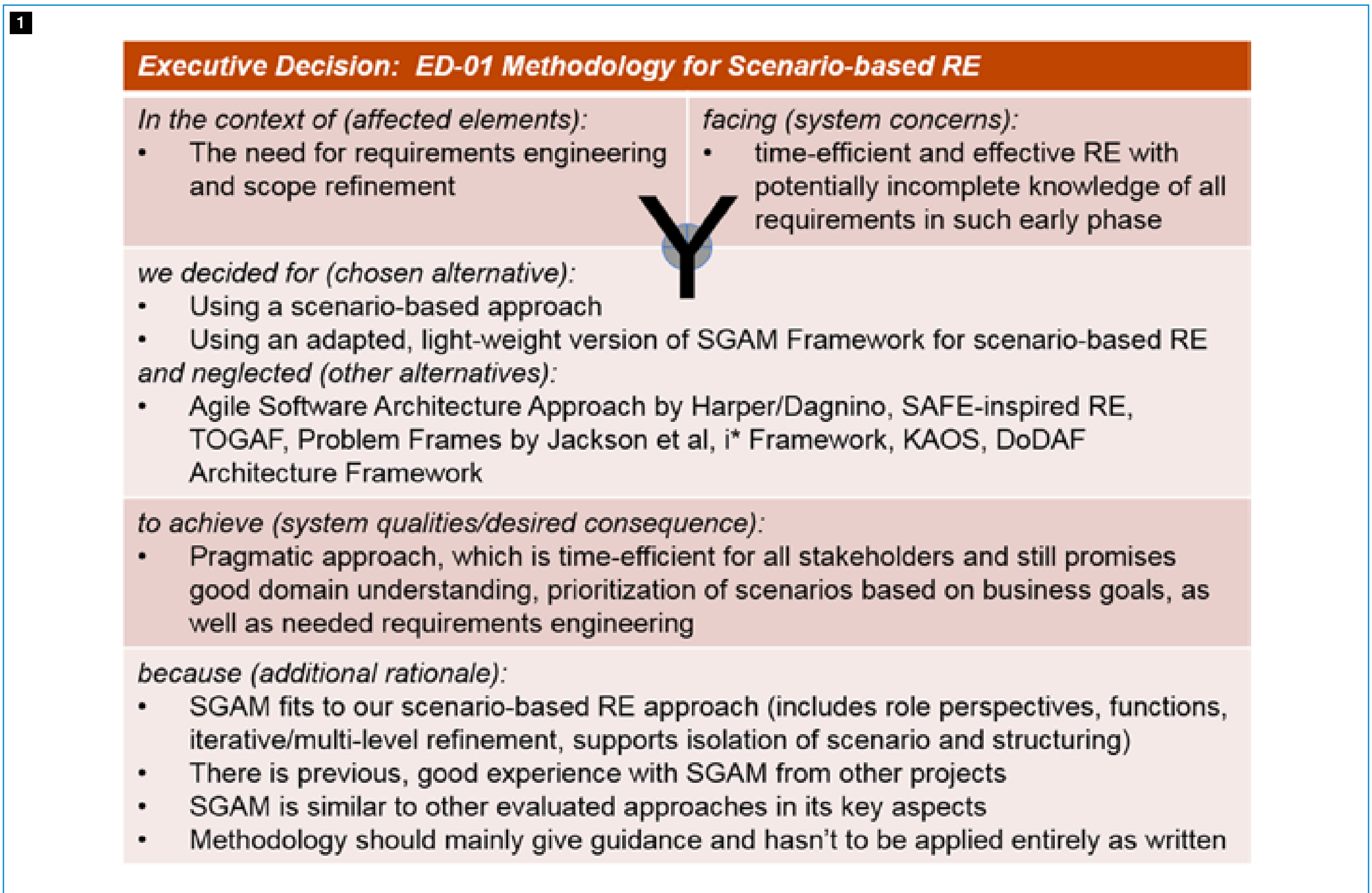

Figure 2 shows the SGAM Model extended by us. Main extensions were to define prioritization points in our iterative process. These iterative prioritizations should keep requirements engineering efficient in terms of time and cost by focusing the subsequent iteration step mainly on the high priority items – ignoring the low to medium priority items in the further refinements.

First, Business Actors and relevant Business Goals are defined. Business goals reflect business perspective, such as selling points and market requirements. Subsequently, Scenarios defined that could realize a single or even multiple business goals. Scenarios represent a more technical viewpoint, but are still high-level and cannot be reduced to a single system or product feature or technology.

In order to collect business actors, business goals and scenarios, we conducted two 1-day workshops with our stakeholders. We invited people with various backgrounds, such as research and development, product management, and business development. Our first prioritization point was implemented on scenario level, as can be seen by the Scenario Decision element added to the original SGAM Meta Model. At this point, we aimed to agree on maximum seven high priority scenarios based on collected stakeholder priorities. This is more or less a magic number, which is based on our former experience. It helps to keep the subsequent refinement process and the large domain scope manageable.

These seven scenarios then served as input for the next step: Refining Scenarios into Use Cases. Once a better understanding of the scenarios was achieved via derived use cases, we implemented the second prioritization step. Again, we added a new element to SGAM Meta Model – a Use Case Decision. At this point, we aimed to reduce the high priority scenarios to a maximum of three and to focus on maximum three use cases per scenario – again these numbers are based on experience, aiming at keeping the process manageable with reasonable efforts while still having high-quality results. These use cases then could be optionally refined into Use Case Workflows – another addition to the original model. Use case workflows facilitate a better understanding of the use case and help to reach consensus in team on what a Use Case actually means.

Finally, features and non-functional requirements were derived from use cases. In turn, the features and use cases are the basis to elicit actual high-level functional requirements. This last refinement step into features and requirements again is an addition to the original model. At the end, we rated the results based on stakeholder feedback and collected lessons learned.

As we were mainly aiming at requirements engineering for better understanding of the business opportunities and market needs, we did not use Design Phase and Information Modeling of the SGAM-adapted Meta Model depicted in Figure 2.

Tooling

Now, let's have a look on the actual tooling that was used to document the results of our requirements engineering process. In the beginning, we started with an internal meeting involving only a small part of the project team to collect a first set of business actors, business goals, and if possible, some first scenarios. We mainly used brainstorming techniques, complemented by some other creativity techniques such as brainwriting. As the project team was entirely composed of researchers, defining business actors and goals was much more challenging compared to finding reasonable scenarios. Nevertheless, we created a comprehensive starting point for further discussions with our stakeholders. Post-processing the results of this workshop started with information cleanup and clustering. We simply used Powerpoint slides in order to summarize the results.

The second meeting started with a short peek into initial results, whereby details were not disclosed to the new participants and stakeholders in order to avoid biasing their way of thinking. While a very good progress with business actors and business goals was made due to the different expertise of the new meeting participants, the scenario discussion was challenging and here the material, which we prepared in advance, became useful to guide the discussions. We used some of our collected material to find a common agreement on what scenarios are and which granularity they should have. This time, we used an Excel template to post-process the results, due to the large result volume. The Excel template was defined by us in a way to fit to the extended SGAM Meta Model. Besides other information, it contained columns to document, for instance, stakeholder priorities and persons responsible for each entry. Beyond, using an Excel template allowed for fast bulk editing and restructuring without having the overhead of typical requirements management tools.

Some insights into Results

In order to make this requirements engineering process more tangible to the interested reader, we will briefly go through the entire process and give some concrete examples on collected business goals, scenarios, and other items. In addition, we provide some insights into our experience with the actual refinement and prioritization process and its expected simplicity.

To give a concrete example of our results, we identified the "Building User" as a potential Business Actor. A Business Goal of the building user could then be "Room Comfort"[1]. This

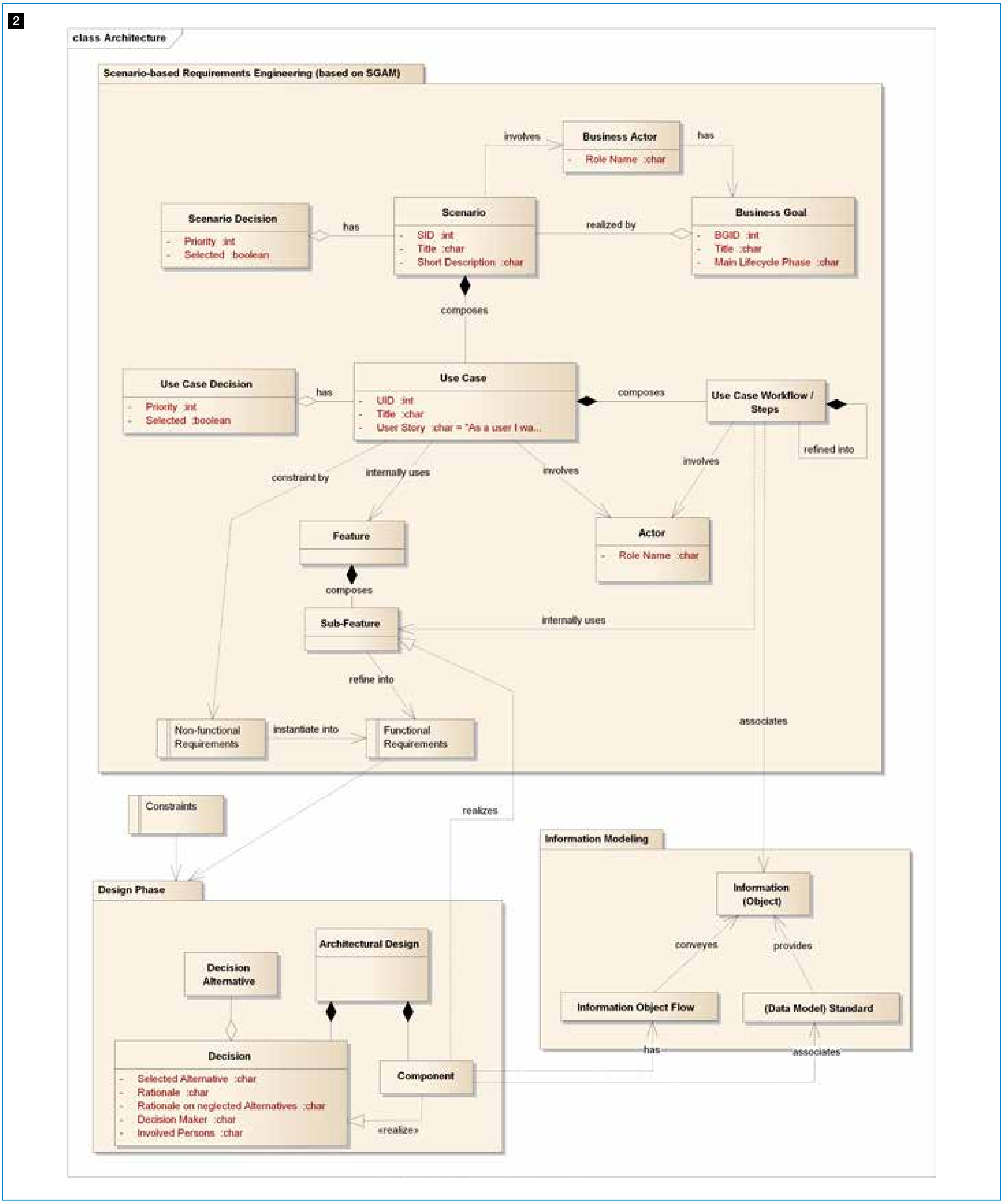

Figure 2: Adapted SGAM Meta Model to serve as requirements engineering process guideline

business goal could, for instance, be realized by a scenario "Automated Rooms" that focuses on automation of room functions and room behavior in order to achieve room comfort in general, e.g., a temperature-based heating control that keeps room temperature at a constant level without manual user interaction with the thermostat.

At this point, we arrived at the first prioritization point of our process. Thus, we asked our stakeholder to rank the 34 collected scenarios from low to high priority. Optionally, they were allowed to give at most three times a top priority. We expected a reasonable priority distribution of each stakeholder and similarities in the priorities. In fact, there were 25 scenarios with a common agreement in priorities and only 9 scenarios that received diverse ratings. For 6 of those, we could clearly see that priorities were different depending on the rating being from a person from Living Space® or Building Space®. To agree on a rating for the last 3 scenarios a phone conference was used. At the end of this part of prioritization process, we had 6 high-priority scenarios selected to focus on during the refinement into use cases – note that 7 was the maximum defined for this process step.

Next, we refined our scenarios into various use cases. Doing so, we also collected some use cases for scenarios that were not selected as high-priority, mostly as a side effect of the brainstorming or because some use case were later re-assigned to different scenarios. Example use cases for scenario "Room Comfort" are, e.g., temperature-based heating control or multiple available room usage modes. In the latter, a building user can simply select a mode that fits his needs best, e.g., presentation, training, or meeting mode for an office room where lights, blinds, ventilation, and IT equipment are set up automatically in accordance to the selected mode. Overall, we collected around 200 use cases, with around half of those being assigned to high-priority scenarios.

At the second prioritization point that we now arrived at, we first added another new scenario that emerged while clustering the collected use cases to our existing 34 scenarios and even agreed on having it on the list of high priority scenarios – which was now at 7 scenarios. Then we had a second round of prioritization to narrow down to 3 scenarios, which was rather consentaneous. Finally, prioritized the use cases of these 3 scenarios – still around 25% of use cases – and selected the top 10 use cases for further refinement.

In the last step, around 40 features and 180 requirements were derived to serve as input to technical follow-up projects. We should mention here that the features and requirements still were high-level requirements and not yet at a level of granularity and preciseness for product development. Features collected are, for instance, "Architecture: Data Storage" and "Communication: Remote Access". Examples of requirements are "The system must allow versioning functionality for project data" or "The system must ensure backward compatibility with older system versions and configurations".

Conclusions and Lessons Learned

In this final section, we want to wrap-up by summarizing stakeholder feedback as well as providing some insights into lessons learned both successful aspects as well as potential for improvement.

The process was a good fit to manage the complexity of requirements engineering for a broad scope. It supported the iterative approach to prioritization, and a common agreement could, in fact, be comparably easily reached. Stakeholder feedback regarding the results of the requirements engineering process was mainly collected from BU (business unit) participants and result receivers that were not closely involved into the process. Overall, all stakeholders were very positive regarding the result. Furthermore, the scenario-based approach was perceived as very good fit to the various different stakeholders, the understandability of the process, and it allowed for thinking outside of daily business demands. Having a clear description of the SGAM-based methodology that defines basic terms and relations was also appreciated. It was especially well received that we not only had a long list of scenarios, use cases, requirements, etc. but that the results came also with a clear prioritization as inherent part of the process.

On the other hand, it is obvious that a process with iterative prioritization and refinement of selected entities cannot create a full picture of the building automation domain. So, it is one of the challenges for follow-up technical projects to carefully check if essential requirements are missing due to the iterative prioritization and the resulting partial picture.

From a result point of view, we also had some interesting findings. As we prioritized scenarios instead of business goals, there were some business goals that were perceived as very important but none of the associated scenarios was selected during the prioritization. This might be an indication that we missed some key scenarios. In our activity, however, we agreed that others simply are more important when thinking from a technical portfolio perspective, i.e., in terms of scenarios and use cases.

As to the required efforts and associated cost, the overall effort was high but acceptable related to the high quality of the results and the challenge of requirements engineering in such broad scope of an entire industrial domain. The iterative nature of our process allowed for an asynchronous working

[1] While this is a rather simple example, we cannot share more interesting and challenging examples due to confidentiality reasons.

mode most of the time. Thus, domain, business, and requirements engineering experts were rarely needed at the same time. It kept the process manageable and allowed for continuous ramp-up of all participants.

For future projects, we recommend to limit the number of people actually working on result documentation; we explicitly advice against more than 3 person, as management effort increases significantly, and quality and consistency typically decrease due to misinterpretations, unclear changes, and different perception of reasonable granularity and clustering criteria. Additionally, using an Excel template means also not having a detailed change tracking, which complicates work with more than 3 people unreasonably. Finally, we end with a word of caution: Process execution and result quality obviously require multiple participants that are experts in their field, face-to-face workshops, and active contribution of BU experts.

Acknowledgments

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Customer / Internal Customer

Division: Electrification Products, BU Building Products and Global Product Group Building Automation
Vertical Program Building Automation

Contact

Dr.-Ing. Thomas Gamer
Phone: +49 (0) 6203 71 6024
Email: thomas.gamer@de.abb.com

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Topology Engineering: Virtual Plants for Brown-Field Projects

Mario Hoernicke

This contribution presents a novel approach for the automatic generation of simulation models for existing plants. Whereas most research approaches for simulation based control code testing focus on green-field projects, the author developed a method that considers the type of planning, as well as engineering data, which is given in brown-field projects, as well. In addition, a prototype has been implemented. The paper presents the validation results of a first field study on a North Sea oil production plant – one of the largest oil discoveries in the UK North Sea.

Motivation

The correct configuration of the control code is a critical part of every process control system engineering project. To ensure conformity of the implemented functions with the specifications, test activities, e.g., the factory acceptance test (FAT), are conducted in every control engineering project. These test activities are based upon manual interaction with the process control system in order to provoke reactions of it and thereby verify the control functions correctness.

In order to perform the manual tests, simulated I/O (switches) are connected to the I/O modules. Wiring up simulated I/O is an expensive business, the simulated I/O equipment itself has a capital cost associated with it and so has their wiring to the I/O modules. Setting up of simulated I/O also impacts on the overall delivery schedule. Testing hours associated with the manual manipulation of switches and potentiometers to mimic plant device and process behavior further adds to this burden on project cost and delivery schedule. These manual steps often have to be repeated several times during the course of a test, especially if rectifications to the application software are required.

Since this is a very costly and error-prone procedure, which often leads to poor process control system quality, the need to execute tests against a plant simulation is increasing.

About the Pilot Plant – Today ...

The pilot plant for this technology is the largest oil discovery in the UK North Sea in the past two decades. The plant consist of four platforms: Production, Quarters and Utilities, Wellheads and Production Sweetener. These Platforms are automated using System 800xA with a combination of AC800M for the process and Safeguard 400 controllers for the safety system, including in total around 8000 I/Os.

In 2014, ABB was awarded with a five year service contract for it. In order to perform best service for the project, a development suite was built in the Aberdeen office. The development suite includes a replication of the offshore system and is used for modernization, service and other operation tasks. Its main purpose is to test new engineering solutions, control system extensions and changes in 800xA, before those are replicated into the production system.

The 800xA control system is staged in the Aberdeen office in order to have a test platform for the control system changes. At present the development suite is used as a stand-alone platform, without simulation of the plant.

... and in future

In future, testing control system changes against the stand-alone controllers shall be enhanced using simulation to imitate the plant behavior, get direct feedback into the onshore control system replication and have a platform to discuss changes with the client. The idea is to create the process simulation using Virtual Plant tools that have been developed within Corporate Research Germany.

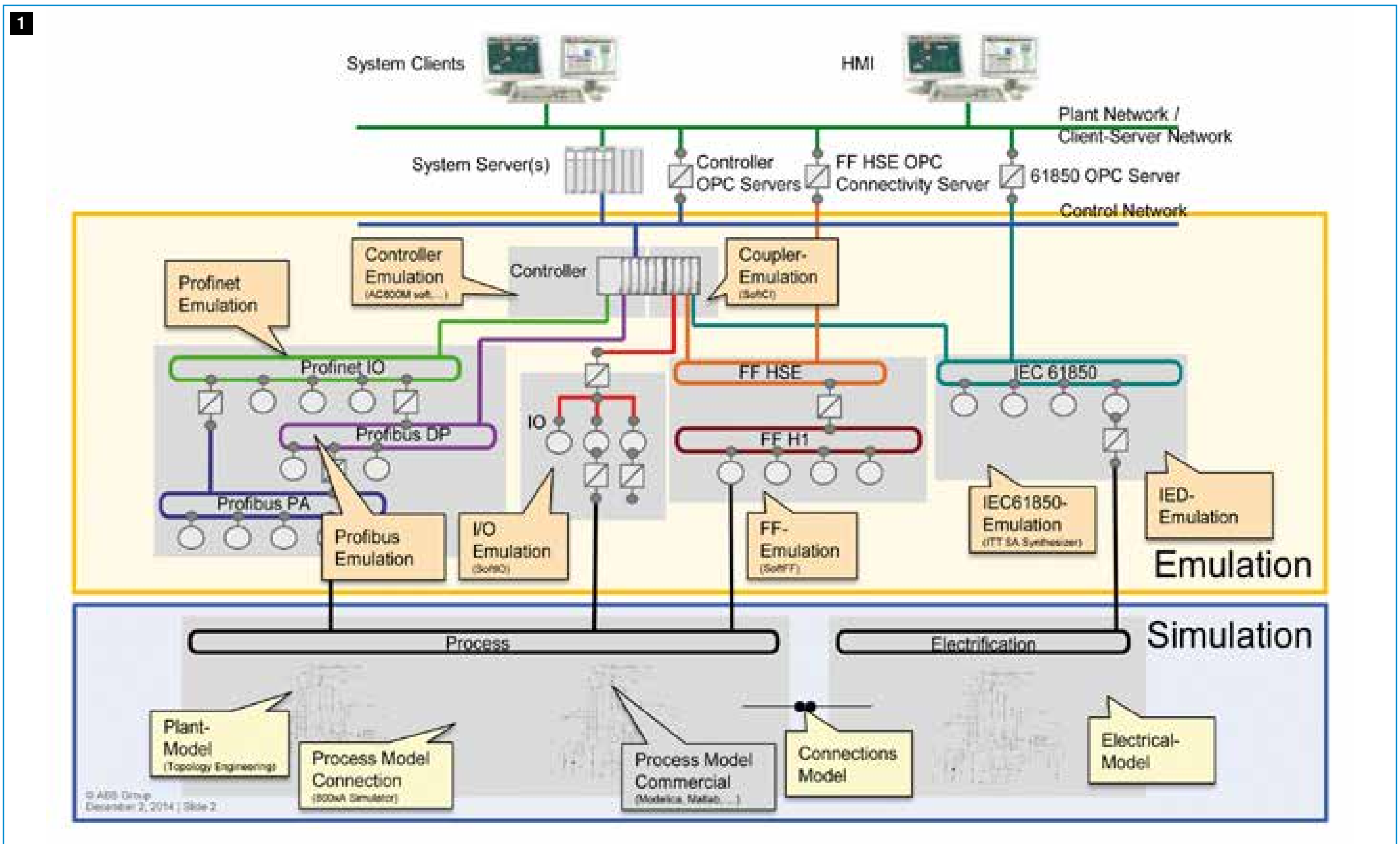
The requirements from the service team are that the simulation is automatically created from the given automation system and process information. The effort for producing the simulation shall be as low as possible. In addition to that, the simulation shall be easy to extend if new process equipment is installed in the system or the automation system changes. For most process control system tests, low-fidelity simulation is good enough. The reason for using a low-fidelity simulation for testing is the very good cost-performance ratio.

Fundamentals of Virtual Plant

Virtual plant is still a vision used in only few projects. The main cause for this is the immense effort that is required to produce it for a specific project. Applicability of the concept is therefore very dependent on results of further research in this area. There is an ongoing initiative, which has the goal to a) reduce the effort for developing simulation and b) research for emulation possibilities for the different subsystems.

The topic can basically be split into two different parts, which is a) emulation of control system hardware and b) simulation of plant behavior. Figure 1 gives an overview about the available tools for System 800xA and develop-ment work that is done in this area.

Figure 1: Virtual Plant Tools for System 800xA



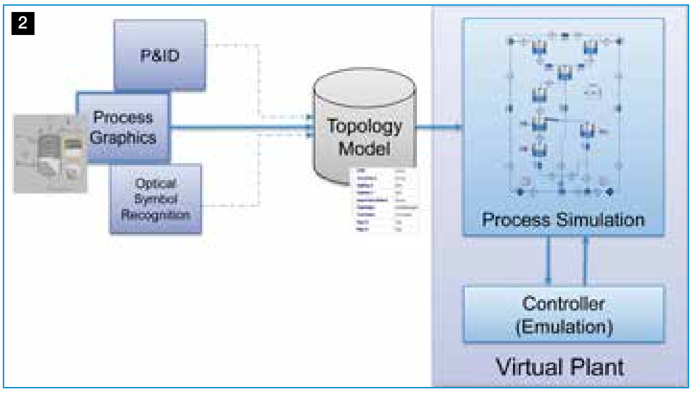


Figure 2: Context of Virtual Plant

Topology Engineering
Since the pilot has a complete replication of the control system, the focus was on delivering a concept for creating a simulation of the plant.

In 2012 a research project called Topology Engineering has been initiated. The goal is to make "Automation of Automation" [1] applicable in industry. "Automation of Automation" is an academic attempt to generate engineering artifacts from topological information of the plant.

Today it is not applicable, because the plant topology is actually not available in a computer interpretable form for automation engineering. One of the "Automation of Automation" algorithms is to generate a low-fidelity plant simulation from a given topology.

The main goal of Topology Engineering was to find information sources in the process control system that can be used to re-engineer the plant topology and afterwards use "Automation of Automation" for engineering projects. Generation of simulation models was the main use case in the project in order to verify that the information from the sources is sufficient.

The result of Topology Engineering is a tool that can use various sources to regenerate plant topologies from engineering artifacts and further translate those into a low-fidelity plant simulator. A possible method to use the tool is to take the process graphics (operator displays) to generate a topology model from, as shown in [2], and then generate a low-fidelity simulator, as shown in [3] and [4].

For the pilot project this is an appropriate method, be-cause the operator displays are already engineered and can be used to derive the required information from. The application of Topology Engineering in the context of the Virtual Plant is shown in Figure 2.

Low-fidelity plant simulation
One of the main purposes of the Topology Engineering tool is to further use it to generate a low-fidelity plant simulation. The resulting simulation model cannot be treated as being a high-fidelity representation of the plant, but it describes and dynamically simulates the plant dependencies.

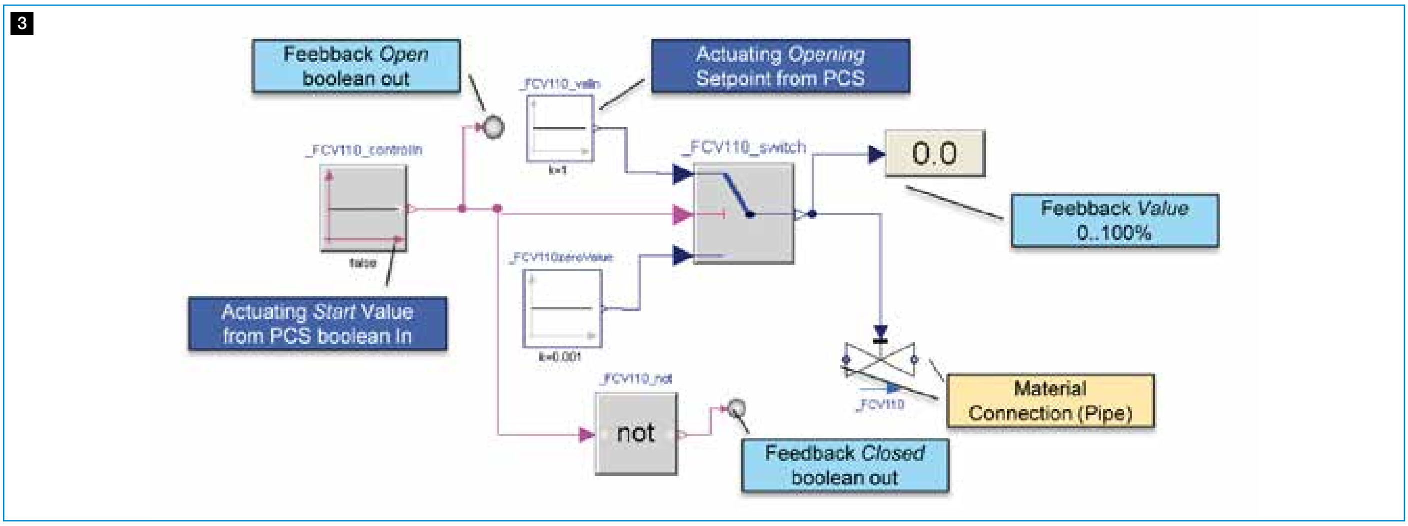
With Topology Engineering, the operator displays are used to generate a static formal description of the topology from the plant, comprising pumps, valves, measurements, vessel, etc. and the interconnections in the material flow using pipes. This description is used to map the objects from the topology to simulation object in the modelling language Modelica. Since both models are object oriented, a one to one mapping is possible. The simulation objects are parameterized using object attributes from System 800xA Aspect Objects. Concluding, the simulation that is automatically produced from the operator displays is able to simulate: Actuators: pump, valve (binary and continuous), compressors and blowers. Plant Equipment: Vessels (open and closed), heat exchangers, flow heaters, pipes, and pipe connections. Sensors: temperature, pressure, density, level and flow.

From the operator displays the dimensioning of the plant equipment is not known. Thus, standard values are used. These values have been chosen to simulate fast value changes in the process behavior, e.g. a vessel is high, but very thin in order to make the level increasing fast. This is helpful for testing. The engineer doesn't have to wait until the equipment is for example filled with liquid, like in the real plant, but can quite quickly see a value change.

As process medium water has been chosen. This allows simulation of a cold commissioning procedure according to [5]. Since usually the exact medium types are not known by the automation engineering, for testing purpose, this has been proven to be sufficient.

Connection with System 800xA
The simulation model has to be connected to System 800xA. Between the control system and the simulation values have to be exchanged. The simulation produces measurement values that are transferred to the input signals of the controllers and System 800xA produces actuating values that have to be transferred to the simulation in order to e.g. open or close valves or start pumps.

For this connection, OPC has been chosen. The simulation model is finally executed in Dymola and therefore, an OPC interface to the simulation is accessible. System 800xA provides the OPC Servers to the controllers and therefore, the connection can be established using an OPC to OPC client. Since the



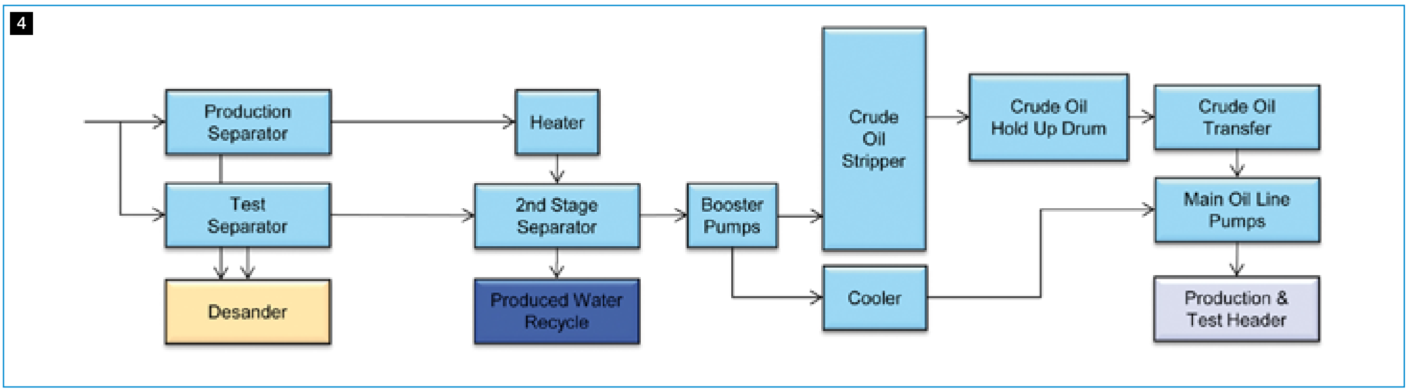


Figure 3: Feedback Creation for a Continuous Valve | Figure 4: Oil Production System

variables from the simulation are known (because the simulation is generated), these can be mapped automatically to System 800xA properties. The mapping connects the variable with each other.

Last but not least, the simulation has to provide feedback values of the actuators. The valves and pumps from the simulation get actuating values from System 800xA and have to respond using a feedback in order to make Sys-tem 800xA know that the actuation took place correctly. Without this feedback, the control code will not work. The feedback has been included in the simulation model by very simple feedback models. An example for a continu-ous valve is shown in Figure 3.

A Virtual Plant for the Pilot

The described methodology of Topology Engineering has been used for generating a virtual plant for the pilot project. As a first step, a replication of the pilot plant has been used within Corporate Research to install the Topology Engineering tool and simulation environment on it. Within the Corporate Research test environment, the AC800M controllers have been replaced by soft controllers. As an example for Topology Engineering the oil production system has been used. The simplified process of the oil production system is shown in Figure 4.

The oil production system consists of about 13 relevant operator displays and uses seven AC800M controllers as process control system. The 13 displays have been used to create an initial topology from. For some displays manual adaptations of single connections had to be made, but in general about 95% of the topology could be derived from the displays.

After deriving the topology of the 13 displays, the topology had been combined in order to have one topology for the entire area. This can be done semi automatically using Topology Engineering, as well. The buttons on the operator displays are considered being connections to other topology parts and therefore, most connections between single models are known.

Afterwards, the System 800xA properties for the objects contained in the topology have been read from the system and

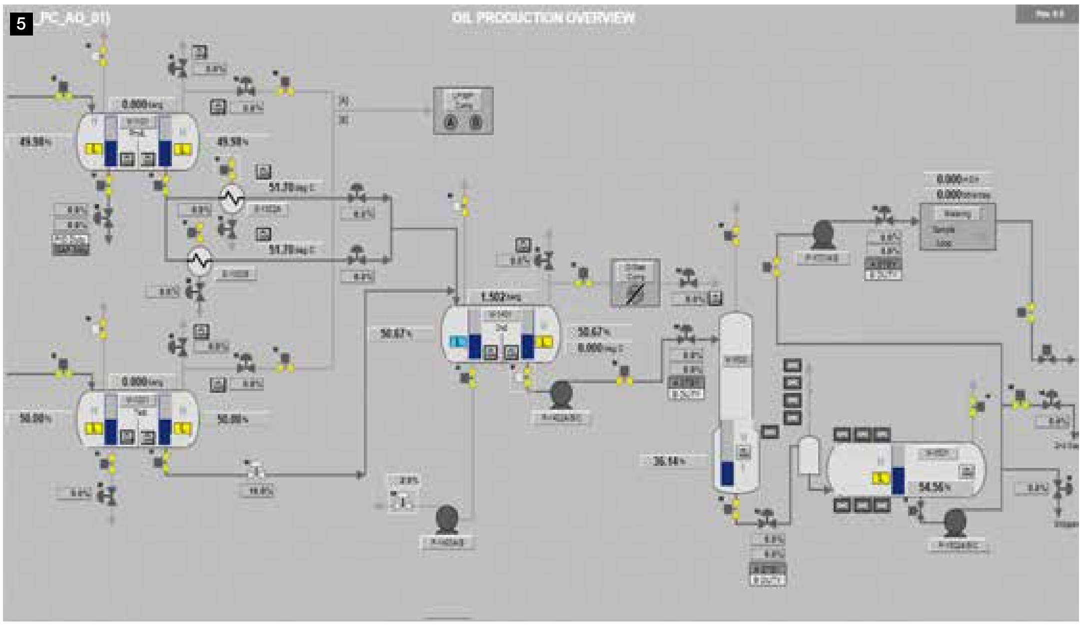


Figure 5: Oil Production Area in Simulation

been included in the topology. Those are required for automatic parameterization of the simulation. This task can be automated completely. There is no user interaction required. In addition to the values of the parameters, the references to the I/O values of the objects are automatically extracted and stored in the topology.

The gathered information is sufficient for the generation of the simulation. Using Topology Engineering, eventually, a simulation for the entire area is automatically created.

Afterwards, the simulation can be executed, the connection to System 800xA is automatically executed and the simulation can be used for testing. The overview display of the oil production process, including simulated online values is shown in Figure 5. With the application of Topology Engineering in the pilot project, it had been proven that the methodology works and is applicable in industry.

Conclusion

Reaching the vision of the virtual plant is a tough task. Although there are obvious advantages in deploying the virtual plant concepts for test execution during automation engineering, these are seldom used in practice. The research initiative for the Virtual Plant tries to flatten the way for these concepts.

The first industrial application of generating a simulation from a topology of the plant shows that the methodology of Topology Engineering works. The evaluations about the effort for producing the simulation shows that the effort is quite low compared with the reached results. Instead of using moths for manual creation of the simulation models, this method reduces the effort to days – with same result.

Obviously this study shows that the way forward is with Topology Engineering. The tool should be further used in industrial applications to create the simulation models and finally Virtual Plants for every engineering project.

Internal Customer

Process Automation – Oil, Gas and Chemicals

Contact

Mario Hoernicke
Phone: +49 (0) 6203 71 6266
Email: mario.hoernicke@de.abb.com

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NAMUR Data Container

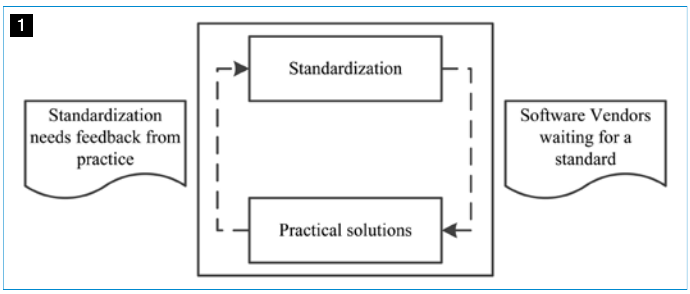
Dr.-Ing. Rainer Drath

Standardization of data models in automation industry is a tedious, time-consuming and multidisciplinary process. The absence of a successfully standardized and established data exchange methodology for PCE (Process Control Equipment) Requests as the most informative capsule of data is an unsolved gap between process and control engineering tools. This contribution describes the first application of a novel and agile standardization method, applied by means of PCE Requests. In the result, within 10 month, leading CAE tool vendors and users of engineering tools have developed a detailed standard electronic data model of the PCE Request, as well as prototype exporter and importer for process and control engineering tools. Consequently, the bidirectional data exchange of PCE Requests between multiple software tools in various disciplines have been successfully demonstrated at the NAMUR Annual General Meeting 2014.

Problem description

Smooth electronic data exchange between process and control engineering is an unsolved problem for decades. Instead, the data exchange happens via printed paper or Excel sheets. Having no standardized electronic data exchange leads to costly manual work, data inconsistencies and finally reduced quality of the engineering. It is a key cost driver. The obvious solution seems to be simple: standardized Syntax and Semantic seem to be the two fundamental principles of having a neutral engineering data exchange format [1]. A “Super Data Model” that meets the majority of most important engineering data models would be a perfect solution. This idea is the driving force of all related standardization activities such as NE100 [2], STEP [3], ISO 15926 [4], and many more. However, up to now, this has not succeeded. Figure 1 shows the reason: a standardization deadlock. Mature standardization requires feedback from practical application, and practical application requires mature standards, since the related software vendors do not implement pre-standards. Consequently, the standardization is delayed. On the other hand, having

Figure 1: Standardization deadlock [1]



such standards is an important prerequisite in order to make Industry 4.0 a successful approach. How can we reach this?

Solution

In the last years, two major innovations appeared helping to overcome the deadlock: a) a new way of standardization, and b) a new way to store standardized data and non-standardized data mixed in the same data container.

A new evolutionary way of standardization

A key principle of classic standardization is to create a super data model, causing the deadlock. The new way of standardization leaves this path and pursues the following principles according to [1], [5]:

- Standardization should proceed stepwise. Each step should be tested against the practicability by end users and in some iterations be matured.
- Only the necessary required data should be standardized and transported as a specific subset. Presumably, this subset should be usable without dependency on standardization of the complete data model. Incompleteness or even proprietary storage of data without any internal standardization is explicitly allowed.
- Data storage should follow the concept of object-oriented data modeling.
- Neutral and proprietary data will be transported in a mixed set of data and can be interpreted further in the target software tool.
- Further data sub-models of new concepts should be based on the available data format.
- Standardization should be followed collectively and agile.

Especially the concept of storing both standard and proprietary data models in the same file apparently contradicts to the classic fundamental principles of getting a neutral data exchange. However, in practice, fulfilling these prerequisites promises to increase the pace of standardization.

A new way of storing data

The data format AutomationML ([6], [7]) enables to model any kind of object libraries within the same syntax. A class consists of attributes, interfaces, and may contain further internal elements which contain further attributes, interfaces and further internal elements. These generic principles enable modelling any kind of object library. Standard libraries are modelled in the same way as a vendor specific libraries. Hence, AutomationML allows modelling object hierarchies by instantiating standard and vendor specific classes with the same mechanisms. A receiver of an AutomationML file can simply differentiate between data he knows and data he does not know, and he has explicit knowledge about unknown classes. This is a prerequisite to develop individual import routines aside the standard, and this is a starting point for a stepwise evolutionary standardization.

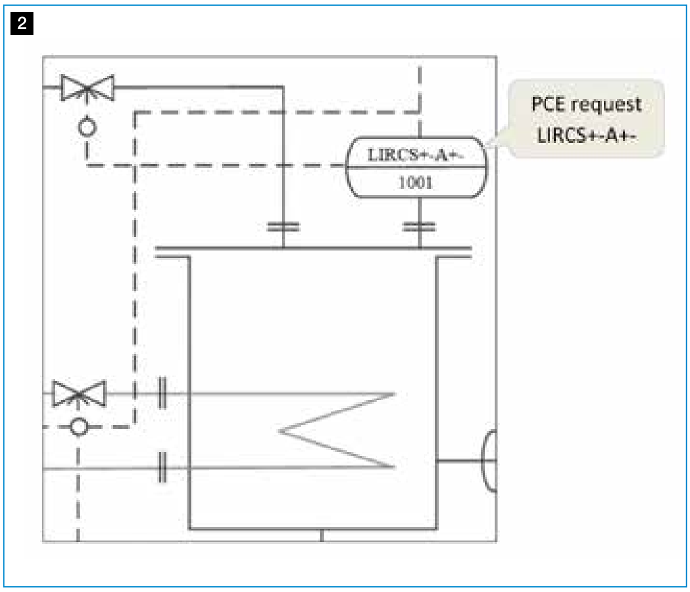


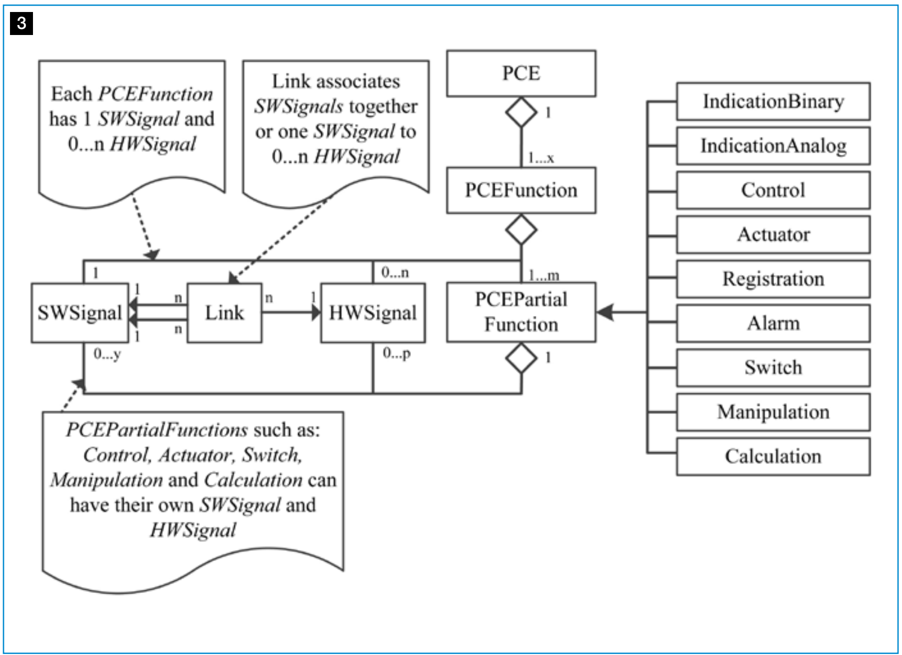
Figure 2: PCE request LIRCS+-A+-

Implementation

The technical committee GMA 6.16 has adopted both principles in order to model a single piece of engineering data that is of high relevance for process industry and control system vendors: the PCE request. The PCE request is shows in P&I diagrams in form of almost elliptic graphic shapes, containing letters which encrypt required functionality. The PCE Request is an interdisciplinary engineering object in the data model and acts as an interface between control systems and process design tools with a significant special importance. Examples of process control equipment include actuators, sensors, and transducers. Figure 2 shows an example of PCE for measuring the level of tank and controlling the inlet flow [8].

Based on the attributes of the NE 150 [9], the GMA 6.16 developed an object model for the PCE request. Figure 3 shows the result of the UML-Notation, a generic class model of a PCE Request:

- A PCE Request often includes only one PCE function, but may also include a loop with multiple process control functions. In general the PCE Function name (IEC 62424: PCE Category) would follow the first alphabetic character of typical identification (e.g. “F” for Flow or “P” for Pressure). A list of all possible characters and their respective meanings is available in IEC 62424.



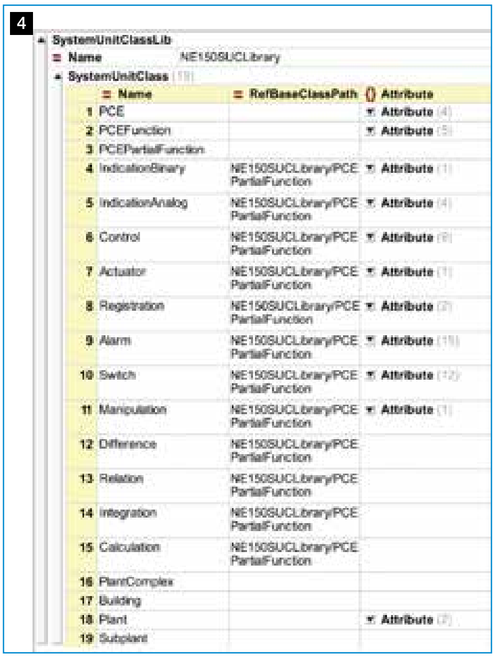


Figure 3 PCE Request Object model and classes | Figure 4 Modeling with AutomationML Editor (Classes)

- Each PCE Request includes at least one PCE sub-function (IEC 62424: PCE Processing Function). The sub-function is generally named after the following character of typical identification. For the first step the generated data model describes the functions with the help of classes that have been created for *"IndicationBinary"*, *"IndicationAnalog"*, *"Control"*, *"Actuator"*, *"Registration"*, *"Alarm"*, *"Switch"*, *"Manipulation"* and *"Calculation"*. This library of classes is extendible based on future developments and improvements.
- Moreover, each PCE function includes one Software-Signal that models the primary control signal (e.g. filling level 0…1 m). Additionally, all sub-functions are associated to this "Master Software-Signal". For example, control functions are activated when level exceeds above or falls below defined values of this software signal. As a rule, for each software-signal a hardware-signal (e.g. 4…20 mA) is also aggregated and as the result, value transformation from 4…20 mA to 0…1 m can be explicitly defined. There is a possibility of having PCE functions with multiple or no hardware-signals e.g. redundant or soft-sensors. On the other hand, some sub-functions have software and hardware signals, such as circuits or controller outputs.

The GMA 6.16 decided to use AutomationML as XML based modelling language. Figure 4 exemplarily shows the class model in its AutomationML representation. Every class in the UML model is described as separate SystemUnitClass in the AutomationML model.

Result

The Technical Committee has kept its promise: Within 10 month, the data model for the PCE Request has been implemented and seven commercial design software tools including ABB (800xA), AUCOTEC (Engineering Base), ESP (ESPlan), Rösberg (Prodok NG), Siemens (COMOS and PCS7) and Yokogawa (Centum VP) have verified it. Participants of NAMUR Annual General meeting could investigate the solutions live from different tools. Other companies such as Emerson (DeltaV), Honeywell (Experion PKS), Schneider Electric (Foxboro EVO) and Wago (WAGO 750) gave official commitments to develop an interface for the explained data model. Although it may sound very simple, but for decades there was no solution for the explained problem and now it is possible for CAE tools to export the relevant information and the control design tools can import the data with low effort and no data loss.

Many ingredients played a role in the success of realizing this concept. The most important factor was utilization of modeling procedures for standardizations [1] which broke the deadlock. Therefore, the effort was not invested to create a comprehensive "Global model" of engineering data. Mostly the project was concerned about performing the data exchange in a heterogeneous tool environment without or with only partial standardization. This allowed the project members to focus on a single engineering artifact, which is the PCE Request. This increased the pace of progress in data modeling as well as reducing the time needed for iterative testing of software solutions. The multiple and iterative passes through the cycle of standardization and practical verification was essentials in the agile maturation.

Further important factors were reuse of existing works. NE 150 is providing a comprehensive list of PCE attribute including their Semantics. AutomationML is providing the necessary syntax and required environment for modeling of PCE classes using NE 150 features. The combination of AutomationML and NE 150 (Syntax and Semantic) build a powerful tool for agile engineering standardization. Simplicity of programming with AutomationML interfaces [10] and special capabilities of AutomationML such as storing the non-standardized data were crucial for the agile implementation without extensive prior knowledge.

A clear data model of PCE Request not only simplifies the data exchange between CAE and Control Design Tools, it also allows future automatic preliminary assessment of the data consistency and completeness during export, or import [11]. The results are planned to be documented and pub-lished as a new NAMUR recommendation. However, the PCE Request itself is just one example of an agile standardization principle. The proposed concept – the NAMUR Data Container – is directly applicable and transferable to other specific engineering artifacts. The process for standardization of data models has been significantly simplified.

Customer / Internal Customer
Division: Process Automation

Contact
Dr. Rainer Drath
Phone: +49 (0) 6203 71 6471
Email: rainer.drath@de.abb.com

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Gantt: A flexible scheduling tool – Making scheduling everyday business

Dr. Iiro Harjunkoski, Dr. Martin Hollender, Dr. Reinhard Bauer, Werner Schmidt, Jens Doppelhamer, Dr. Subanatarajan Subbiah

For many industrial companies, a production scheduling solution – be it manual or optimized – is in many ways still a complex and "exotic" functionality that seldom finds its way into the daily practice of the plant floor. As it lies within the interface between business and control systems, scheduling is often seen as something decoupled and theoretical that requires high-level experts to configure, to use and to maintain it. An ongoing technological transition towards stronger automation integration helps to alleviate the major challenge to establish efficient information sharing across industrial production management systems. Information comprising production orders to be scheduled, processing plant structure, product recipes, available equipment, and other resources are necessary for producing a realistic short-term production plan. DECRC has investigated the standard ISA-95 and applied it as a neutral data-exchange platform for a generic scheduling solution. A user-friendly and flexible Gantt-based scheduling prototype was developed and tested on various use cases.

Introduction

In the past two decades, there have been many significant achievements in the development of scheduling models, methods and solutions. Nevertheless, an extremely important still partly unresolved technical challenge remains: How to efficiently deploy these in an industrial context? A common approach to bring a theoretical solution "live" is to connect the plant experts and process owners with optimization experts to locally build a solution that is adapted to their needs. This often results in strongly tailored implementations that are normally not reusable and difficult to maintain due to the complexity. This restricts a wider distribution of novel approaches and easily leads to a completely isolated software solution. With the ever increasing availability of data and higher level of automation and electrification, production scheduling cannot anymore be seen as an autonomous solution. Concepts such as Internet-of-Things, Smart Grids, Smart Manufacturing, Big Data, Industry 4.0, Software as a Service and enlarged scope on Enterprise-wide Optimization topics [1] increase the pressure to connect to and interact with neighboring solutions and systems.

In most industrial environments, a scheduling solution should be closely connected to the production environment – for instance to a distributed control system (DCS), manufacturing execution system (MES) or collaborative production management (CPM) system – in order to be able to automatically obtain all the production and process data that is necessary for scheduling. A connection to the enterprise resource planning (ERP) is often a must since the whole production is triggered by customer orders mostly entering via an ERP interface. ERP systems are further also used for procurement to ensure that all material and resources are available when needed according to the production plan.

For successful scheduling the following information must be known:

- Resource availability, not only for equipment but for also materials, personnel, utilities etc.
- Dependencies and rules related to the processing steps, cleaning needs
- Current state of production and capacity of the production resources to anchor the plan to ongoing production
- Production orders with their due dates and priorities
- A target for the scheduling

This information is only partially static – some pieces of information can change even minute-wise. This highlights the need of connectivity, else the schedule may not be up-to-date. In the considered prototype most of this information has been modeled using the standard ISA-95 [2], which makes it easy to share and communicate it between system components.

Benefits of scheduling

It is very important to understand what industrial production companies truly need. In the times of hypes and trends, the technologies themselves easily become the drivers and in the enthusiasm of embracing them it may be forgotten what the primary needs of a typical customer are. Some of the main and most important aspects that are sought from advanced solutions are

- Safety: Scheduling can impact this by for instance providing an overview of future operations, avoiding complex changeovers or larger simultaneous operations on the plant floor
- Lower cost and simplified operations: This becomes more and more critical with the increasing complexity. An operator who uses the solutions should be able to get a better grip of the cost and feel being supported by the solution
- Production efficiency: Typical scheduling targets that customers aim to achieve are throughput maximization and minimization of setup times
- Better asset utilization (return on assets): It is important to ensure that the expensive assets on a plant perform the work they were planned to do. Here scheduling can be instrumental and even indicate if there are redundant assets
- More effective decisions: An automation system should first and foremost help managing the process and taking better decisions faster and more reliable in order to ensure that everything is going as well as possible

In general, a working scheduling solution contributes to providing a better overview of the plant operations and early detection of bottlenecks. It can also improve the performance through a more balanced machine utilization and higher reliability. Also automated scheduling can be instrumental when it is required to adapt fast towards changing situations. Further, independent of the operator skills it can help to find high quality schedules.

For the interested reader, a number of benefits, trends and challenges, as well as lessons learned from practical scheduling deployment projects can be found in [3].

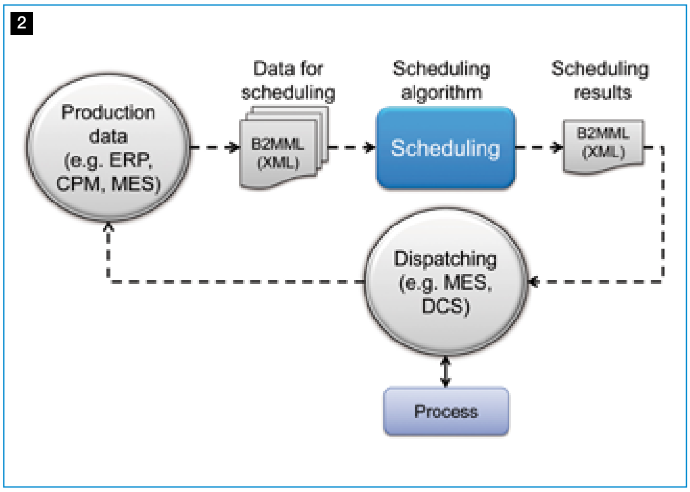
The scheduling prototype

For a successful scheduling prototype it must be ensured that the main challenges that apply to the productization of scheduling solutions can be addressed:

- Define a landscape that can host the algorithmic environment, gather the necessary data and communicate the results into production
- Find a generic problem description that is able to express realistic problem instances
- Provide algorithms that work efficiently for various cases and provide good and feasible solutions
- Maintain the solution through a non-expert manageable configuration environment

Landscape

One of the cornerstones of the prototype is the ISA-95 standard, created to act as an interface between business- and control systems. It defines most of the required data fields and offers an XML-based implementation for the integration called B2MML (business to manufacturing markup language). We refer to [4] for a basic introduction with a simple walk-through example on how to use it for scheduling. The standard offers supporting functions such as XML-schemas and many programming languages have built-in support to enable easy handling of XML data. All input information for a scheduling problem can be provided through B2MML. Similarly, the scheduling results are provided in the same format. Most common scheduling-related information is directly supported and can be complemented through extensions.



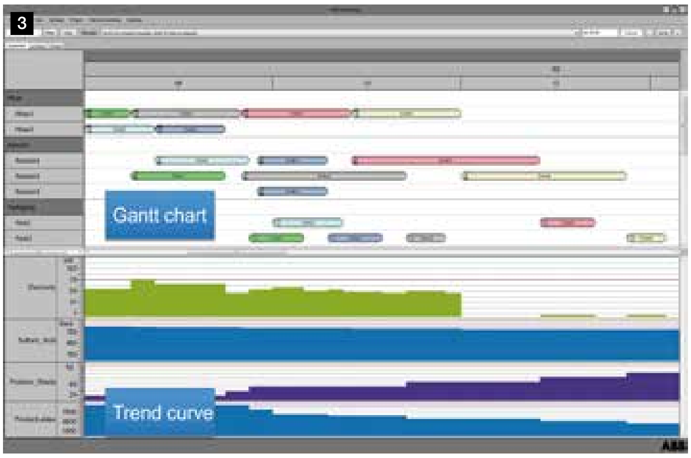


Figure 1: ISA-95 and B2MML elements providing full information required for scheduling. | Figure 2: Example of a workflow using B2MML data exchange. | Figure 3: Screenshot of the scheduling system. Above the typical Gantt-chart and below the trend curves for tracking electricity and material.

As can be seen in Fig. 1, information related to equipment, material, personnel, production recipes and production targets are included. The actual production situation is also communicated through the operations response data structures. The data is passed to the scheduling algorithm only through XML and this offers twofold flexibility: integrate the scheduling functionality and allow using various types of algorithms as the input data is neutral and usable to any selected solution approach.

In Fig. 2, an example of the workflow with B2MML is shown. First the data for scheduling is collected from various systems (left). The data can be offered by a push or pull principle. After executing the scheduling algorithm, the scheduling results are provided to a dispatching system, which interacts directly with the process. Ideally, the entire ISA-95 data can be stored in a common database, regularly updated by all related SW-components and thus keeping the data always up-to-date.

Algorithms

The prototype hosts a set of heuristic-based algorithms. This was a natural choice since the aim was to provide a fast-responding generic algorithm that does not necessarily reach the global optimum (best possible solution) but quickly finds a feasible and good solution. The algorithm can take into account all major equipment constraints, working hours, standard limitations in energy, material and personnel and the scheduling system can track the consumption of utilities as well as the use and production of material. A novel feature of the prototype is the manual drag-and-drop functionality and due to the fast performance it is possible to combine the automatic algorithm with the manual drag-and-drop functionality. The GUI components of the described scheduling system are provided by a third-party supplier [5]. The prototype also offers a purely manual-driven mode, where the decision logic is fully left to the operator without any repair actions. This is done by moving the orders using the drag-and-drop functionality. A sanity check is done against the production recipes; if violated the move is rejected. Alternatively, the manual actions can be supported by algorithms, for instance by rescheduling the complete schedule or parts of it based on the manually initiated change. The manual option allows to perform intuitive rule-based actions that would be too complex to reflect within a generic algorithm.

Thus, the scheduling solution can operate in various modes, from purely visual manual tool to complex algorithmic solver. It is also possible to extend the prototype with additional algorithms, which can be implemented in any .net language.

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```
- <OperationsSchedule xmlns="http://www.wbf.org/xml/B2MML-V05">
    <ID>Factory A schedule requests</ID>
    <Description>This example shows the schedule *after* optimization</Description>
    <StartTime>2012-08-30T08:00:00</StartTime>
    <EndTime>2012-08-30T17:30:00</EndTime>
    <ScheduleState>Forecast</ScheduleState>
    <PublishedDate>2012-08-30T07:40:00</PublishedDate>
  - <OperationsRequest>
      <ID>Order1</ID>
      <StartTime>2012-08-30T08:00:00</StartTime>
      <EndTime>2012-08-31T08:00:00</EndTime>
      <Priority>1</Priority>
      <OperationsDefinitionID>Chemical1</OperationsDefinitionID>
    - <SegmentRequirement>
        <ProcessSegmentID>Mix</ProcessSegmentID>
        <EarliestStartTime>2012-08-30T08:00:00</EarliestStartTime>
        <LatestEndTime>2012-08-30T08:30:00</LatestEndTime>
        <Duration>PT0H30M</Duration>
      - <PersonnelRequirement>
          <PersonnelClassID>Mixeroperator</PersonnelClassID>
          <PersonID>Mixeroperator-2</PersonID>
        </PersonnelRequirement>
      - <EquipmentRequirement>
          <EquipmentClassID>Mixer</EquipmentClassID>
          <EquipmentID>Mixer1</EquipmentID>
        </EquipmentRequirement>
      - <MaterialRequirement>
          <MaterialClassID>Electricity</MaterialClassID>
          <MaterialUse>Consumable</MaterialUse>
        - <Quantity>
            <QuantityString>30.0</QuantityString>
            <DataType>double</DataType>
            <UnitOfMeasure>kW</UnitOfMeasure>
          </Quantity>
        </MaterialRequirement>
      </SegmentRequirement>
    </OperationsRequest>
  - <OperationsRequest>
      <ID>Order2</ID>
      <StartTime>2012-08-30T08:00:00</StartTime>
```


Figure 4: Example of a B2MML file "OperationsSchedule". The text in black reflects the case-specific data and the ISA-95 standard tags are shown in red.

Configuration

The configuration mainly comprises creating the needed B2MML-files. The main benefits of using standards, such as ISA95, is to avoid problems on agreeing to the data model and this also makes it easier to communicate between systems from different vendors. An example of a B2MML file is shown in Fig. 4. Another aspect that speaks for the standard is that ISA-95 is per se becoming the industrial standard between ERP and the manufacturing layer and more and more professionals are trained in using B2MML. Therefore, maintaining more generic data for instance in an ISA-95 database is much easier than collecting data that is specifically aimed for a certain proprietary scheduling model.

Ideally, the B2MML data can be even used for modeling the scheduling problem in a more operator-friendly way for instance through some graphical user interface elements and using terminology that is closer to the operations.

Conclusions and further research

The ongoing technical trends are challenging the traditional automation pyramid hierarchy, where decisions are taken in a more isolated manner. As a consequence, more complex systems should become simpler to manage, as has happened within the mobile phone industry. Since scheduling is basically less worthy as an "island" solution, integration is the key. It is also important to align technology and business properly to ensure meaningful and valuable results. The natural "home" for a scheduling solution is within a production management system, where the short-term decisions are made and where the necessary process information is available. The prototype solution has been successfully tested on several example problems across industrial domains and shows a high benefit potential for many industries. The heuristic approach is scalable and flexible. Through the fast execution time it can act as an interactive solution and it is straightforward to model various requirements and possible to extend it according to future needs. Regardless of the hierarchical structure the main function and tasks of a scheduling solution remain: to visualize the process, support the decision-making ensuring that it is always up-to-date and help optimizing complex logic decisions.

Internal customer

Division Process Automation, BU Control Technologies, BU Process Industries

Contact

Dr. Iiro Harjunkoski
Phone: +49 (0) 6203 716014
Email: iiro.harjunkoski@de.abb.com

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Dicing the load – energy aware production planning in industry

Lennart Merkert, Dr. Iiro Harjunkoski

Many energy-intensive industries such as steel, pulp and paper and cement face the challenge of how to deal with the effect of increasing and fluctuating energy prices on daily production operations. New collaboration schemes offered to these industries through intelligent and flexible electricity networks (smart grids) significantly reduce total production costs by optimally timing electricity consumption. The main concern is how to make the production process flexible enough that a company can buy electricity when it is cheap – and even sell it back to the grid during peak hours. At perhaps a hundred times the purchase price. ABB has investigated and developed new approaches to this business proposition.

Replacing traditional stable and controllable energy sources with fluctuating renewable sources means energy supply and price can no longer be taken for granted. Because of this, market tools for purchasing and selling electricity have become almost a necessity for large consumers. Since the price of electricity has a direct impact on production cost, large consumers have also started to consider including energy forecasts in their production planning. This concept, coupled with energy efficiency, is called demand-side management.

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In contrast to energy efficiency strategies, which aim to produce the same using less energy, demand-side management focuses on profitable time-shifting of the load (Figure 1). In practice, this means that an industrial plant needs to adapt production according to the energy cost situation. If future electricity pricing information is available – and in this discussion will assume it is – many processes can take it into account in short-term planning or scheduling.

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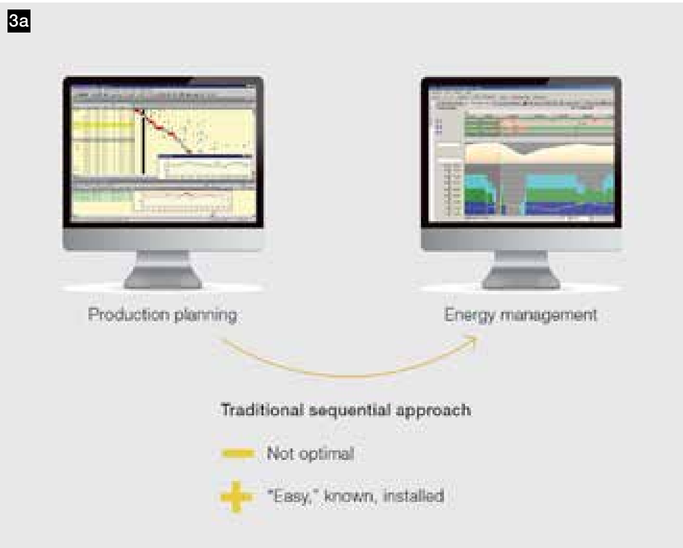

3b

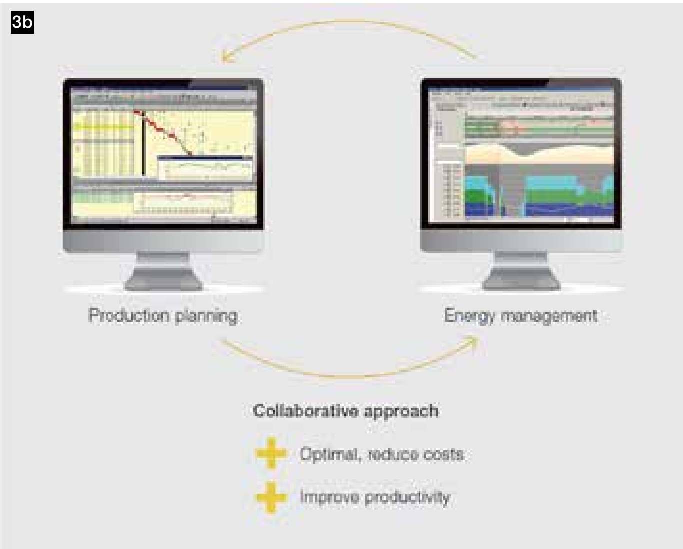

Figure 3a: Here, at least a partly prespecified production schedule is assumed. | Figure 3b: Here, the production schedule and the electricity purchase strategy are simultaneously or iteratively optimized.

Energy management solution

ABB already offers a solution for optimizing the energy portfolio for a given production plan: cpmPlus Energy Manager has been available for more than a decade and covers energy conversion (eg, fuel to energy), purchasing from various markets and also some production planning decisions – especially for continuous processes. The solution has been installed by many types of customers – including pulp and paper, metals and mining – as a part of ABB's collaborative production management (CPM) solution and has demonstrated significant benefits.

Figure 2 shows the cpmPlus Energy Manager Optimization solution for industries. A mathematical optimization is used to simultaneously consider all energy-consuming and energy-producing units together with the option of purchasing from or selling the energy to the grid based on current prices. The electricity consumption of the production lines is shown in the bar graph in the lower part of Figure 2 and the varying electricity price is indicated by the yellow line.

This example illustrates how a CPM solution can collect and connect information from various sources and generate the most cost-efficient production strategies, while also taking into account electricity costs. As the solution also includes other production units, it decides when to run which production line, taking into account, for example, total downstream steam demand, the capacity and cost of alternative steam sources, the production plan, and the minimum and maximum production limits of each production line.

Industrial demand-side management

ABB developed new concepts allowing industrial demand-side management (iDSM) by automatic optimization of the production schedule against the electricity costs. The first step toward the iDSM solution was to investigate the use of monolithic models for the integration schemes shown on the far right in Figure 3.

Figure 4 depicts the idea in which an additional time grid is added to the original scheduling formulation in order to check the electricity consumption in each of the slots formed. The electricity provider or the electricity market defines the energy price for each of these time slots (15 to 60 min). Theoretically, this holistic-model-based optimization may lead to a so called global optimum, ie, the best possible solution with respect to both the production and electricity costs. However, holistic models are very often complicated or impossible to solve within a reasonable time, so some refinement is required. In addition they do not represent the situation in many industrial plants where energy management and production planning is done in separate departments using different support tools.

Refining the models

In production processes that require multiple production steps, such as batch-oriented steel manufacturing, typically not all equipment is continuously occupied. This allows flexibility to adapt production according to energy management needs. Multistage production processes also usually have buffers to store raw material, and intermediate and final products – for limited periods of time. In the melt shop process, for example, intermediate products are very hot so inadequate coordination of subsequent production stages causes energy loss through cooling. Another constraint is that large electricity consumers commonly have to commit their forecasted load pattern upfront and suffer financial penalties for deviations from it.

In the work done by ABB, the continuous-time (exact) melt-shop scheduling model has been refined to take into account both the electricity price as well as deviations from a committed load curve. The benefit of this approach is that the energy considerations can be included in the original scheduling model by adding new decision variables to map the electricity consumption for each grid-defined time slot. This results in feasible solutions with clear energy savings potential. However, this basic approach is not efficient for more complex instances. Therefore, various alternative approaches have also been looked at including other modeling philosophies – eg, resource-task network – as well as decomposition algorithms.

Energy pricing and usage scenarios in steel production

Based on realistic data, a hypothetical case study has been carried out to investigate how strongly three different energy tariff scenarios might influence the energy bill for a typical 24-hour scheduling problem (Figure 5). The scenarios are each assumed to buy a fixed amount of electricity at a known rate using a base load contract. The total energy bill can be reduced by reselling any surplus electricity. The committed load aspect is also taken into consideration.

The first scenario represents a day with "normal" electricity prices in the volatile day-ahead market. When the scheduling driven by energy price is employed, the net electricity cost is around $ 110,000. The second scenario uses weather-driven prices, which result in an additional cost of $ 27,000. The third scenario ignores energy price considerations, ie, only production throughput is optimized – resulting in a cost double that of the second scenario. This demonstrates how much the plant could potentially save by collaborative scheduling and energy optimization on a day with extreme prices.

In this case study, energy-driven scheduling contributes to significant reductions of the electricity bill. However, comparison of the schedules of scenarios two and three clearly shows that the energy-driven schedule tries to avoid extreme prices of

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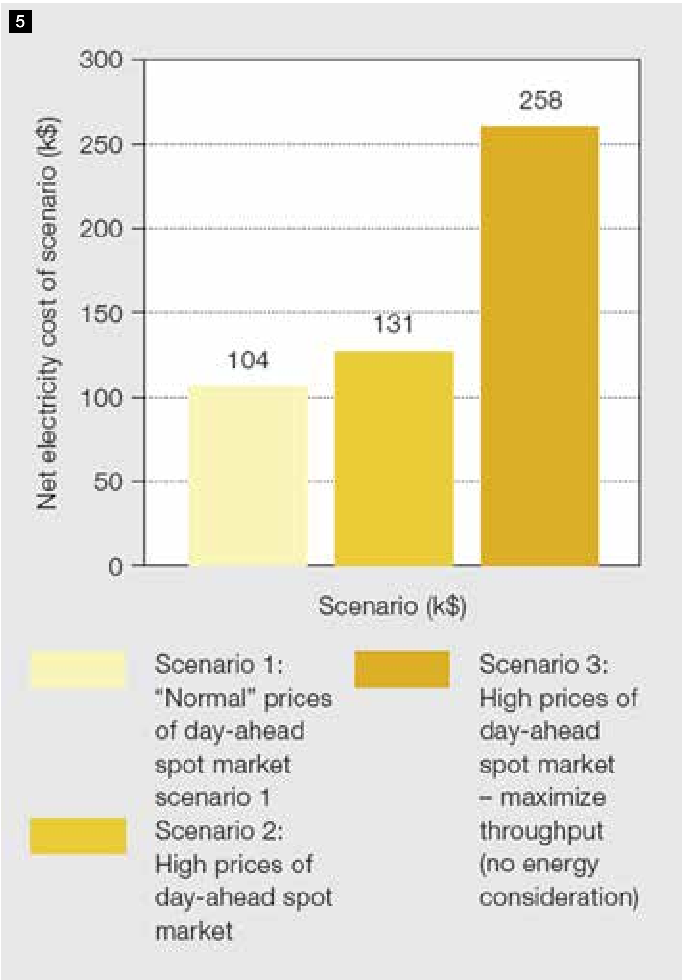
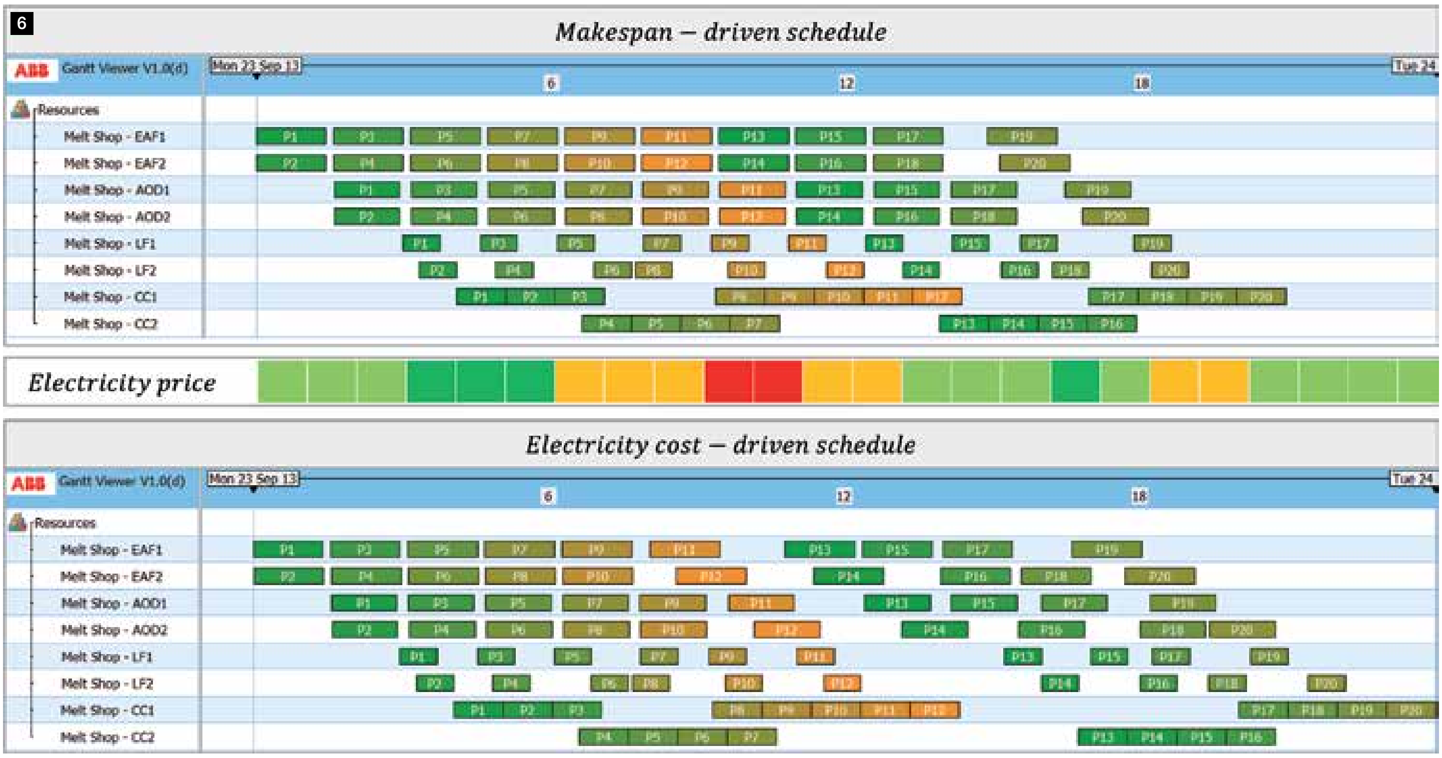


Figure 4: The grid delineating the electricity price time slots

Figure 5: Total electricity coast for various energy prices and optimization strategies



the peak hours (marked in red and orange in Figure 6) at the expense of extending the overall makespan (the total time needed for production) (Figure 6). Some of the production operations are delayed – perhaps incurring reheating costs. In the study, the cost of thermal losses has not been included in the savings calculation. However, with realistic cooling models it is certainly possible to account for potential costs that can be associated with production delays.

Demand side management in pulp and paper industry

Besides steel production ABB had a closer look on pulp and paper industry as well. A prototype for energy aware production scheduling using resource task networks was developed and tested with real world production and energy price data of a Northern European paper mill. The pulping process was studied in detail as thermo mechanical pulping is a very energy and electricity intensive process.

In thermo mechanical pulping the wood chips are split up into fibers with mechanical force. This process takes place in refiner lines that are powered by electricity. One refiner line easily consumes several MW of electric power. In most plants there are several refiner lines split up into two stages. The main refiners are the first production step in thermo mechanical pulping. Reject refiners are used to smoothen clumps that have not been crushed in the first refining steps. After this refining step the pulp is washed and bleached. Now the pulp is ready to be consumed by a paper machine producing paper. In order to decouple the different process steps usually there are pulp tanks after main refiners and before the paper machine in order to buffer in case of production stops of one unit. (Figure 7)

These pulp tanks offer flexibility that can be used for intelligent energy aware production planning. Using the industrial demand side management prototype to shift pulp production from high to low price times significant energy cost saving have been shown. Figure 8 shows a pulp production plan considering electricity price variations. With Nordpoolspot day ahead electricity prices from summer and winter 2014 energy cost savings of 5-10% compared to a conventional operation would have been possible. As price volatility on Nordpoolspot has been increasing in summer 2015 energy cost savings of up to 20% could have been achieved by the developed demand side management concept.

Flexibility is key

The complexity of production scheduling is increasing in many industries, mainly due to smaller and more customized orders. Production plants now have to be agile and flexible to respond to short-term changes. These industries also face the complexity arising from variable, but potentially more affordable, electricity pricing on an hourly basis in the day-ahead market. Consequently, combined energy and production planning processes must always be well integrated with real-time data.

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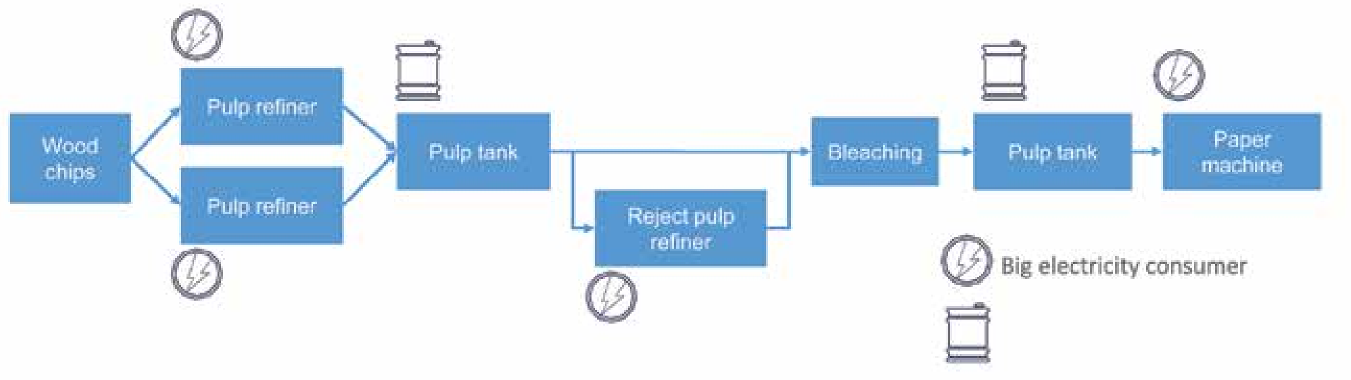

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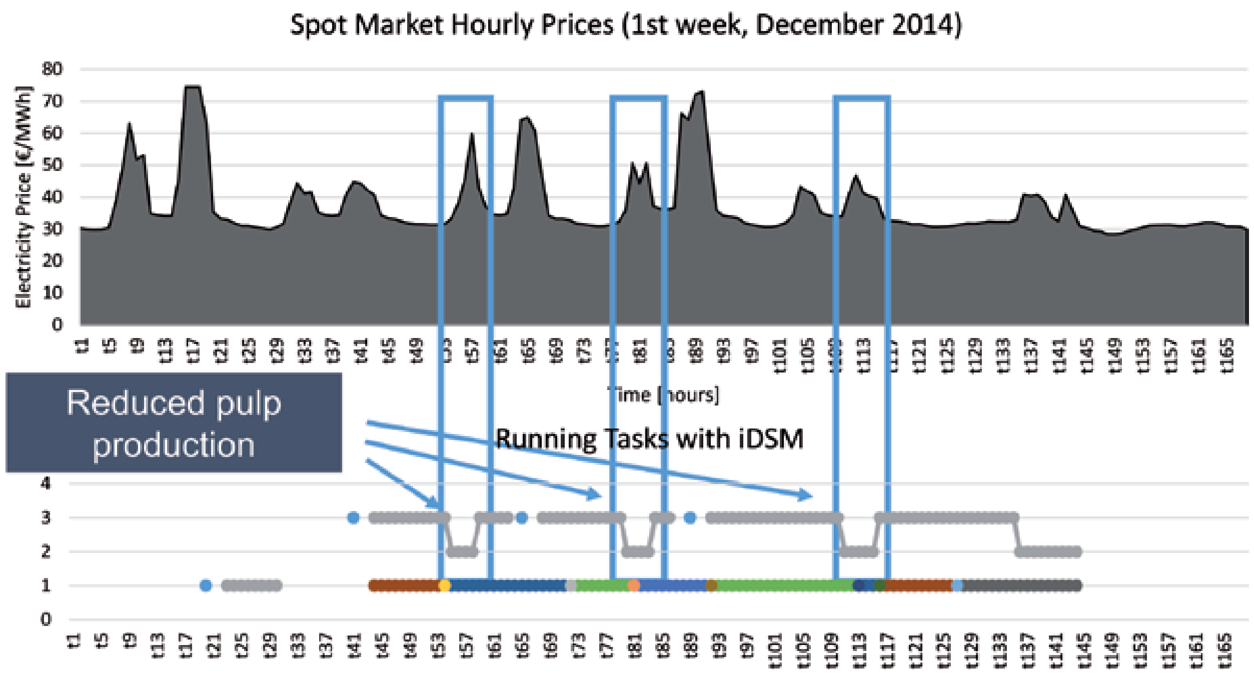


Having a full offering of process and grid automation, ABB has the tools to realize a proper matching of supply and demand using internal buffers in the process and production load shifting for a wide range of industries.

Internal Customer

Division: Process Automation
Business Unit: Process Industries

Contact

Lennart Merkert
Phone: +49 6203 71 6021
Email: Lennart.merkert@de.abb.com

Electro Active Polymers – Actuators with lowest energy consumption

Sebastian Breisch, Veronica Biagini, Ondrej Frantisek, Thomas Stahl, Holger Reutner

Dielectric elastomer actuators (DEAs) are an emerging technology that offers an attractive balance of work density and electromechanical efficiency relative to conventional actuators. Key benefit of this technology is the low power consumption compared to conventional actuators such as solenoids. Depending on the referenced operation, the power consumption can be 80% less than with conventional actuators. The basic physical principle shown in Figure 1 can be applied in different topologies and functionality has been demonstrated through many laboratory scale prototypes in various topologies and first niche consumer products.

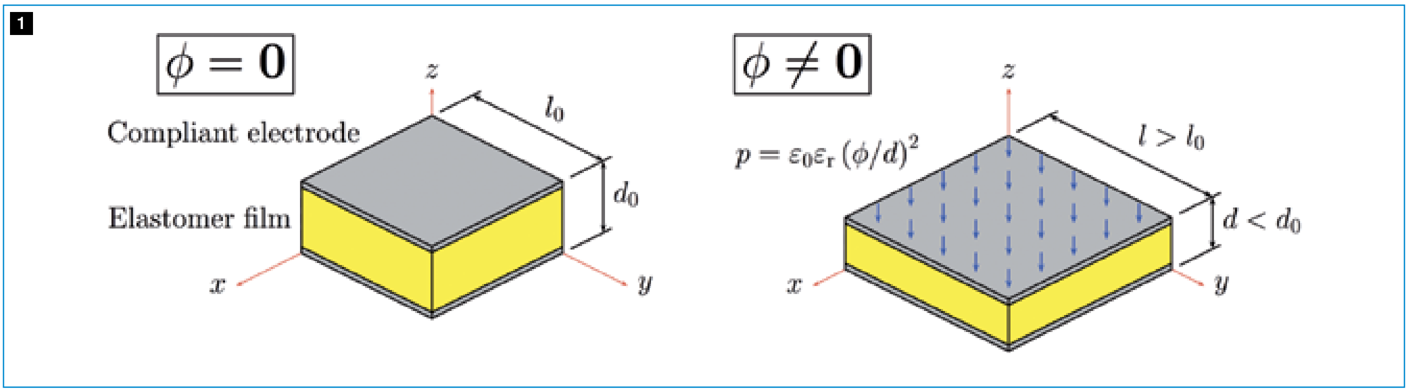
To power an actuator driving voltages of 1… 2,5 kV are required depending on the topology. At present there are no cost efficient power electronics available on the market to power capacitive loads. Therefore, several investigations on suitable schematics have been performed and a suitable power electronics based on a flyback converter was developed.

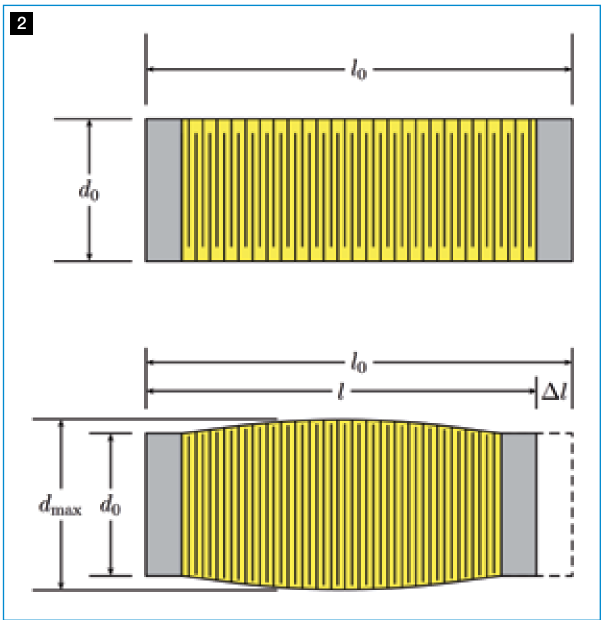
Dielectric Elastomer Actuators

As illustrated in Figure 1, DEAs consist of an elastomer film coated on opposing sides with a compliant electrode. The electroactive response is primarily attributed to electrostatic stresses defined by the "Maxwell pressure" across the membrane. This stress is related to both the electrical permittivity of the film and strength of the applied electric field. The mechanical deformations resulting from the application of this stress can be determined by the application of a suitable viscoelastic material law.

As it can be seen the principle in general is based on a capacitor, which explains the high power efficiency: Once the capacitor is charged (here equal to the deformed/actuated phase) no further power is required to keep that actuated status.

Beside the simple "on/off" functionality there is also the possibility to do position control. By metering the capacitance a feedback of the compression is provided which can be used for control algorithms or directly as a cheap and flexible "pressure sensor"





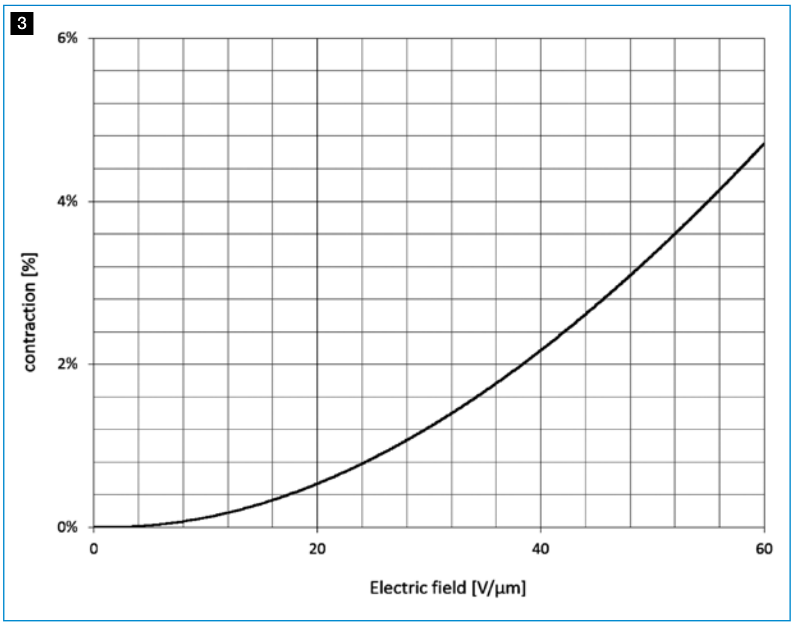


Figure 1: Principle of operation of dielectric elastomer film actuators | Figure 2: Stacked dielectric elastomer actuators offer a favorable balance of output force and stroke capabilities | Figure 3: No-load strain of a standard stacked actuator depending on the applied electric field (Voltage per thickness of dielectric material)

Today's thicknesses of the film are ≤ 50 µm and thereby the achievable strain in z-direction is negligible. In order to derive a usable stroke in the range of "mm "several approaches exist which lead to different topologies with different characteristics. At present the ABB focus is on two different topologies namely "stacked actuators" and "spring biased membrane actuators".

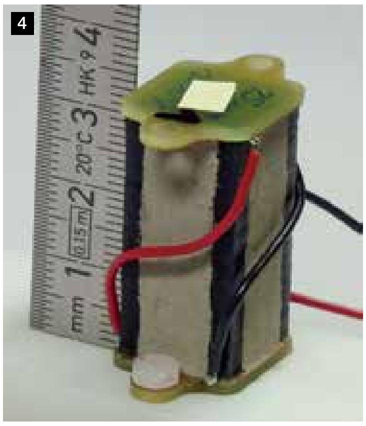
The conventional fabrication of a Dielectric Elastomer Actuator in general is to print an electrode onto an either molded and cured (dielectric) elastomer or use of pre-manufactured elastomers from a roll. In general this is done in a relative large scale, and the individual actuators are cutted afterwards to its final dimensions. Thereby this process is highly flexible and allows for dedicated actuators for individual use-cases.

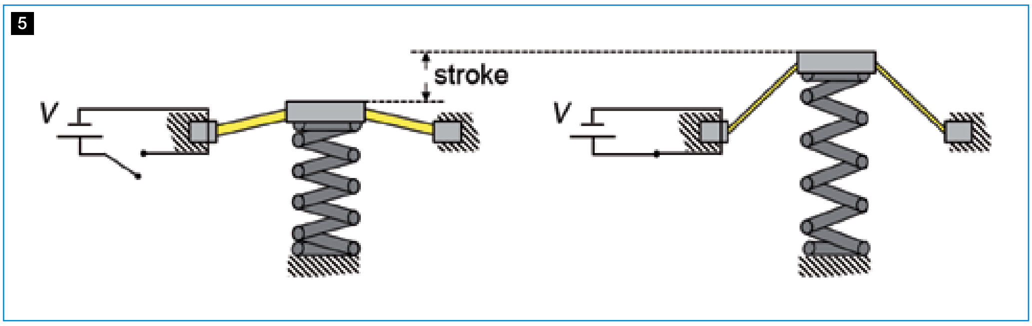
Stack Actuators

As illustrated in Figure 2, stacked dielectric elastomer actuators consist of multiple layers of dielectric elastomer membranes stacked or folded on top of each other and terminated by relatively rigid end-cap fixtures. This configuration has been shown to exhibit a favorable balance of force and stroke.

Depending on the applied voltage a contraction of the elastomer takes place. As it can be seen in Figure 3 the ratio of contraction is not linear but square to the applied electric field. The horizontal axis represents the applied voltage divided by the thickness of the dielectric layer (equal to the electric field).

Depending on the manufacturing process thicknesses between 15µm and 100µm can be handled with an accuracy and repeatability of an industrial level. To operate these actuators





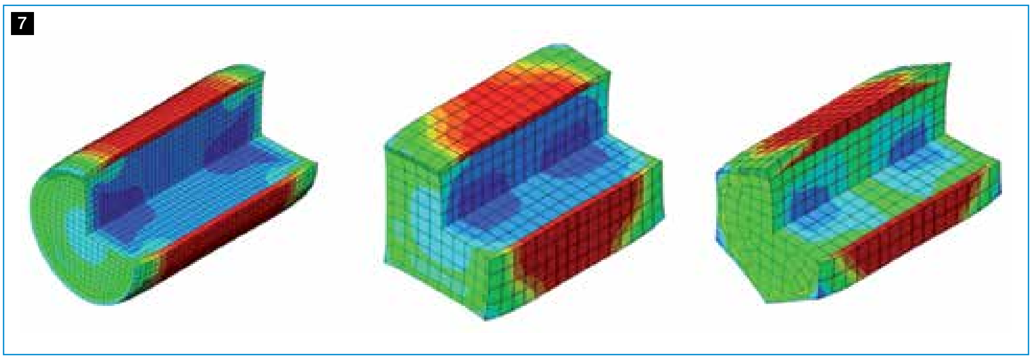


Figure 4: picture of a dielectric elastomer actuator (CT Systems) in stacked topology | Figure 5: schematics of a spring biased membrane actuator [4] Figure 6: picture of a dielectric elastomer actuator in membrane topology (here not spring biased) [4] | Figure 7: FEA Model of stacked dielectric elastomers in different geometries

voltages in the range of 1 kV … 2,5 kV are required. Since this voltage level cannot not be provided in a common industrial environment it is mandatory to have a dedicated power electronics to convert 12 V to e.g. 1,5 kV. Since costs for the power electronics raise with the required output voltage the general approach is to reduce the dielectric thickness to a manageable minimum. Limiting factor is both the mechanical handling of such small thicknesses as well as the “breakthrough voltage” of the dielectric material.

Spring biased membrane Actuators

Spring biased membrane actuators consist of a circular shaped dielectric elastomer (Figure 5 – yellow) with a compliant electrode on each side. On a stiff center part the mechanism is biased by a spring. As illustrated the “mechanism” elongates when a voltage is applied. The physical principle is exactly as described above: When a voltage is applied the Maxwell forces lead to a volume constant planar contraction and in plane elongation. Biased by the spring the center plate lifts. Beneficiary is to implement a spring with a negative ratio (NBS=“negative biased spring”) instead of a common helical spring as shown in Figure 5. Here the spring forces are higher when the spring elongates. This contributes to both a higher stroke and higher actuation forces.

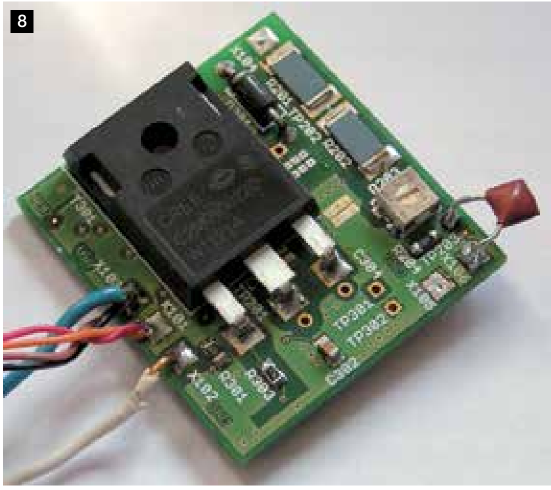
Testing and Simulation

Material parameters of DEA and other viscoelastic materials can be derived from results of common compression tests with two loading scenarios. Once material parameters are obtained a material model for finite element method software can be defined and performance can be simulated. For DEA a broad range of analyses and optimizations was carried out. Thereby it is possible to evaluate different sizes, shapes, behaviors in time etc. Simulation tools allows us thereby to analyze various design features without manufacturing of many prototypes. DEAs can be designed with desired properties and expensive and time demanding testing can be used only for proving concepts and fine tuning.

FEA Model of stacked dielectric elastomers in different geometries

Figure 7 shows the finite element analysis of different geometries. The here shown analysis was to investigate the effect of the outer shape in general. All geometries were defined with the same height and a characteristic dimension “d”, which was the diameter for the circular shape, side length of the square and diameter of the inscribed circle of the hexagonal shape. The colors indicate the stress distribution.

A variety of DC-DC converter topologies (potentially unidirectional or bidirectional) were investigated, based on work by



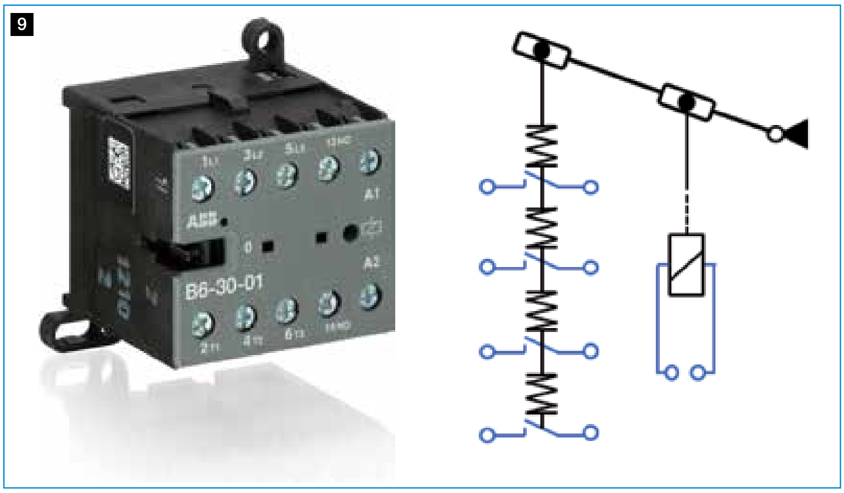
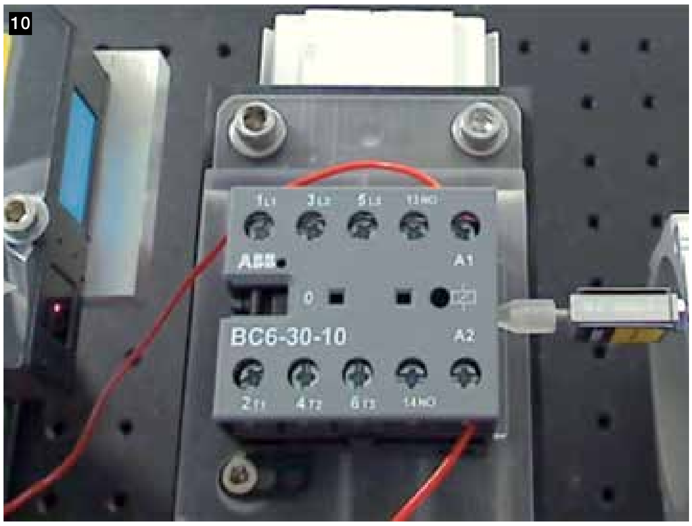


Figure 8 Developed power electronics based on a flyback converter
Figure 9: Low-voltage switching products are prime candidates for high-efficiency DEAs | Figure 10 Laboratory testing of low voltage switch [4]



Eitzen, Graf, and Maas [1]. Such topologies included flyback converter, IBFBC (isolated boost full bridge converter), and DAB (dual active bridge).

Due to the significant complexities of controlling IBFBCs and DABs and based on the findings and conclusions in [1] the flyback converter was finally chosen as being the most suitable and feasible schematics.

A prototype was developed to provide an adjustable output voltage between 400V and 1.5kV operating with an input supply voltage range between 24V and 60V. In addition, the prototype was designed to fulfill the demanding dimensional constraints defined for a selected Low Voltage switching application. Although the upper range of 1.5 kV is likely insufficient to fully actuate all current DEA topologies, it was deemed a suitable compromise of costs and performance. As described above the driving voltage for future DEAs is expected to be continually reduced as technology and processing improves. At present the complete joint function of DEA and power electronics module has only been proven for stacked topology (spring biased membrane actuators have a driving voltage of 2,5 kV at present) [3].

Major Results to Date

The project is to evaluate the technology of dielectric elastomer actuators in general as well as the readiness for future product implementations. Based on one suitable product application the technology is characterized in terms of provided stroke, forces, response time, temperature range, lifetime and long-term behavior. Furthermore manufacturing readiness for mass production, costs, production stability and repeatability are observed. In the second step further potential product implementations will be evaluated.

Two configurations of DEAs have been observed and tested. Therefor the investigation was split into a DECRC internal project and a public funded project called “DIELASTAR” which will end by end of May 2016. The technology in general consist always of both the actuator and the required power electronics. Conclusion to date is that the technology definitely is a potential future actuator technology. As an assumption further 3…5 years are expected to reach an industrial level and a state for mass production.

Customer and ABB Internal Benefit

Conventional low-voltage switching products utilize electromagnetic actuators that dissipate significant amounts of energy in the form of heat while the control circuit is energized. Conversely, leakage currents are typically very small for DEAs and thus they offer superior electrical efficiency as a

Draft overview of characteristics of observed actuators:

	Stacked configuration	Spring loaded membrane configuration
actuation	Position Control & Bi-stable (On / Off)	Position Control & Bi-stable (On / Off)
Standard actuator stroke*	0,1…1,5 mm	0,1…5 mm
Standard actuator force*	4…10 N	0,05…50 N
Response time**	5…50 ms	1…10 ms
Actuation frequency	≤ 100 Hz	≤ 150Hz
Standard driving voltage	≤ 1500 V	2500 V

* nominal values are to have an impression on the performance. Performance might vary and be further developed for special use cases
** limiting factor is speed of power electronics to reach a certain voltage (depending on capacitance of DEA)

clear benefit. This improved efficiency cuts the electric power required to operate the device while simultaneously eliminating undesirable heat dissipation, and thus overall system costs are reduced.

Internal Customer

Division: Electrification Products
BU: Protection & Connection

Contact

Sebastian Breisch
Phone: +49 (0) 6203 71 6353
Email: sebastian.breisch@de.abb.com

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Contact us

ABB AG Forschungszentrum Deutschland
Wallstadter Str. 59
D-68526 Ladenburg
Phone: +49 (0) 6203 71-6400
Fax: +49 (0) 6203 71-6103
berthold.schaub@de.abb.com