# Proceedings of the 2nd Annual SMACC Research Seminar 2017

**Citation**
Aaltonen, J., Koskinen, K., Virkkunen, R., & Kuivanen, R. (2017). Proceedings of the 2nd Annual SMACC Research Seminar 2017. Tampere: Tampere University of Technology.

**Year**
2017

SMACC
DIGITAL BOOST FOR FINNISH INDUSTRY

# Proceedings of the 2nd Annual SMACC Research Seminar 2017

Jussi Aaltonen, Riikka Virkkunen, Kari T. Koskinen & Risto Kuivanen (eds.)

Tampereen teknillinen yliopisto - Tampere University of Technology

Jussi Aaltonen, Riikka Virkkunen, Kari T. Koskinen & Risto Kuivanen (eds.)

# Proceedings of the 2nd Annual SMACC Research Seminar 2017

Tampere University of Technology

Tampere 2017

ISBN 978-952-15-4040-0

**TABLE OF CONTENTS**

## FOREWORD

The Annual SMACC Research Seminar is a forum for researchers from VTT Technical Research Centre of Finland Ltd, Tampere University of Technology (TUT) and industry to present their research in the area of smart machines and manufacturing. The 2nd seminar is held in 7th of November 2017 in Tampere, Finland.

The objective of the seminar is to publish results of the research to wider audiences and to offer researchers a forum to discuss their research and to find common research interests and new research ideas.

Smart Machines and Manufacturing Competence Centre – SMACC is joint strategic alliance of VTT Ltd and TUT in the area of intelligent machines and manufacturing. SMACC offers unique services for SME`s in the field of machinery and manufacturing – key features are rapid solutions, cutting-edge research expertise and extensive partnership networks. SMACC is promoting digitalization in mechanical engineering and making scientific research with domestic and international partners in several different topics (www.smacc.fi).

Tampere 26th of October, 2017

Editors

# I LIFECYCLE MANAGEMENT

# 1. DIGITAL ASSET MANAGEMENT SERVICE OFFERING AS AN INTEGRATED PART OF CUSTOMERS' BUSINESS

Toni Ahonen, Jyri Hanski & Pasi Valkokari
VTT Technical Research Centre of Finland
Toni.ahonen@vtt.fi

## ABSTRACT

Large Finnish technology companies had already started developing knowledge-based services long before any widespread discussion of the topics of digitalization or the industrial Internet had appeared. However, one key problem is that the service development has included rather product-centric practices and real integration to customers' processes has not often taken place. While customer's decision-making processes have remained unknown and the real potential of the service offerings underexploited, many companies have also developed ICT solutions from the perspective of bilateral partnerships, neglecting the customers' multi-vendor problematics and needs for integrated solutions. Current paper discusses the challenges of digital asset management service development from the perspective of how these services are connected to the customers' asset management processes and systems. Furthermore, we discuss the needs for finding the optimal development practices, thus finding the balance between long-term visions and rapid experiments and developing the new digital capabilities in-house.

## INTRODUCTION

The impact of the Industrial internet and digitalization is expected to be systemic in many industries. Therefore, understanding the business environment and the networked nature of the business is crucial. Although the literature does include a number of examples of digitalization in asset management (e.g. Baines & Lightfoot, 2013; Lee et al. 2015), there are relatively few examples of thorough transformations involving the efficient integration and exploitation of digital channels of data in industrial environments.

While many of the impacts of digitalization are difficult to predict beforehand due to their systemic nature, many companies have adopted productivity, lead times, features, quality and cost as the drivers behind the creation and development of digital concepts (Sommarberg 2016). In order to effectively develop services, one needs to understand how value related to these topics can to be created and how customers' assets are to be managed. There is a risk of individual tools being isolated from the customers' business processes and remaining underexploited, despite their potential of creating customer value. Thus, creation of novel digital solutions requires thorough understanding at strategic, tactical and operational levels.

## CONSIDERATIONS ON CREATING DATA-BASED DIGITAL SERVICE OFFERINGS

Development of digital asset management services calls for new capabilities in the organization. Understanding the customer needs and the requirements related to the networked business environment is in the core of the development. The transition from bilateral partnerships towards business ecosystems is challenging the companies to think differently. Furthermore, the company networks produce lots of data, which are rarely efficiently integrated in the decision-making processes in the ecosystem. Thus, in addition to the understanding of the networked business environment, we find the capabilities to integrate the various sources of data as the core competitive advantage of the future asset management ecosystems.

In addition to the organizational capabilities, understanding of the phenomena related to the customer's production environment is crucial. According to our findings, service development needs to address the following generic trends and to define the approach to respond to them:

- increase in automation level and the step-wise approach towards autonomous systems
- value-based business models and earning logics in a business network
- from analytics-based and consultative services towards AI-based automated decision-making processes

## FROM DISTINCT SERVICES TOWARDS INTEGRATED ASSET MANAGEMENT SERVICE OFFERING

Companies often collaborate in large business ecosystems in order to maximise the value creation. Customers are offered a variety of services, platforms and digital tools. Making all the solutions work together and integrating all the new solutions with the older ones and the strategic, tactical and operational practices of the company is a challenging task. Development of data-oriented digital tools is often seen as a straight-forward software development effort where agile practices and quick experiments have been found important. However, OEMs have limited knowledge of the complexity of the customers' process. Therefore, development is too often carried out with a narrow perspective. From customers' point of view, the selection and development of the service platform should be done very carefully in order not to reduce the future opportunities. Table 1 presents the scenarios that define the OEM's role with respect to service offering and IT solutions.

*Table 1. Scenarios for OEM with respect to service and IT solution development (based on Kortelainen et al. 2017).*

| Service strategy | IT solution strategy |
|---|---|
| OEM companies develop their information or knowledge based offering mainly to support the customer´s daily operations. | OEM focuses on the provision of measurement solutions, on-board analytics tools and data transfer technology to enable the provision of asset level data. |
| OEMs and service providers develop the excellence in refining data in a way that delivers more value to the asset owner. | OEM companies build the analytics capabilities and integrate the resulted information-based service in the platform used by the end customer. |
| OEM companies take the responsibility of managing and optimising the performance of customers' assets in the business ecosystem. | OEM builds the capabilities for the provision of platform for managing the data and the services in the network. |

There are a number of operational asset management processes, such as spare parts order and delivery processes, maintenance processes and customer support, that can be supported by digital technologies. Both larger and smaller OEMs have started development of new tools for supporting these processes. This may not have to be dependent on the choices made related to the above-described service and IT strategies. The fact that customers are different in their needs, requires that OEMs need to be adaptive in how they integrate to customers' processes. Thus, while OEM develops the digital toolset, it needs to be carefully planned how these tools are integrated in the customers' processes and IT infrastructure. Figure 1 shows an example of the various sources of data in customers' production environment and the needs for integration at 1) operational, 2) tactical and 3) strategic levels.

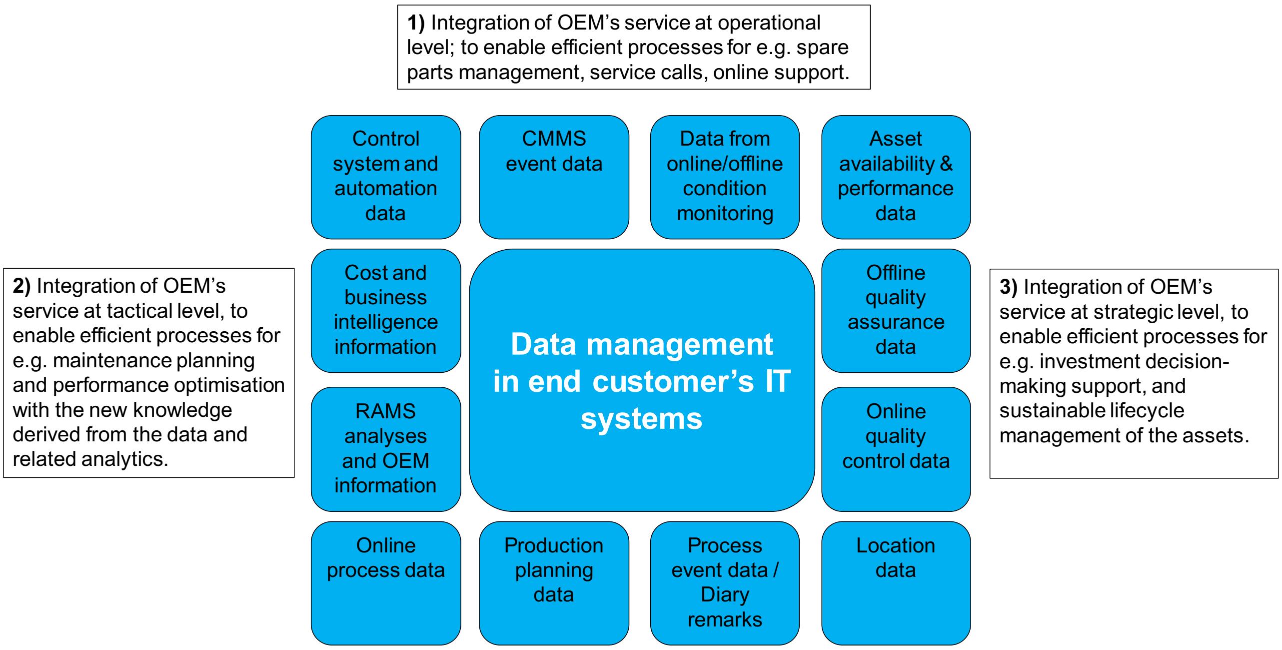


*Figure 1. Example of the need for integrating different sources of data and the services of OEM at strategic, tactical and operational levels.*

## CONCLUSIONS

In order to develop successful digital asset management services, OEM company needs to understand the complexity related to the business ecosystem, various sources of data, decision-making levels and service and IT strategies. Therefore, OEM company needs to understand how digital asset management services are integrated into customers' decision-making, asset management processes and IT infrastructure.

## REFERENCES

Baines, T. and Lightfoot, H.W. (2013), "Servitization of the manufacturing firm", International Journal of Operations & Production Management, Vol. 34 Iss. 1, pp. 2-35.

Kortelainen, H., Happonen, A. and Hanski, J. (2017). "From asset provider to knowledge company - transformation in the digital era", WCEAM 2017 Conference, Brisbane, Australia, 2.-4. August 2017.

Lee, J., Bagheri, B. and Kao, H-A. (2015), "A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems", Manufacturing Letters, Vol. 3, pp. 18–23.

Sommarberg, M. (2016), "Digitalization as a Paradigm Changer in Machine-Building Industry", (Tampere University of Technology. Publication; Vol. 1436). Tampere University of Technology

# 2. MACHINE PERFORMANCE AND AVAILABILITY PREDICTION THROUGH THE LIFETIME

Päivi Kivikytö-Reponen, Risto Tiusanen, Jari Halme, Kalle Raunio, Olli Saarela
VTT Technical Research Centre of Finland Ltd, Machine Health Team
paivi.kivikyto-reponen@vtt.fi

## ABSTRACT

Machine performance, availability and long lifetime play important role in operations and maintenance planning for industrial players e.g. with heavy working machines. Recently, circular economy discussions have even more highlighted the role of the maintenance and lifecycle design from the efficiency and sustainability perspective. [1] The new technologies are considered enablers for circular economy change e.g. additive manufacturing enables advanced solutions for both functional optimization and local manufacturing, furthermore the increased intelligence of the products and the data availability during the whole lifetime enable reliability and predictability of machine performance.

The manufacturing companies have a crucial role for implementing these changes into the products and machines they produce. Furthermore, in machinery industry, change from single machines to automated machinery fleets brings new challenges for safety, reliability and maintenance; autonomy in mobile machine applications will increase and operator-assisting technologies will be widely utilized. New energy supply systems in machinery, like hybrid technologies, full electric and fuel cell systems are coming to mobile work machines as well. We concentrate in this paper to the importance of early state concept design, design for maintenance, reliability, availability and safety and how significant advantages in Overall Equipment Effectiveness (OEE) can be gained through hybrid modelling and an increased understanding of the system's behaviour throughout its whole life cycle.

## INTRODUCTION

Increased awareness of sustainability and new profitable circular (economy) business models are currently under discussion. Circular (economy) design strategies heavily include product longer life, life extension strategies and product maintenance strategies. Still longer product life strategies such as, reparability, refurbishment, remanufacturing are currently underdeveloped. [2]

Data-driven modelling, including "Deep Learning" and "Big Data Analytics" receives currently significant business focus and publicity. It has proven successful in several application areas. Further challenge is to integrate detailed knowledge and data through the lifecycle in all levels (e.g. application domain knowledge with measurement data etc.) for product lifetime optimization, maintenance and operation optimization and in order to identify new risks and probable failures, and to prove system safety and availability. New systemic concepts and tools increase understanding of the systemic challenges, e.g. in System Integrated Metal Production [3] show example for solving recycling related challenges.

## NEW CONCEPT DESIGN - NEW OPPORTUNITIES AND NEW RISKS

Novel technology access to market and customer satisfaction, with confidence of safety and reliability in the first of the kind implementations will create new business opportunities and improves profitability in the machinery business. Especially safety needs to be ensured in all circumstances when developing new technology. Systematic concept design and systemic risk assessment approach supports the development of new technology, including traceable documentation throughout the development and decision making process. It is essential to find new opportunities for longer machine lifetime, to identify uncertainties and risks in new technologies involved and find solutions to control risks already in concept design level for managing lifecycle costs and optimizing profit.

## DESIGN AND MANUFACTURING FOR MAINTENANCE

Investment in the predictive maintenance increases the considerably safety, reliability and availability of the machine or fleet. The goal of maintenance is to avoid the failures typically by using sensor data to monitor a system. The knowledge and data from maintenance and operation conditions are vital information for system understanding. Machine design process generally combine the data related to lifecycle (design-manufacturing-use/operations-remanufacturing-reuse/operations-end-of-life), unfortunately this data can be partly lacking, especially in new technology launch. Still deep application domain knowledge, understanding of the machine performance during multiple operation conditions and available on-line monitoring history date would give additional input towards the design and engineering.

Additionally design and manufacturing lay ground for maintenance and machine operation optimization. Novel product data and operational data management including predictive maintenance may require re-design starting from early steps of product design process in order to re-built and manufacture built-in maintenance and predictive capabilities seamlessly into the machine. These could be e.g. embedded intelligence, on-line measurement systems inside the structures etc. integrated into structures in a manufacturing phase.

## KNOWLEDGE DRIVEN OPERATION AND MAINTENANCE PREDICTION

Measurement data together with application domain knowledge provide a key basis for optimizing both machine operation and maintenance (O&M). Significant advantages in Overall Equipment Effectiveness (OEE) can be gained through an increased understanding of the system's behaviour throughout its whole life cycle and anticipating the wear, corrosion, fatigue and other failures of machines, structures, and process parts. In practise for example the fracture mechanics equations and interpretation of acoustic emission signals from the structures and the material dislocation movements are combined for increasing phenomena understanding for maintenance purposes.

Data-driven models are in general fast and cheap to develop, and can consequently be developed for most applications with a fixed amount of resources. For machinery O&M, however, the data-driven approach utilizes only part of available information. In hybrid modelling, data analytics and knowledge of machine design, its operating characteristics, and degradation mechanisms are used to supplement each other. This combination of the application data through lifecycle provides a significantly more reliable basis for analytics by, e.g., reducing sensitivity to data quality and representativity issues. Even though large amounts of data are continuously accumulated from machine fleets, the problem space spanned by possible operating and load histories of mobile machinery, different machine designs and instrumentation setups, and potential (possibly multiple simultaneous) failure modes cannot be covered by any practical data set. The relative strengths of the modelling approaches are depicted in *Figure 1*.

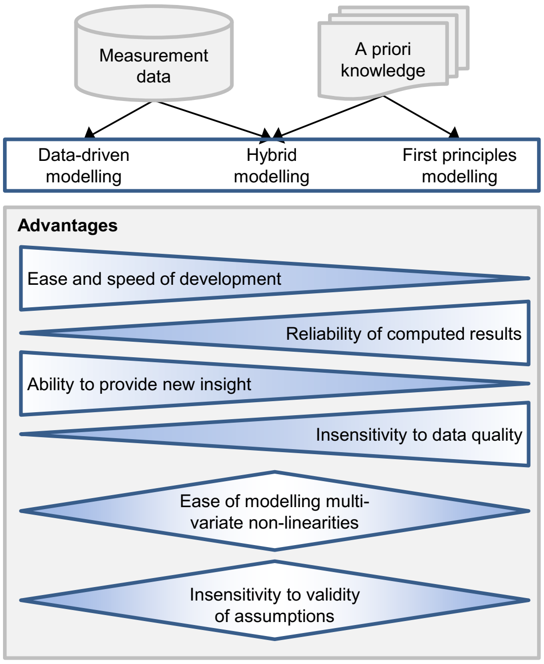


*Figure 1. Hybrid modelling combines data-driven and first principles modelling, balancing the relative advantages of each.*

## CONCLUSIONS

Systemic thinking and data-driven tools with application data through the lifecycle can be seen as enabler for solving and understanding systemic challenges in design, operations and maintenance in macro, meso and even micro level. Data-driven modelling has proven successful in several application domains. Furthered with system approach, combining the domain data to the measured data, the next step in performance understanding and predictions can be reached by utilizing hybrid modelling. In hybrid modelling, data analytics and knowledge of machine design, its operating characteristics, and degradation mechanisms are used to supplement each other. Integration of detailed knowledge and data through the lifecycle will increase the safety, reliability and more accurate failure predictability.

## REFERENCES

[1] Circular Economy System Diagram14.10.2017
https://www.ellenmacarthurfoundation.org/circular-economy/interactive-diagram
[2] Conny Bakker et al. Journal of Cleaner Production, Volume 69, 15 April 2014, Pages 10-16, http://www.sciencedirect.com/science/article/pii/S0959652614000419
[3] Markus Reuter, Plenary lecture, Recycling Metals from Industrial Waste. A Short Course and Workshop With Emphasis on Plant Practice June 23 - 25, 2015.

# 3. ENHANCED MODELLING CONCEPT AND COMPUTING PLATFORM FOR SYSTEM LIFECYCLE ANALYSES

Jussi-Pekka Penttinen, Arto Niemi, Kari Koskinen, Eric Coatanéa
Tampere University of Technology, Mechanical Engineering and Industrial Systems
jussi-pekka.penttinen@tut.fi

## ABSTRACT

This paper introduces an open modelling concept for system availability and reliability studies and a compatible distributed computing platform. Uniquely our approach allows combining and connecting risk assessment and operation models defined with different techniques. This ensures a high degree of freedom to accurately describe the modelled system. The concept also supports to include custom process performance indicators for example to measure manufacturing productivity. We use Monte-Carlo methods to create versatile analysis results. The vast and complex models require heavy calculations especially for sensitivity analyses. As a solution we create a parallel computing environment to permit very efficient simulations. We see high potential in using our approach in performance, energy efficiency and system lifecycle analyses of industrial processes.

## INTRODUCTION

Risk assessment and probabilistic safety analyses have a long history in systems engineering [1]. Same techniques can be used for assessing lifecycle performance of production and manufacturing processes. For these analyses industry favours Overall Equipment Efficiency (OEE) [2] as the Key Performance Indicator (KPI). The OEE depends on reliability and availability but might not be direct result of them. This was the case in CERN collider operations [3], which motivated us to define an Open Modelling concept for Availability and Reliability of Systems (OpenMARS). The concept is created in collaboration with CERN, Tampere University of Technology (TUT) and risk analysis expert company Ramentor Oy. The special needs recognized in modelling CERN particle accelerators are combined with the decade long experience [4, 5] in modelling of concrete use cases that go beyond the scope of traditional risk assessment techniques.

The OpenMARS concept allows defining models with the most common risk assessment modelling techniques [6], such as Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), Markov analysis, Failure Mode and Effects Analysis (FMEA) and Petri Net (PN). Furthermore, our approach is scalable and open to support additional modelling techniques and their combinations. This allows to collect all the information to a comprehensive Reliability, Availability, Maintainability and Safety (RAMS) model. Figure 1 illustrates how the RAMS model, technical performance and design requirements can affect each other and form the information for the system design and development. This information allows to compare different KPIs of alternative scenarios and designs.

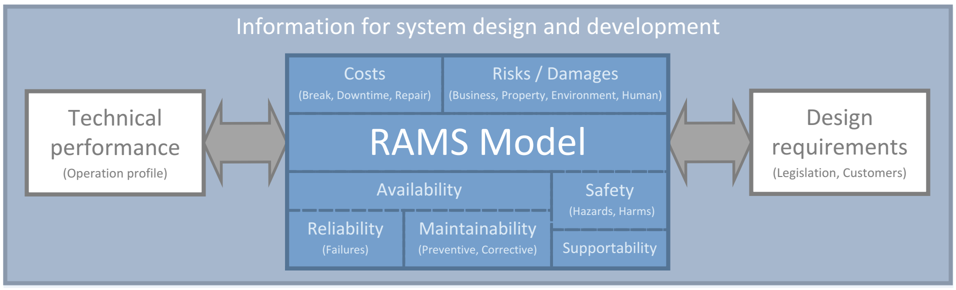


*Figure 1. RAMS model is an integral part of the system information*

Various data formats exist for the definition of RAMS models [7, 8]. The OpenMARS uses an object-oriented approach that allows to use single data format for definition of all techniques. As illustrated in Figure 2, this makes it possible to create single calculation engine for Stochastic Discrete Event simulation (DES) to produce detailed, concrete and explicit results from models made with any technique.

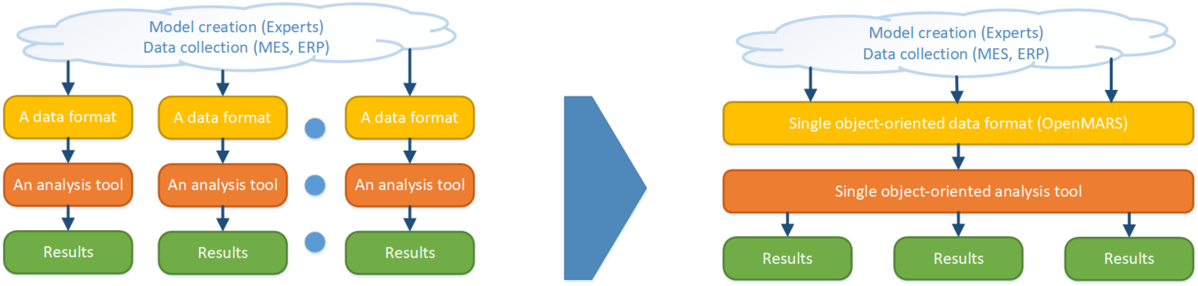


*Figure 2. Single data format and calculation engine for various modelling techniques*

## OPEN MODELLING CONCEPT FOR AVAILABILITY AND RELIABILITY OF SYSTEMS

The OpenMARS models consist of elements that have classes. The class defines which kind of attributes the element has. Each risk assessment modelling technique has a catalogue of available classes. The goal is that the most cases should be covered with them. To guarantee that the framework is always applicable, the expert users are allowed to extend the model specific classes to tailor them for their specific needs. For example new KPI can be added by introducing a new class for the framework.

The OpenMARS defines models in tabular format. Tables are natural way to store the models into a database and can be used for example to efficiently define vast models with repetitive structures [9]. The model tables are platform independent and human readable. The Figure 3 illustrates how the user selects the studied approach and analyses the model. The OpenMARS database collects the expert knowledge and links to other databases containing for example history data. Optimally the results of the calculation jobs are stored again to the database.

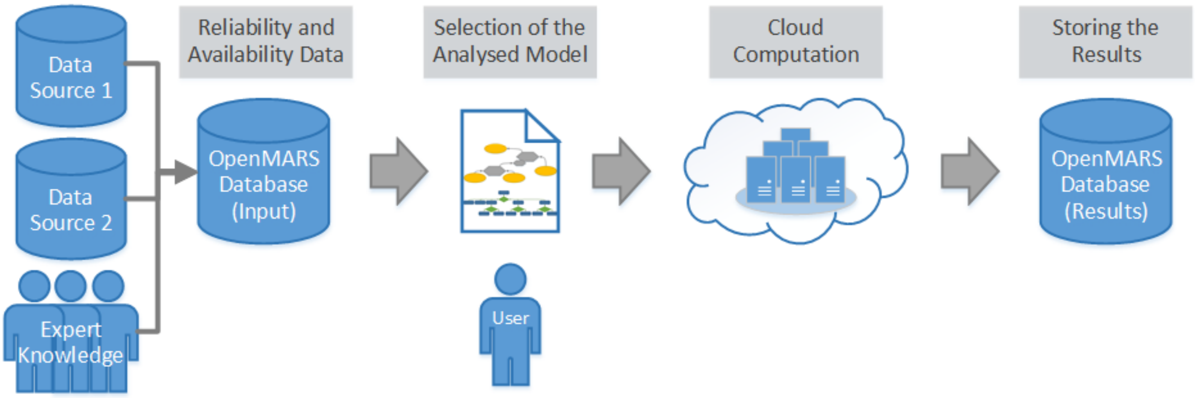


*Figure 3. The computing and data storage environment*

The model for CERN collider operations [3] required to combine semi-Markov operations model with a fault tree. The active operational phase can change the failure probabilities and the failure events can activate a Markov transition. In our model the KPI is the collision production, which depends on time spend on certain operation phase. However, this is not a linear relation. A custom mathematical function is required to calculate this specific KPI. Our aim for OpenMARS is to form an object-oriented approach that can support common standard techniques. We also give the expert users a possibility to tailor the methods, which makes the approach expandable.

## CALCULATION ENGINE FOR STOCHASTIC DISCRETE EVENT SIMULATION

The object-oriented framework is designed to decouple the model specification and the simulation engine from user-interfaces and custom user-supplied code. The Monte Carlo simulation based assessment of a system is parallelizable in a distributed computing cluster leading to simulation speedup by a factor 10 to 100. Very efficient calculations can be made remotely from any location with the layout illustrated in Figure 4.

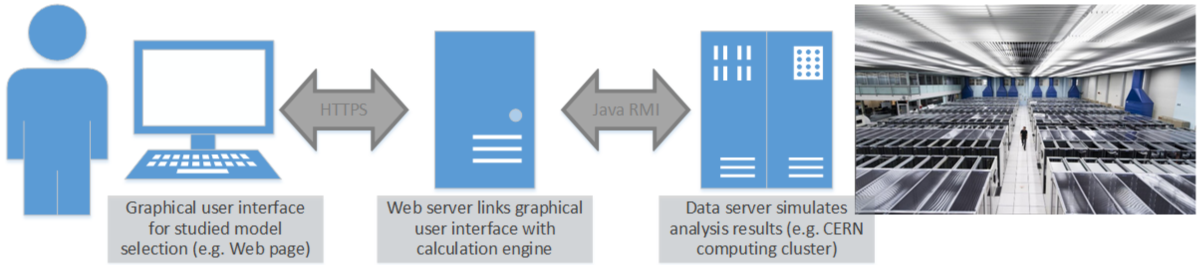


*Figure 4: Distributed computing environment*

## CONCLUSIONS

OpenMARS approach allows combining models made with common standard risk assessment techniques and permits tailored features for special needs such as defining specific KPIs. The approach is suitable for distributed computing environment, which can vastly speed up the Monte Carlo simulations. The adaptability of our approach for different modelling cases makes it very efficient for complex system life cycle analyses and we see high potential in further applications of our approach.

## REFERENCES

[1] W. Vesely, F. Goldberg, N. Roberts, and D. Haasl, Fault Tree Handbook (U.S. Nuclear Regulatory Commission, Washington, 1981).
[2] T. Kanti Agustiady and E.-A. Cudney, Total Productive Maintenance: Strategies and Implementation Guide (CRC Press, Boca Raton, 2015), p. 111.
[3] A. Niemi et al. Phys. Rev. Accel. Beams 19 (2016) 121003.
[4] S. Virtanen, P.-E. Hagmark and J.-P. Penttinen, Proc. of the RAMS ’06. Annual Reliability and Maintainability Symposium, (IEEE, 2006), pp. 506–511.
[5] J.-P. Penttinen and T. Lehtinen, Proc. of the 10th World Congress on Engineering Asset Management (WCEAM 2015), (Springer, Cham, 2016), pp. 471–478.
[6] European Committee for Electrotechnical Standardization, Risk management. Risk assessment techniques, EN 31010:2010, (2010).
[7] E. Steven and R. Antoine eds. Open-PSA Model Exchange Format (The Open-PSA Initiative, 2017).
[8] International Organization for Standardization, High-level Petri nets -Part 2: Transfer format, (2011).
[9] O. Rey Orozko et al. Proc. 7th Int. Particle Accelerator Conf. IPAC’16, (JaCoW, 2016), pp. 4159–4162.

## 4. LIFETIME ASSESSMENT FOR MECHANICAL COMPONENTS

Satu Tuurna, Pertti Auerkari, Timo J. Hakala, Anssi Laukkanen, Sanni Yli-Olli
VTT Technical Research Centre of Finland Ltd.
Satu.tuurna@vtt.fi

### ABSTRACT

Lifetime assessment of components under extreme conditions, such as high temperatures and high pressures, require characterization, testing and modelling. By extending the lifetime savings can be achieved and unpredicted shutdowns prevented. Here we show two industrially relevant cases for lifetime assessment; high temperature component in power plant, reheater, and gear, and how their lifetime can be evaluated and extended. Here we have calculated the remaining lifetime for the components with defined design and condition parameters. At the time of inspection, the reheater tube had been in service for about 180 000 h approaching the design lifetime and based on the evaluations carried out, the estimated minimum residual life of comparable tubes was predicted to be 50 000 h. The lifetime of coated gear can be extended by almost 300% when surface texturing used.

### INTRODUCTION

The aim is to present which kind of tools can be used for the life assessment of different industrial cases. The first aims to show how the appearance of creep damage in ferritic steels can provide useful clues for life assessment under varying initial and operational conditions. In general, the expected life is not a strong function of the material grade for the same extent of damage or degradation, mainly because the operational conditions should largely compensate for the differences in material performance. The example case for boiler internals was selected to demonstrate the long term impact of microstructural degradation and oxidation, and the effects on the estimated service temperature.

The FE modelling was used to show why the coatings with lower surface roughness have better wear resistance in the gear applications, considering the location and propensity of wear damage initiation at different scales of roughness topographies. The initiation of surface damage in gear contacts is quantified for surface design purposes by introducing a wear resistance FE model. The FE model can be applied to estimate the time the gear can operate before initiation of damage becomes likely for different surface loadings and topographies.

### LIFETIME ASSESSMENT OF COMPONENT IN POWER PLANT

Observations of in-service thermal degradation and oxidation are widely used to support life assessment of superheaters and reheaters, particularly to establish the effective tube material temperatures. In parallel, observations of creep cavitation damage in hot headers and steam lines are commonly providing indications of the current and expected integrity of welded components. Though relatively common, the methods are not fully standardized, but guidelines exist for evaluating creep cavitation damage.

One of the principal quantities of interest in life assessment of superheaters and reheaters is the effective metal temperature during service. As creep and other damage mechanisms are highly sensitive to temperature, uncertainties in assessing this temperature can result in considerable errors in the expected life. Sources of uncertainty (error) for different temperature indicators are shown in Table 1.

*Table 1. Error sources in estimating tube metal temperatures.*

| Indicator | Sources of error | Notes |
|---|---|---|
| Microstructure | Limited t-T range | Insensitive at low temp. |
| Hardness | Limited range | Mainly for 10CrMo9-10 |
| Internal oxide | Spalling, porosity | From layer imbalance |
| Thermocouples | Drift, temp. limits | Often K-type |
| Diffusion couples | Non-standard | - |

Superheaters and reheaters often have metal temperatures exceeding that of the steam by some 15-50°C. For a fixed outlet steam temperature such a range of metal temperatures can mean a wide range in the expected tube life, as 10°C increase may approximately halve the tube life. The tubes are subjected to the fireside environment with through-wall temperature gradients and non-constant material temperatures in addition to wall thinning by external oxidation, hot corrosion and erosion in the flue gas. Also, thermal insulation by the growing internal oxide is resulting in progressively increasing material temperature of the tube, if approximately constant heat flow is extracted from the superheater/reheater section. To counter the effect of the internal oxide, this layer may be removed by chemical cleaning.

The microstructure and internal oxide for a reheater of a coal fired plant is shown in Fig 1. This reheater tube (10CrMo9-10 or T22 steel) had been in service for about 180 000 h. Life prediction for the tubes was based on a simplified effective temperature history, essentially reducing the three past oxide cleaning episodes to a single effective cycle and then to a natural oxide growth prediction from the time of assessment onwards. An in-house software tool was used to combine the effects of stress, temperature and creep strength evolution to obtain a predicted life (*ref. Auerkari et. al. 2010*). In this case the thickness of internal oxide failed to indicate the metal temperatures due to oxide spalling, and estimates were based on microstructural evolution and hardness. A Larson-Miller type of expression was applied to provide a time-temperature master curve with constant features in the microstructures. The estimated minimum residual life of comparable tubes was predicted to be 50 000 h.

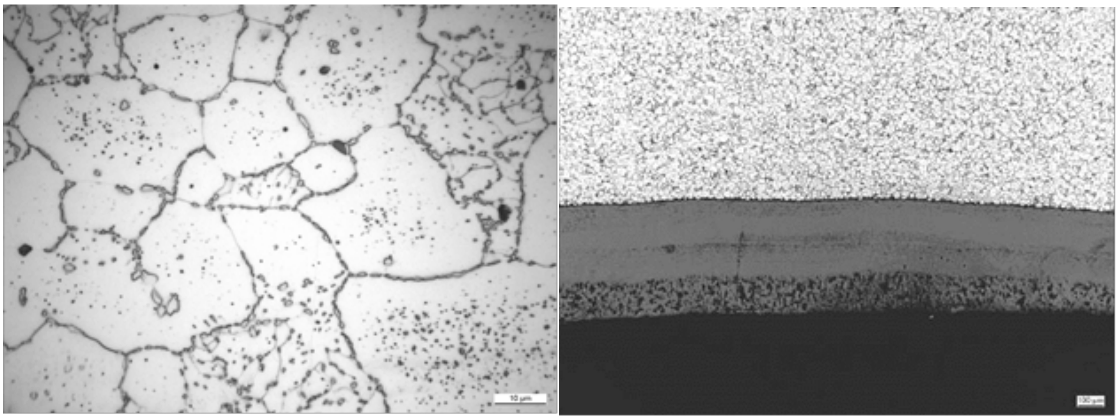


*Figure 1. Degraded microstructure of a reheater tube, suggesting an effective service temperature of 575-600°C and observed internal oxide layer*

## LIFETIME ASSESSMENT OF COATED GEAR

A finite-element (FE) model of gear contact was created (Fig. 2). The mesh size of the model was one millimeter. The model was operated with certain parameters and the generated forces were applied into another model where two rough surfaces were sliding on each other.

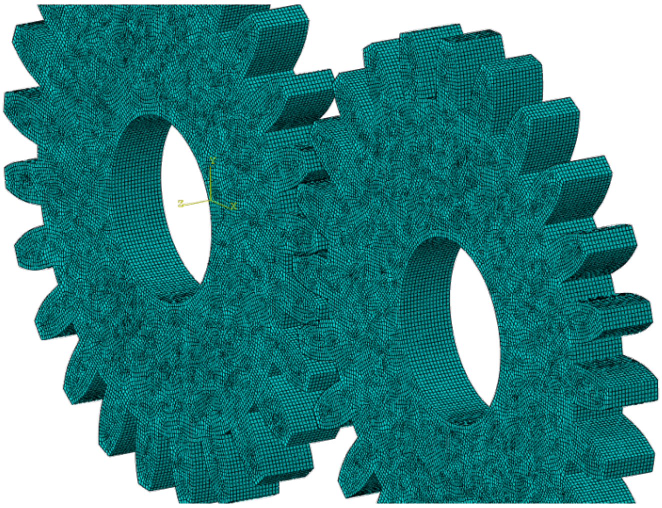


*Figure 2. FE-model of gear contact*

Based on the simulations (Fig. 3) there are both tensile (red) and compressive (blue) stresses formed on the teeth surface. The values of these stresses were applied into another model (*ref. Holmberg et.al. 2017*) where two rough surfaces were sliding on each other.

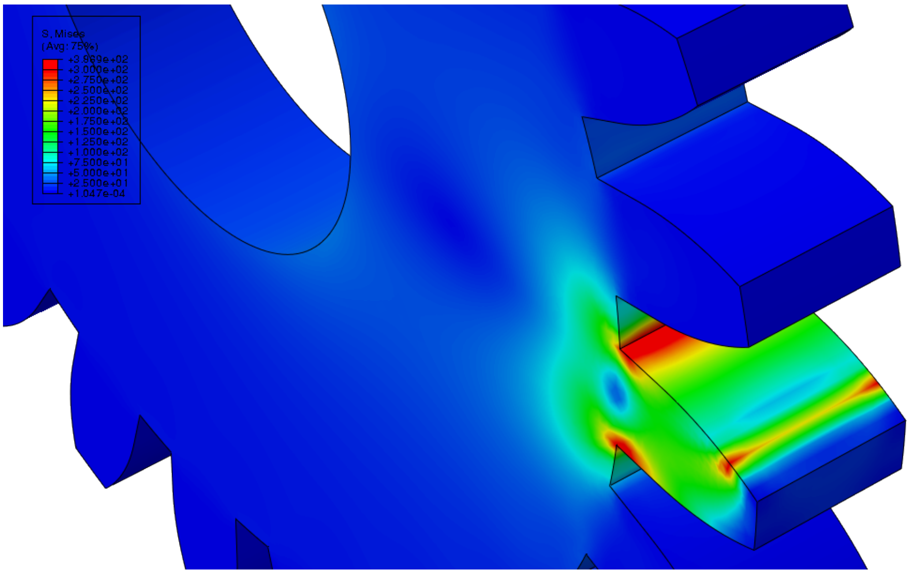


*Figure 3. Simulation of stresses formed in gear contact*

The stresses formed on the simulation were applied into the model where the stresses between two rough surfaces were simulated. The surface rough surfaces had three different roughness levels; smooth, average and rough. The texture was formed by grinding marks. The average and smooth surfaces were formed by polishing the rough samples.

From the simulation results it can be calculated the lifetime (cycles) of the gear if the failure of the gear origins from the coating cracking. As shown in Fig. 4 the lifetime of the gear is significantly extended when the sliding of the surfaces is in 45 degrees direction toward each other. In that case there is a complex stress field formed into the coatings and no high tensile stresses are formed.

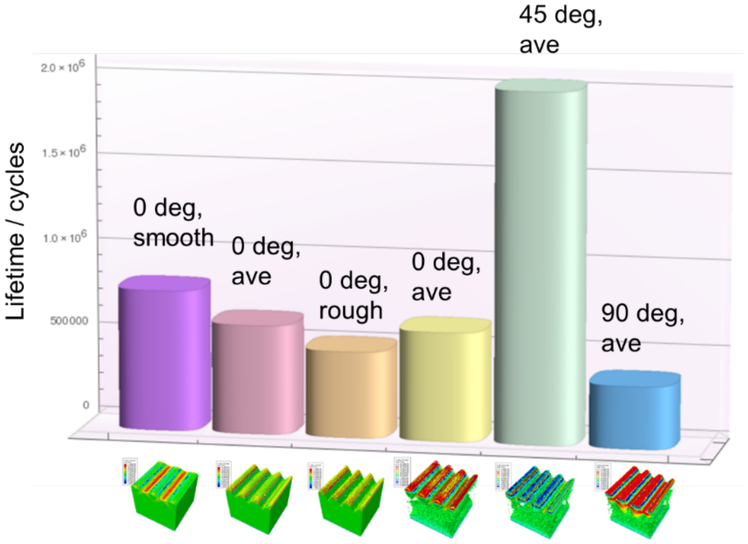


*Figure 4. Lifetime (cycles) of the gear in 0, 45 and 90 degrees direction toward the grinding marks*

## CONCLUSIONS

The estimated minimum residual life of comparable tubes was predicted to be 50 000 h. The reheater section was included in a follow-up inspection program, and no incident has contradicted the prediction after more than 20 000 h of further service.

Finite-element (FE) - model for gear contact was created. By simulations the lifetime for coated gears can be calculated. The lifetime can be extended by 300% when sliding occurs in direction of 45 degrees compared to grinding grooves.

## REFERENCES

Auerkari, P., Salonen, J., Holmström, S., Laukkanen, A., Laaksonen, L.; Mäkinen, S.; Väänänen, V.; Nikkarila, R. High temperature damage as an indicator of operating conditions and residual creep life. 12th International Conference on Creep and Fracture of Engineering Materials, May 27-31, 2012, Kyoto, Japan

Laukkanen, A., Holmberg, K., Ronkainen, H., Stachowiak, G., Podsiadlo, P., Wolski, M., Gee, M., Gachot, C., Li, L. Topographical orientation effects on surface stresses influencing on wear in sliding DLC contacts, Part 2: Modelling and simulations (2017) Wear, 388-389, pp. 18-28.

# 5. DYNAMIC SERVICE DECISION SUPPORT PLATFORM

Henri Vainio, Ananda Chakraborti, Jussi Aaltonen, Kari T. Koskinen
Tampere University of Technology, Mechanical Engineering and Industrial Systems
henri.vainio@tut.fi

## ABSTRACT

Connecting multiple sources of data from different levels of a manufacturing process opens up possibilities for analysis and optimization of the process. These data sources include work piece locations, sensor readings from manufacturing equipment, process data such as ERP and MES data, and eventually expanding to subcontractor data as well as other third party data, e.g. weather data. Combining these sources in a meaningful way enables the discovery of system-of-systems level phenomena and patterns and thereby creates knowledge to support process optimization and service delivery. The technology required for a decision support system like this include the data gathering, transfer, storage, preprocessing and analysis methods as well as presenting the relevant results to the end user in a clear and intuitive manner. This work concentrates on processing, analyzing and visualizing data gathered from storages and databases of a number of stakeholders. A Decision Support Platform is created using open source software and an industrial case is presented. The main contribution of this work is the utilization of interlinked open source analytics to perform data fusion, analysis and decision support creation for a manufacturing process.

## INTRODUCTION

The Industrial Internet of Things paradigm enables new and more efficient ways of supporting products and offering industrial services in the Product-Service System (Goedkoop et al., 1999) concept. Gathering data and information from multiple sources related to an industrial process makes it possible to create new knowledge using multiple mutually supporting analysis methods (Assahli et al. 2017). These methods can be linked to run on a server and automatically analyze and predict the states of the process, offering near-real time decision support for industrial services. Such a Decision Support Platform was tested by connecting a manufacturing process of a machine part factory to cloud servers and combining production information in the form of lead time plans. These data were gathered in a database and then used as inputs for the Decision Support Platform, with an Agent Based Model as its basic structure, enhanced with internal analytical functionalities. The platform was able to provide near-real time situational information as well as breakdowns of past event chains. The results were visualized using both HTML-based dashboards and a 3D-model of the factory, displayed on a website. All of the tools used in the storage of data, analysis and visualization were created with open source software.

## DECISION SUPPORT PLATFORM STRUCTURE

Data from an industrial process is gathered in various ways and by several organizations. Sensor data, process data and maintenance data are saved to a number of locations by the process owner and service providers and often some form of preprocessing is performed. The data can be accessed using a number of protocols, such as HTTP queries or network socket connections in case of a cloud server database, or even periodical manually acted transmissions in case of on-site data. In each of these cases there are ways of limiting the access to the data, so that only the data relevant to the application requesting it is available. Accessing the data using these methods, a service provider is able save the data to a database for preprocessing. Timestamps and measurement frequencies must be matched; outliers and clear measurement errors as well as missing data must be cleaned (Tsai et. al, 2014). After preprocessing, data fusion and analysis can be performed. The approach taken in this work uses an Agent Based Model as the basic structure of the Decision Support Platform. The various data are used as inputs for the Multi Agent System (Weiss, 2013), which represents the components in the industrial process, such as work orders, NC-machines or machine subsystems. These agents, aware of their current and pasts states, are also able to access process information, e.g. lead time plans, and compare their actual situation to their intended situation. They are able to trace delays in the past and associate them with error reports from other agents, creating a holistic view of the causes of production delays and errors. Once enough data accumulates, machine learning methods can be directly added to the model and bottleneck detections, delay predictions and learning optimizers become possible.

The output of the model is visualized on a website using HTML-based dashboards and a 3D-model of the factory. The 3D-model offers an intuitive view of the situation at a glance, featuring color codes for machine and subsystem statuses as well as location information of work pieces and their past and planned paths. The dashboards offer more detailed results from the agents, such as root cause analyses for delays, usage rates of machines and subsystems and lead time breakdowns.

The Decision Support Platform can be created using open source software. The tool set is built using Python. Data preprocessing and fusion is performed using PANDAS and SciPy, Agent Based Models are created with Mesa, while machine learning tools are provided by Scikit-learn and Keras. Analytical models built with OpenModelica can be interfaced. The results of these analytics can be shown on a website run on a NodeJs-server with a HTML-based user interface as well as 3D-visualizations created using Blender and Blend4Web. These open source methods are extremely versatile and can be tailored to meet the requirements of vastly different use cases.

## RESULTS

The Decision Support Platform was tested in a factory that manufactures machine parts. The work orders that move through the process were fitted with radio tags that allow their locations to be monitored. Some of the NC machines in the process were also fitted with radio sensor tags monitoring vibration and heat. The radio tag data was collected and preprocessed by the company providing the tags and saved on their cloud server. The PLC data of a storage management system integral to the process was also accessed through the cloud server of the company that had manufactured the system and acted as an industrial service provider in this case. Lead time plans of the manufacturing process were sent by the company owning the factory.

The Agent Based Model included agents representing the work orders, the NC-machines and the subsystems of the storage system. The work order agents were able to calculate delays and create lists of delays with related error reports. The structure of the Decision Support Platform is presented in Figure 1.

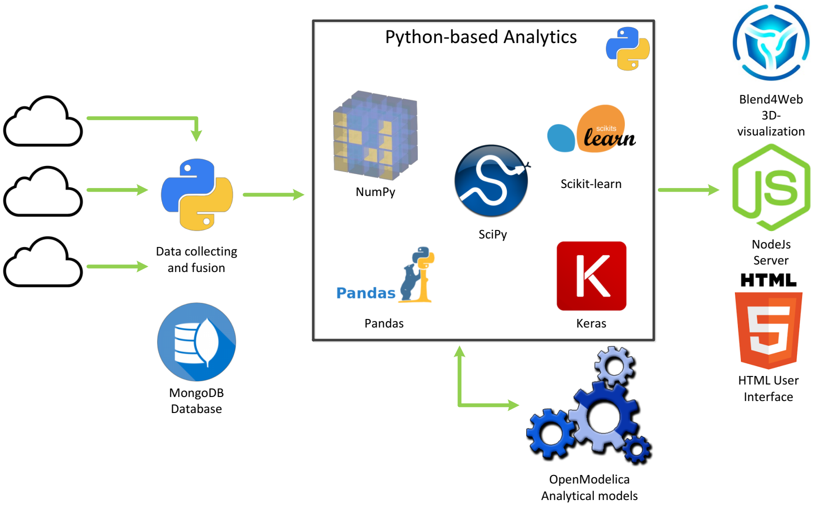


*Figure 1: The structure of the Decision Support Platform*

The visualization included a 3D-model of the factory in question, created from a SolidWorks file using Blender and Blend4Web. Changing status colors for the machines and subsystems were added as well as annotations displaying the current status of the machine in more detail. Work order locations and delay information was displayed as well as the past and planned paths of the work orders in the process. The model could be scaled upwards to present the entire production network including multiple sites owned by the process owning company as well as subcontractor statuses, though no subcontractors were involved in the case at this time. The HTML-based dashboards could be used to offer more detailed historical analyses of this information. The different views of the visualization are presented in figure 2.

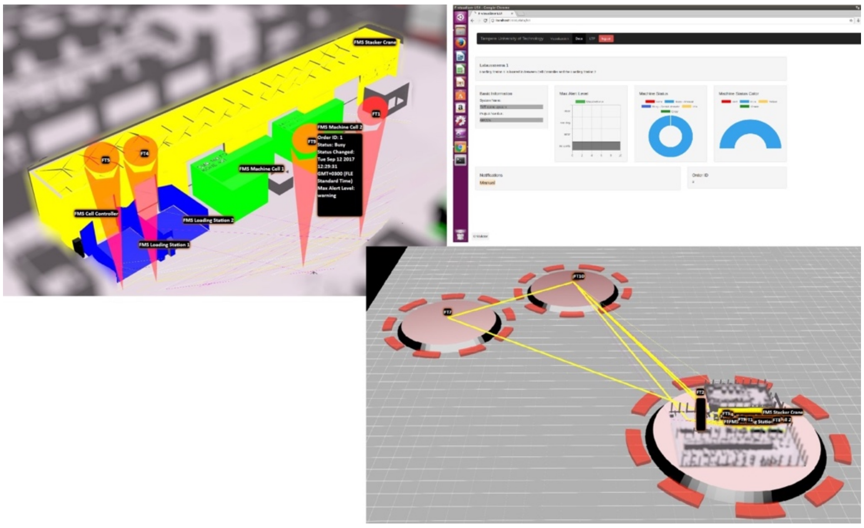


*Figure 2: Machine level status visualizations, work piece location information and production network visualization*

## CONCLUSIONS

Gathering data and information from an industrial process enables efficient process optimization. Such optimization models can be created using open source software, which allows the customization of the solutions to meet the needs of the end user. Since it is likely that a real world scenario includes both software provided by companies, as well as open source tools, it would be advisable for the software companies to provide standard interfaces and transparent methods in order to facilitate whatever customization their customers need. Future work includes data analytics with machine learning methods and extending the model to include subcontractors for full network visibility. Adding data from third party sources such as weather agencies would enable the detection and analysis of the effects of even larger scale phenomena.

## REFERENCES

Assahli, S., Berrada, M., Chenouni, D. 2017. Data preprocessing from Internet of Things: Comparative Study, Wireless Technologies, Embedded and Intelligent Systems (WITS), 2017 International Conference on.

Goedkoop, M., van Halen, C., te Riele, H., Rommens, P. 1999. Product Service Systems, Ecological and Economic Basics.

Tsai, C., Lai, C., Chiang, M., Yang, L.T. 2014. Data Mining for Internet of Things: A Survey. IEEE Communications Surveys & Tutorials, vol. 16, No. 1.

Weiss, G. Intelligent Robotics and Autonomous Agents : Multiagent Systems. 2013. MIT Press, 2nd edition. 917 p.

# 6. IMPACT OF MAINTENANCE ON CIRCULAR ECONOMY

Pasi Valkokari, Jyri Hanski, Toni Ahonen
VTT Technical Research Centre of Finland
pasi.valkokari@vtt.fi

## ABSTRACT

Novel business models that leverage the largely untapped potential of circular economy are gradually emerging in several industries. The widespread use of circular economy has implications for asset management in manufacturing industry, as they bring new challenges and opportunities for managing and maintaining machinery and equipment. The importance of asset management and maintenance for the circular economy is studied in the Tekes funded "Data to Wisdom" project.

Circular economy can be defined as a system which creates value by minimizing waste, energy and the use of natural resources. It also utilises solutions that aim at slowing, closing and narrowing loops of material and energy. These solutions include, for instance, long-lasting design, design for easy disassembly and maintainability, maintenance actions such as repair and refurbishing, reuse, remanufacturing and recycling.

In this paper, we analyse circular economy archetypes from the life cycle management perspective. This is done by comparing circular economy archetypes against the fundamentals of asset management. Opportunities and threats produced by the circular economy for asset management and maintenance are addressed with real cases presented in Sitra's list of the most interesting companies in the circular economy in Finland.

## INTRODUCTION

Asset management (AM) is a "coordinated activity of an organization to realize value from assets" (ISO 55000, 2014). Considering physical assets, AM aims at optimising the life cycle business impact of cost, performance, risk exposures and ensuring the availability, efficiency, quality, longevity and regulatory/safety/environmental compliance (IAM, 2008). Asset management realises asset value through operation, maintenance and investment activities (Komonen, 2008).

Circular economy (CE) is a system which creates value by minimizing waste, energy and the use of natural resources (Geissdoerfer et al., 2017). CE solutions aim at slowing, closing and narrowing loops of material and energy. These solutions include, for instance, long-lasting design, design for easy disassembly and maintainability, maintenance actions such as repair and refurbishing, reuse, remanufacturing and recycling. Figure 3 visualises the connection between AM and CE.

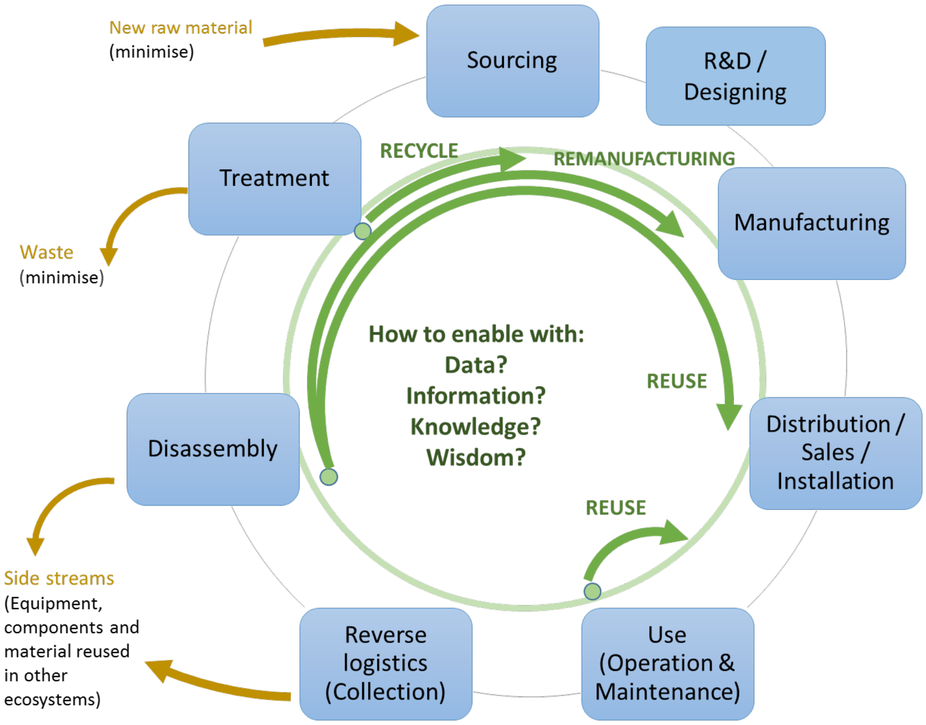


*Figure 3. Asset management and circular economy.*

From the perspective of CE, figure above illustrates mainly technical cycles such as life cycle of machinery and equipment. AM activities take place in different life cycle phases and feedback loops. Even though the goals of CE, maintenance and AM are largely congruent, the research on the impact of CE on maintenance and asset management has been scarce. Descriptions of CE solutions generally do not consider the opportunities and threats for AM.

Therefore, our aim is to analyse circular economy archetypes from the life cycle management perspective. We compare circular economy archetypes against the fundamentals of asset management described in ISO 55000 (2014). Opportunities and threats produced by the circular economy for asset management and maintenance are addressed with real cases presented in Sitra's list (Sitra, 2017) of the most interesting companies in the circular economy in Finland.

## OPPORTUNITIES AND THREATS OF CIRCULAR ECONOMY FOR MAINTENANCE

The impact of maintenance and asset management on CE can be viewed through the four asset management fundamentals: 1. *value* that is provided to the organisation, 2. *alignment* of plans and activities, 3. *leadership* and culture that ensures that employees in the organisation have clear role and responsibilities and are competent and empowered, and 4. *assurance* that assets fulfil their purpose (ISO 55000, 2014). Sitra (2017) classifies CE solutions into five categories: product-life extension, product as a service, sharing platform, renewability, and resource efficiency and recycling. Other often referred classifications are presented in Bocken et al. (2016) and Lacy and Rutqvist (2015).

*Table 1. Impact of maintenance on CE solutions.*

| CE model/example | Threats | Opportunities |
|---|---|---|
| **Renewability**<br>Closing resource loops<br>**Example**<br>St 1: Petrol substitute from organic waste<br>**Asset type**<br>Fleet of production units | **Value**<br>Treatment of hazardous materials and occupational safety<br>Potential quality challenges for the end product (heterogeneous raw material)<br>Uncertainty about the durability of machinery and equipment due to changing characteristics of raw material and lack of usage history data<br>**Alignment, leadership & assurance**<br>More actors and stakeholders in the value chain increase the complexity of the production system and the organisation and cause new challenges for decision-making, leadership and the assurance of performance<br>Demand for interoperability of technical and information systems of different actors in the ecosystem to show the sustainability of products | **Value**<br>Several small production units increase delivery reliability in comparison to one large unit<br>Fleet of production units may have a common spare part stock<br>**Alignment, leadership & assurance**<br>Increased control and flexibility for the execution of planned shutdowns due to small production units<br>Accumulated fleet data can be used to support the assurance of the machinery reliability |
| **Product-life extension**<br>Slowing resource loops<br>**Example**<br>Valtra: Remanufacturing tractor gearboxes<br>**Asset type**<br>Tractor gearbox | **Value**<br>Recognizing when it is not feasible to extend the lifetime of gearboxes<br>**Alignment, leadership and assurance**<br>In order to use the concept, there is a need for extensive information about the utilization, condition and location of machinery<br>Remanufactured machinery needs to be compliant with the requirements<br>New kind of life cycle phases (due to remanufacturing) require the implementation of new assurance processes | **Value**<br>Using same equipment for remanufacturing reduces costs (e.g. reduction of new materials and energy consumption in production)<br>**Alignment, leadership and assurance**<br>Predictive maintenance enables early detection of wear/defects before failure occurs<br>Remanufacturing demands an advanced performance monitoring and support processes to be successful. This enables indirect benefits such as decreased failures and disturbances, and new service opportunities |

## CONCLUSIONS

Asset management and maintenance play a major role when CE solutions are implemented and targeted strategic objectives are pursued. Challenges related to the maintenance of machinery increase due to the heterogeneous materials. Additionally, CE solutions increase the need for data of usage history. On one hand, the implementation of CE solutions often requires the renewal of the data collection and analysis. On the other hand, increased utilisation of fleet data enables more efficient decision-making in AM activities.

## REFERENCES

Geissdoerfer, M., Savaget, P., Bocken N.M.P. and Hultink, E.J. (2017) The Circular Economy - A new sustainability paradigm? *Journal of cleaner production*, 143, pp. 757-768.
Bocken, N.M.P., de Pauw, I., Bakker, C. and van der Grinten, B. (2016) Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, 33:5, pp. 308-320.

IAM (2008) Institute of Asset Management. London.

ISO 55000 (2014) Asset management standard.

Komonen, K. (2008) A Strategic Asset Management Model: A framework of a plant level model for strategic choices and actions. Proceedings of Euromaintenance 2008 Conference on asset management & production reliability, Bryssel, 8 - 10 April 2008, pp. 1-10.

Lacy, P. and Rutqvist, J. (2015) Waste to Wealth: The Circular Economy Advantage. Palgrave Macmillan.

Sitra (2017) The most interesting companies in the circular economy in Finland. Available at: https://www.sitra.fi/en/projects/interesting-companies-circular-economy-finland/.

# II DIGITAL AND ADDITIVE MANUFACTURING

## 7. DIGIMATURITY IN MANUFACTURING INDUSTRY

Simo-Pekka Leino, Juha-Pekka Anttila
VTT Technical Research Centre of Finland Ltd.
Simo-Pekka.Leino@vtt.fi

### ABSTRACT

The generic VTT Model of Digimaturity helps in understanding and structuring the concept of digitalisation. This paper discusses how it should be extended and made more profound towards the specific needs of manufacturing industry and product processes.

### INTRODUCTION

We are in middle of the fourth industrial revolution which is based on Internet technologies, real time information flow and combination of available technology in a new way (Kagermann et al., 2013). This is not based on totally new or unknown concepts, but the scale and complexity of digitalization will be in totally new level in the future. Therefore frameworks and holistic perspectives on business models, strategies, processes, and enterprise architectures for structuring the complex concept of digitalization are required. Germany based Industrie 4.0 (Kagermann et al., 2013) is one name for the fourth industrial revolution. However, Industrie 4.0 only describes the vision, but does not provide a clear definition. Even more unclear is how it fits to Finnish companies. Our hypothesis is that Industrie 4.0 will rule also the Finnish industry in near future, which requires radical improvement of data and information flow within value networks.

VTT Model of Digimaturity (http://digimaturity.vtt.fi) helps in understanding and structuring the concept of digitalisation (Leino et al., 2017). Additionally, it gives an estimate of organisations' current capabilities and maturity as well as general directions toward a desired maturity level. Since it is a generic model, it should be extended towards more specific needs of manufacturing industry. This paper discusses how it is developed and made more deep, taking manufacturing, product processes and the Industry4.0 vision into account. The extension is partly based on the ongoing Tekes-funded "Digital Extended Enterprise – Dexter" –project (http://smacc.fi/projektit/dexter, funded by Tekes, VTT, TUT and participating companies), and its preliminary results and conclusions, particularly the "Dexter-model". Dexter builds on the Chrysler Corporation based notion of Extended Enterprise (EE) and studies how digitalization enables better collaboration, flexibility, information flow, transparency and total productivity.

### RESEARCH APPROACH

The research approach is constructive. It builds on top of the VTT Digimaturity Model adding the recognized sub-dimensions of the Dexter-model that are important in manufacturing industry and networks of manufacturing companies. The Dexter model is relatively rich having almost 2000 different mentions/topics highlighted in the case companies. The extended sub-dimensions were analysed in Dexter-project case studies with a network of one large OEM company and four SME suppliers of them. The sub-dimensions were reflected with literature. Additionally, the proposed extended model has been tested and discussed in interviews and workshops with several other SME manufacturing companies. These were selected from the list of companies that have applied the VTT Digimaturity Model web tool, and indicated their interest in further discussions.

## RESULTS AND ANALYSIS

Analysis of the Dexter-model raises the following themes in order to build a future digital manufacturing extended enterprise: Strategical collaboration and development of digitalization together, digital and model based integration and feedback of engineering design and product development, transparency on every level, systematization and discipline of high quality processes, development of reliable and predictable engineering change procedures. As can be seen, these themes touch all six dimensions of the original VTT Digimaturity Model, but as can be guessed, the product related models and processes are emphasized. Additionally, digitalization maturity refers to two different, but interrelated things (Leino et al., 2017): Firstly, required capabilities and organisation readiness for digitalisation. This means an organisation's capability and willingness (mindset) to change its function, processes, organisation and capability to effectively adopt new technology. Secondly, maturity refers to an organisation's performance based on digital technology. Thus, the sub-dimensions and elements of the extended models are categorized within these two perspectives (Figure 1). Currently the extended model includes the recognized (Dexter-model and other industrial experience, literature) elements categorized as sub-dimensions of the six main dimensions of the VTT Digimaturity Model. Practically speaking, the sub-dimensions work as more detailed structure and questions that can be used for instance in workshops aiming to help companies creating steps on their future digitalization path. The sub-dimensions cannot be introduced in details in this limited space.

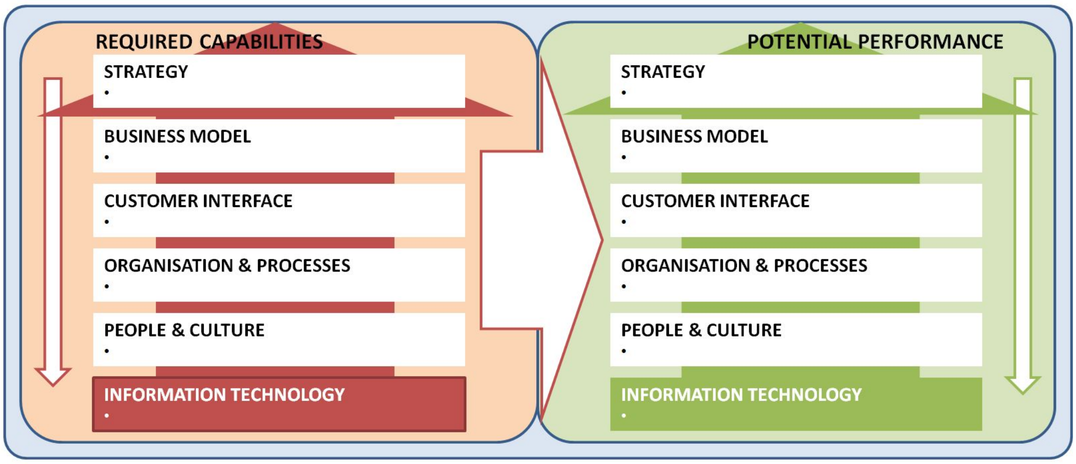


*Figure 1. Required digitalization capabilities are prerequisites for the potential increased business performance. Technology is just one of six digitalization dimensions.*

As an example, the required capabilities of the Organization & Processes dimension studies for instance the importance, definition and development of processes, types and modes of production, types of product development, product and process quality and KPIs, and definition and typology of information streams. Potential performance of O&P includes e.g. levels of information digitation and integration, data flow and transformation towards information and knowledge, level of real time and transparent flows, total optimization of product processes and new roles in organizations.

## DISCUSSION

Maturity models have been a topic in academic research for decades. Maturity models have been developed and utilized for instance in software development and PLM implementations. Our extended model of manufacturing digitalization maturity contributes to the discussion of digitalization as a business concept and maturity model as a method and consultancy tool. From the practical viewpoint it is proposed to boost digitalization in manufacturing industry by enabling understanding and structuring the extensive, complex and systemic concept of digitalization. The first experiences and feedback from companies is positive and encouraging. There seems to be real demand for such a framework. Sample size of companies is still small and results are partly interpretations, so very solid conclusions cannot be drawn. However, the model will be developed continually in dialogue with companies.
Discussions with companies show that starting point for digitalization is mostly good: Commitment from owners and top management, optimism and positive attitude towards new technology, open culture, willingness to share information, readiness for organizational changes. Also digital tools such as Google marketing, social media (LinkedIn, Facebook) are surprisingly well utilized also in SMEs. Many companies are interested in novel concepts and pieces of technology as part of their marketing, sales, product development and user experience: VR/AR, AI, model-based processes, Digital Twin, IIoT.
For Finnish manufacturing companies, customization, flexibility and agility are typically essential competitive edges, which create challenges for digitalization. On one hand digitalization is an enabler, but on the other hand burden and big investment particularly for SMEs. Currently data and information do not typically flow optimally causing waste in processes. Some companies have realized that digitalization could result in new ways of creating value and novel business models with opportunities to provide downstream services, such as management, processing and infusion of data to knowledge. Digitalization may change the strategic position in value networks, and creates opportunities for start-ups to seam digital value networks in a new way. Digitalization is essentially a networked and systemic concept. It requires development of capabilities and interfaces between organizational functions, departments, suppliers, customers, partners, etc. It should be understood that new data based business models usually also require systemic changes for instance to product processes, product data management, and customer interface.

## CONCLUSIONS

Large companies are often seen as digitalization forerunners. However, as part of their supplier networks, SMEs should be strategically prepared for the digital transformation. Actually, digitalization capabilities increase credibility as part of global networks. On the other hand, starting point for digitalization is mostly good also in SMEs. Digitalization is recognized in strategical level and there is commitment from owners and top management, but it is not clear how to proceed. Therefore a framework for digitalization is needed including concept definitions and terminology - together with external perspectives and expertise. The prototype of extended Digimaturity model for manufacturing industry has gained positive feedback from companies, and it will be further developed in dialogue with companies.

## REFERENCES

Kagermann, H., Wahlster, W., & Helbig, J. (2013). Recommendations for implementing the strategic initiative Industrie 4.0. Final report of the Industrie 4.0 Working Group.

Leino, S-P., Kuusisto, O., Paasi, J., Tihinen, Mt. 2017. VTT Model of Digimaturity. In: Towards a new era in manufacturing. Final report of VTT's For Industry spearhead programme. VTT Technology: 288. http://www.vtt.fi/inf/pdf/technology/2017/T288.pdf

# 8. IDENTIFICATION OF FUNDAMENTAL REQUIREMENTS FOR IDEAL METAMODELING FRAMEWORK IN ADDITIVE MANUFACTURING

Hossein Mokhtarian, Eric Coatanéa, Henri Paris, Jorma Vihinen, Mohammad Hosseini
Hossein.mokhtarian@tut.fi

## ABSTRACT

Although Additive Manufacturing (AM) has existed for several decades and its industrial applications are increasing, it still suffers from a reliable part qualification method. It is mostly due to lack of thoroughly understanding the behavior of AM Technologies and the reasons for variability among the additively manufactured parts. Advancement in computational hardware and software are continually improving the modeling and simulation capabilities. However, recent advances in modeling and simulation techniques were not sufficient yet to predict the parts' properties and to certify the manufactured parts. This refers to highly complex interconnections between the different physical phenomena in each AM technology, hence between developed models. In other words, the reliability and accuracy of the models with their specific scope, purposes, and constraints are increasing, but the links describing their interconnection are missing. Therefore, to link different types of models and hence better understanding AM processes, a robust metamodeling framework is required. Toward this end, the following paper aims at addressing and extracting the fundamental requirements for an ideal metamodeling framework for additive manufacturing from the literature review analysis.

## INTRODUCTION

In comparison to conventional processes, AM processes are more complex, less predictable and more difficult to understand due to their multi-physics nature [1, 2]. In spite of the advancement in computational hardware and software and therefore modeling and simulation reliability in AM, the adoption of AM models are still impractical for the industry practitioners [1, 3]. Presenting a suitable metamodeling technique is beneficial to link the models and replace the expensive simulation models. According to Yang et al., although the importance of metamodeling in AM is widely mentioned and well understood in the literature, only limited number of research has been articulated around it [1]. To mention a few of researches focusing on developing metamodels in AM, ontology-based metamodeling is presented by Witherell et al., and Roh et al. in separate research papers [3,4]. Yang et al. focused their research on Polynomial Regression and Kriging method on constructing metamodels [1]. Toward this direction, the prior publications of the authors focus on developing a mathematical modeling framework to establish the simulable casual model between the variables [5-7]. The integrated model is then achieved by linking the causal models. The existence of different approaches motivate the authors to highlight some of the most important requirements (but not limited to) that a successful AM modeling framework should fulfill, in following short article.

## FUNDAMENTAL REQUIREMENTS

For overcoming the challenges and complexities in the modeling of AM processes and therefore being able to certify the additively manufactured parts, a robust metamodeling framework is required [1,3]. Obviously, the ideal metamodeling framework should be tailored for AM. The following list represents the minimum set of requirements (not limited to) for an ideal AM metamodeling framework:

**<u>Requirement 1</u>:** Applicable to all AM technology with a systematic, repeatable approach

The framework should ideally represent a systematic, repeatable approach to model any AM technology and their associated functions and phenomena. It enables comparative study among different AM technologies, AM machines, and different parameter settings and enhances the decision-making process.

**<u>Requirement 2</u>:** Multi-Domain, Multi-Scale Modeling

Each AM process involves with multi-physics phenomena taking place while manufacturing a part. Therefore, the framework should be capable of developing models interacting with different energy domains, and linking models with different level of details. Toward this direction, Williams et al. presented a functional classification framework for the conceptual design of AM technologies [8]. Dimensional Analysis Conceptual Modeling (DACM) Framework is another effort for multi-domain, multiscale modeling [5,6].

**<u>Requirement 3</u>:** Data and Different Model Integration

The modeling procedure should provide the possibility to link different type of models and data. An effective predicting model might be the combination of experimental models and the existing validated theoretical models. Toward this direction, Shaw et al. proposed an approach to decompose the AM processes for representing process-related data [9]. Ontology-based metamodeling is another approach suggested by researchers for data reconciliation [4]. Moreover, another level of model integration is refereeing to integrating the part's model describing its geometrical characteristics into AM process model.

**<u>Requirement 4</u>:** Enhancement and Enabling Machine Learning or Data Mining Techniques

The Inter-laboratory round robin study among demonstrated that AM processes are facing with huge variability in mechanical properties of the parts manufactured with the parameter settings [10]. The variability in mechanical properties not only existed between different laboratory using same parameter settings and same AM process but also between different parts manufactured by each laboratory. It strongly highlights the importance of using machine learning techniques to constantly adapt and converge the developed model to the desired AM process that we are modeling. Furthermore, the machine learning techniques can enable the automatic extraction of unknown relationships between the variables.

**<u>Requirement 5</u>:** Qualitative and Quantitative Simulation, Multi-criteria Simulation and Contradiction Detection

Enhancing the quality of the additively manufactured parts with less trial and error and less experimental costs requires that the framework support the simulation of the process model qualitatively and quantitatively. Another important aspect is the ability of detection of system's weaknesses and contradiction while simulating the model, which systematically leads to understanding where the innovation or optimization is required. Toward this ability, DACM Framework perfectly provides the mathematical basis and the integration of validated theories and method. [5-7]

## CONCLUSION AND PERSPECTIVE

In this paper, some of the most important requirements that a successful AM modeling framework should fulfill were highlighted. Concerning the mentioned fundamental requirements, the authors developed the DACM Framework and tailored it for AM. Authors are currently attempting to integrate a novel Knowledge-based Artificial Neural Network (K-ANN) to the framework. This knowledge-based ANN is not only enabling the machine learning in the framework but also boost the convergence of model in comparison to the conventional ANN.

## REFERENCES

[1] Yang, Zhuo, et al. "Investigating predictive metamodeling for additive manufacturing." Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. 2016.

[2] Kim, Duck Bong, et al. "Streamlining the additive manufacturing digital spectrum: A systems approach." Additive manufacturing 5 (2015): 20-30.

[3] Witherell, Paul, et al. "Toward metamodels for composable and reusable additive manufacturing process models." Journal of Manufacturing Science and Engineering 136.6 (2014)

[4] Roh, Byeong-Min, et al. "Ontology-Based Laser and Thermal Metamodels for Metal-Based Additive Manufacturing." ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, 2016.

[5] Mokhtarian, Hossein, et al. "A network based modelling approach using the dimensional analysis conceptual modeling (DACM) framework for additive manufacturing technologies." ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. 2016.

[6] Coatanéa, Eric, et al. "A conceptual modeling and simulation framework for system design." Computing in Science & Engineering 18.4 (2016): 42-52.

[7] Mokhtarian, Hossein, Eric Coatanéa, and Henri Paris. "Function modeling combined with physics-based reasoning for assessing design options and supporting innovative ideation." AI EDAM 31.4 (2017): 476-500.

[8] Williams, Christopher B., Farrokh Mistree, and David W. Rosen. "A functional classification framework for the conceptual design of additive manufacturing technologies." Journal of Mechanical Design 133.12 (2011).

[9] Feng, Shaw C., et al. "Fundamental Requirements for Data Representations in Laser-based Powder Bed Fusion." ASME 2015 International Manufacturing Science and Engineering Conference. American Society of Mechanical Engineers, 2015.

[10] Brown, Christopher U., et al. "Interlaboratory Study for Nickel Alloy 625 Made by Laser Powder Bed Fusion to Quantify Mechanical Property Variability." Journal of Materials Engineering and Performance 25.8 (2016): 3390-3397.

# 9. INDUSTRIALIZATION OF HYBRID AND ADDITIVE MANUFACTURING OF METALS - CHALLENGES IN IMPLEMENTATION

Veli Kujanpää, Jorma Vihinen*, Tuomas Riipinen, Pasi Puukko
VTT Technical Research Centre of Finland Ltd.
*Tampere University of Technology
veli.kujanpaa@vtt.fi

## ABSTRACT

Both additive and hybrid manufacturing open many new possibilities and perspectives to manufacturing but until now the systems have been stand-alone technologies without real industrial implementation on workshop floor. The research is concentrated mainly in design and process optimization, and separate part printing. Therefore, automatic and flexible industrial production has not been possible with current technologies. Most of the process steps include manual work and development work is needed especially in pre- and post-processing of the AM machines. Some trials have been made e.g. on powder handling and part removal from system, but real solutions are not seen in markets yet. Also post-processes, i.e. stress relief and other post-heat treatments, as well as machining steps, grinding, polishing etc. need solutions. In addition quality inspection should be included in the total system.

In the presentation the systems in the market are analyzed giving the possibilities for different and the current barriers hindering the controlled automatic production are presented to give perspective to the future work.

## INTRODUCTION

There are a few key factors why the automatic and control systems are going to become more important in the integration and automation of AM processes

- Integration of AM technology into factory floor
- Demand for small batch production
- High variability between products
- Demand for ensuring consistent quality for finished parts
- How to link AM machines to the existing machinery/work flow?
- Capability of AM to be integrated?

The important questions are also:

- What are the processes that should be automated?
- What is the level of automation that can be realistically achieved in a near future ?

## PROCESS PHASES

In metal additive manufacturing there are different process phases that can be separately analyzed. These are presented in Figure 1; design, material handling, AM part manufacturing, separate post processing and quality control.

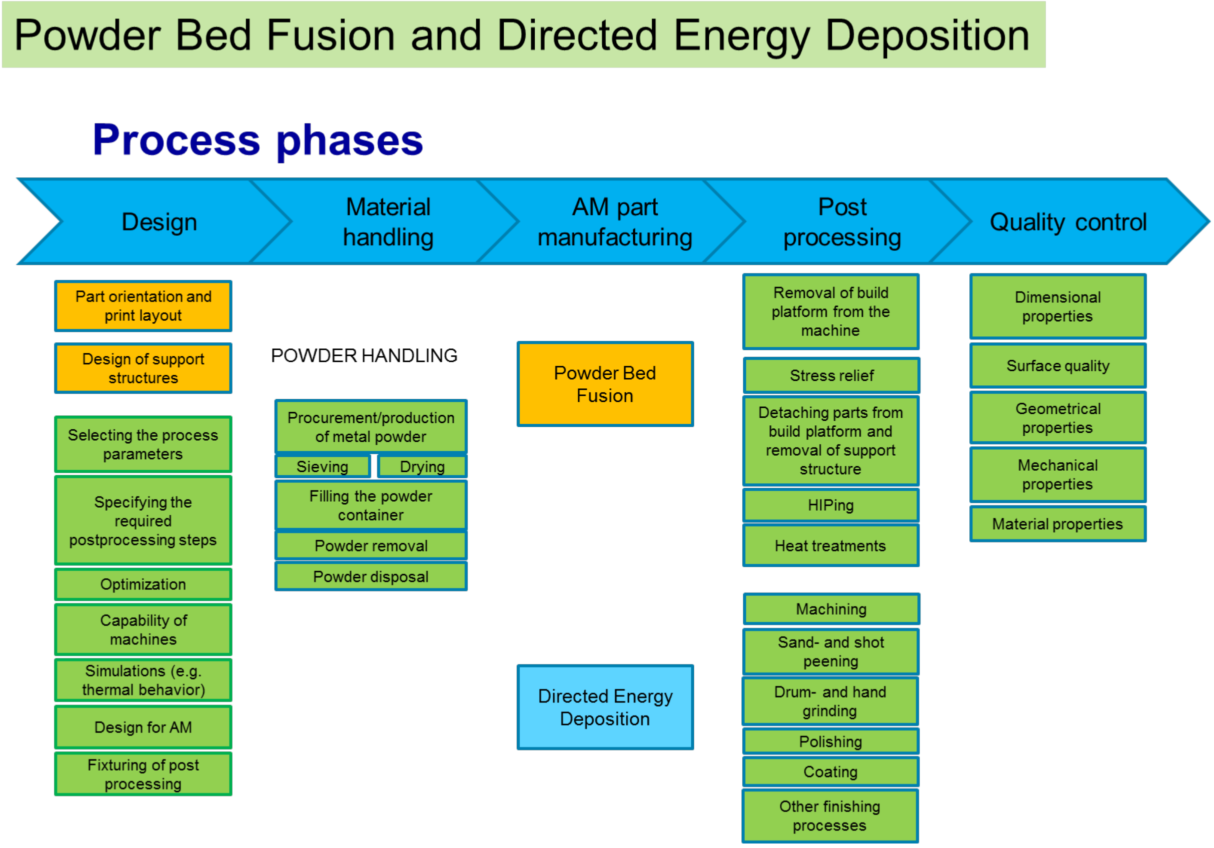


*Fig. 1. Process phases of additive manufacturing (Powder bed fusion and Directed energy deposition).*

*Design phase*

In the design phase a 3D model of the component is created and modified. In some cases modifications to the original 3D model are necessary to improve the printability of the part. The orientation of the part is chosen and the support structures are created based on the geometry and design criteria of the part. The level of automation at this phase is low and user input is required especially for new designs. The design phase can be streamlined for parts with little complexity using best practices in AM design. Critical process parameters include layer thickness, energy input, scanning strategy, platform heating, etc. They affect the quality of printed parts causing issues as high porosity, high surface roughness, thermal distortion and failed prints. Currently the existing solution to these issues is to use parameters from machine manufacturer or parameters that have been obtained experimentally. The challenge in industrial production is the matter of ensuring parameters that function properly between different powder batches, machines and part geometries

*Powder handling*

The necessary steps for powder processing and handling depend on the type and properties of the powder. The quality of the powder material is typically ensured by the supplier who processes the powder to meet the requirements for chemical composition, particle size distribution, morphology, humidity and flow properties. These properties affect the behavior of the powder and are controlled to ensure good quality. If the powder is ordered directly from manufacturer, the customer could be responsible for the processing and inspection of the powder. Information should be collected from all of the process steps to ensure comparability between different powder batches. Challenges in automation lie in handling the procurement and quality control. Some commercial machines have powder-sieving stations with semi-automatic functionality. Powder removal from the build chamber is automated in some SLM machines that have a modular design, but in practice this step is done manually.

#### *AM Part manufacturing*

The build process itself is usually automated, but many of the preparations before and after printing are manual. Build chamber must be cleaned before the next print job. All of the information required for the printing can be transferred between the design phase and the machines. The major challenge in the build process phase is quality monitoring for detecting defects and machine-related problems during the build process. The process parameters, build chamber conditions and powder properties all affect the build process and the quality of printed parts. For example improper process parameters can result in thermal distortions during the build causing re-coater damage and a failed print. The proper function of the machines are ensured by performing routine maintenances. There are also a number of commercial quality monitoring systems (powder bed, melt pool, laser, etc.) under development for the AM machines. The existing monitoring solutions are passive systems, but there is a growing demand for systems that adaptively monitor the build process and make changes to the process parameters when needed.

#### *Post processing*

Post-processing is probably the most challenging part of automation for AM. The technique for removing parts from the platform depend on the print layout geometry, platform size, surface quality etc. The parts are usually removed after stress relief heat treatment. Other heat treatments are also very important steps, e.g. different annealing and hardening processes. In most cases the product must also be machined after the printing and annealing steps. The dimensional accuracy of the printed parts compared to the CAD model depend on material, process parameters and post treatments. The challenge is to predict the microstructure and mechanical properties. In addition, the more complex geometries pose challenges for machining. Currently parts and support structures are removed manually. Conventional heat treatment procedures and machining steps are used. In the future the post processing procedures must be adapted to match the high variability of small batch production.

#### *Quality assurance*

All manufactured parts should meet the required quality standards. A key challenge in adopting AM for industrial use is ensuring consistent quality for finished products. AM machines that are used for large scale printing typically use only one material, which makes quality control measures more straightforward to implement compared to small batch production, where the material is changed frequently. The quality aspects are important in all of the process phases.

### *Hybrid manufacturing*

Hybrid manufacturing are called the systems where additive and subtractive manufacturing are combined in the same machine. They are based on either powder bed fusion or directed energy deposition systems making them very different in practice.

The most usual systems in the market are

- Directed energy deposition combined with 5-axis milling (Fig. 2)
- Directed energy deposition combined with turn mill (Fig. 2)
- Powder bed fusion combined with 3-axis milling
- Cold metal spray combined with 5-axis milling

The advantages of the DED-hybrid process over other solutions are that it can be utilized for repairing parts or for adding additional features to components using relatively high build rates, high geometrical flexibility and the ability to use multiple materials in one build. It can also produce high dimensional accuracy of milled surfaces. A disadvantage is that cutting fluids cannot be used, limiting the milling capabilities of the machines.

In PBF and milling hybrid the laser melting process is represated for several layers followed by high speed milling of selected contours. The advantages are a high dimensional accuracy and low surface roughness and that the process makes milling of internal channels possible. Possibly the entire surface area of the part can be milled, which can be difficult or impossible for complex parts if done after processing. The disadvantages are long build times per part and that cutting chip residue that is left in the build chamber (however small in size). Manufactured parts might require heat treatments depending on the material.

In the hybrid systems the additive process as well as the machining steps are quite well automated but in a similar manner to the standalone PBF and DED systems, the design, powder handling and post-processing, especially heat treatment is not fully automated. Therefore, these aspects require development.. One important question is how to plan the heat treatments for Hybrid manufacturing processes.Namely, the heat treatment is not included in the hybrid system itself. The systems have also quite many limitations, which are not informed by the system manufacturers. Therefore, it looks more or less so that many of the systems are best suited for certain product types. This must be one of the major developments in the future.

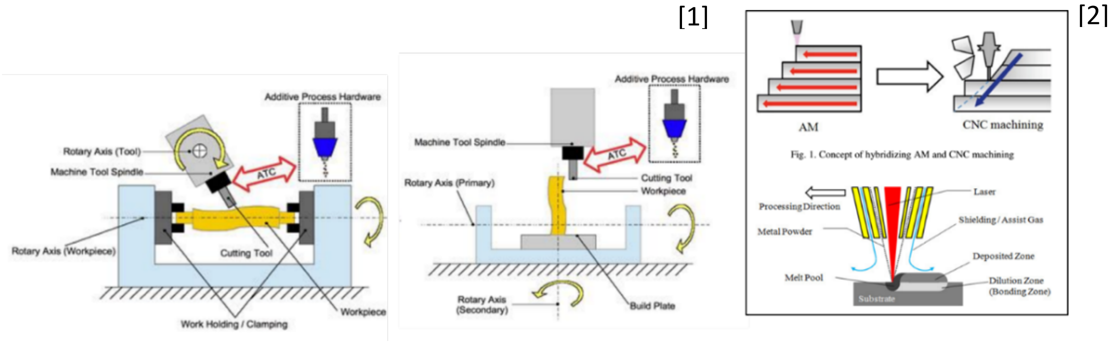


*Fig. 2. Directed energy deposition/Laser cladding combined with 5-axis milling/Turn mill (Mazak).*

### *Control systems*

Control system is a key issue on the factory automation. Most of the AM and hybrid systems in the market are stand-alone machines and are not ready for automated factories. Many developments are going on and in the near future the systems better suitable for automated control systems will likely be available.

## CONCLUSIONS

Additive and hybrid manufacturing systems are currently more or less stand-alone machines, which do not have the readiness for automatic production. The building process itself is usually automated, but pre- and post-processes are not. Design phase, material handling, AM part manufacturing, separate post processing and quality control need a lot of development to be ready to be combined in a fully automated factory concept.

## REFERENCES

[1] Flynn et al (2016). International Journal of Machine Tools and Manufacture, 101, 79-101.
[2] Yamazaki, T. (2016). Procedia CIRP, 42, 81-86.

# 10. IDENTIFYING 3D-PRINTABLE SPARE PARTS FOR A DIGITALIZED SUPPLY CHAIN

Joni Reijonen
VTT Technical Research Centre of Finland
joni.reijonen@vtt.fi

## ABSTRACT

In OEM's producing capital goods, aftersales services is a major part of the business. Managing spare parts cost-efficiently, while providing high service level for the customers is a challenge. Digital spare parts project (DIVA) studies a digital supply chain, where spare parts are 3D printed on demand close to the end user. This could simultaneously reduce costs and increase service level. The first challenge is how to identify parts suitable for 3D printing from the tens or hundreds of thousands of spare parts that companies manage, as not all are technologically or economically viable to 3D print. In this study, a similar method as developed by Knofius et al. (2016) is used to identify such spare parts in two OEMs producing capital goods. Based on the case studies, it is estimated that up to 20 % of the spare parts could be 3D printable in theory. This is reduced to around 6 % having good technological potential to be 3D printed. Furthermore, around 2 % would also be economically feasible to 3D print today. To improve the accuracy and automate the identification process, more structured spare part data is needed.

## INTRODUCTION

In OEMs producing capital goods with lifecycles spanning several decades, aftersales services could account over 50 % of their revenue. The traditional supply chain is compromising between a large inventory for maximum service level versus small inventory for minimum costs. (Deloitte, 2013). A digital supply chain, where parts are manufactured on demand via 3D printing close to the end user, has the potential to disrupt the aftersales service business by simultaneously reducing costs while increasing service level. Digital spare parts could help reduce lead-times, costs related to warehousing and logistics, manufacturing costs and secure the supply of legacy parts. (Holmström et al., 2010). The goal of this study is to identify those parts that could be digital spare parts. Assessing the economic benefit that could be gained via 3D printing is limited by readily available data. As for identifying spare parts that even can be 3D printed, the limiting factor is also the availability and structure of relevant spare part data. The most fundamental classification attributes are material and size, as only relatively small parts consisting of a single material, metallic or plastic, can be 3D printed with today's technology. However, the explicit part information such as material, geometry and tolerances are stored in different files related to the spare part. Such scattered and non-unified data is not easily extracted from a database. Therefore, for a first stage identification of spare parts with highest 3D printing potential, the methodology has to be adapted for the readily available, company specific spare part attributes that are stored in a structured database.

There has not been many studies about how to identify all the potential 3D printable parts from a large spare part assortment and how much such parts exists today. Knofius et al. (2016) proposed and tested such a methodology for one company working in the field of aviation with a selected spare part assortment of 40330. In the studied company, 15.3 % of the scope was identified as technologically possible to 3D print and further, 2.8 % were considered economically viable business cases. The aim of this study is to apply similar method to identify 3D printable spare parts of two additional companies producing different capital goods.

## METHODS

Spare parts of two companies, referred here as Company A and Company B, were classified based on the 3D printing potential. The technological classification attributes were material and size. The material information was indirect information derived from company specific material grouping and commodity codes. As for size, weight and dimensions were used when applicable. It was recognized that after this classification, the potential group still contained parts that are impossible or technologically not feasible to 3D print. To exclude these, images were extracted from the companies' databases for those spare parts that had been photographed (sample size 30 % for Company A and 15 % for Company B) and a visual classification was done. These results were extrapolated with the assumption that parts without images would classify in the same manner as those with an image. The economic classification of 3D printing parts that passed the technological classification was done based on a ranking matrix, shown in table 1. First, the spare parts were divided into metals and plastics and further into stock and non-stock items. Spare parts without specified resupply lead-time were classified into a separate group, called special. Based on the material and to which of the three categories the spare part belongs to, the ranking limits and related attributes were defined.

The economic classification attributes were price, resupply lead-time, demand rate and minimum order quantity (MOQ). High price, resupply lead-time and MOQ or low demand rate indicates increased 3D printing potential. Resupply lead-time is only considered relevant for non-stock items. It was assumed that stock items could not yet be made into digital non-stock items with the current status of 3D printing technology. To make stock items into non-stock items (making the resupply lead-time a critical factor), would drastically reduce warehousing costs, but would require that 3D printing on demand could meet the short (from hours to few days) response times specified in service level agreements. The ranking limits are show for ranks 1-3, which were considered economically feasible. Parts not fulfilling any of these criteria were considered unfeasible. The complete process can be summarized to four steps: define the scope and classification attributes, exclude spare parts that cannot be 3D printed, exclude spare parts that are not technologically feasible to 3D print and rank the remaining spare parts based on their economic feasibility.

*Table 1. Economic feasibility ranking matrix*

| | Non-stock | | Stock | | Special | |
|---|---|---|---|---|---|---|
| Material | MOQ * Price [€] | Resupply lead-time [day] | Price [€] | MOQ / demand+1 | MOQ * Price [€] | Rank |
| Metal | >1000 | | >1000 | | >500 | 1 |
| | 500-1000 | >14 | | >50 | | |
| | >100 | 60-100 | | | | |
| | >10 | >100 | | | | |
| | 100-500 | 30-60 | 500-1000 | | 100-500 | 2 |
| | >10 | >30 | 100-500 | 1-10 | | |
| | | | 10-100 | 10-50 | | |
| | 500-1000 | <14 | 100-500 | no help | 10-100 | 3 |
| | >10 | 60-100 | 10-100 | 1-10 | | |
| | 100-500 | | | | | |
| | 10-100 | 30-60 | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Plastic | >500 | | >500 | | >100 | 1 |
| | 100-500 | >14 | | >50 | | |
| | >10 | 60-100 | 100-500 | >1 | | |
| | >1 | >100 | | | | |
| | 100-500 | <14 | 100-500 | | 10-100 | 2 |
| | 10-100 | 30-60 | 10-100 | 1-10 | | |
| | | | 1-10 | 10-50 | | |
| | 10-100 | 14-30 | 10-100 | no help | 1-10 | 3 |
| | >1 | 60-100 | 1-10 | 1-10 | | |

## RESULTS AND DISCUSSION

Figure 1 illustrates the results from the two case studies. At step 1, the scope was defined and related data retrieved from the companies' databases. Steps 2 and 3 are interlinked, as some of the technologically not feasible spare parts were already identified and excluded at step 2, based on spare part attributes. In the same manner, some spare parts that should have been excluded as not printable already in step 2 were only identified at step 3. Largest of such groups was mechanical parts consisting of multiple materials. At step 4, parts that received rank 1-3, were considered economically feasible. Step 4 was not conducted with Company B.

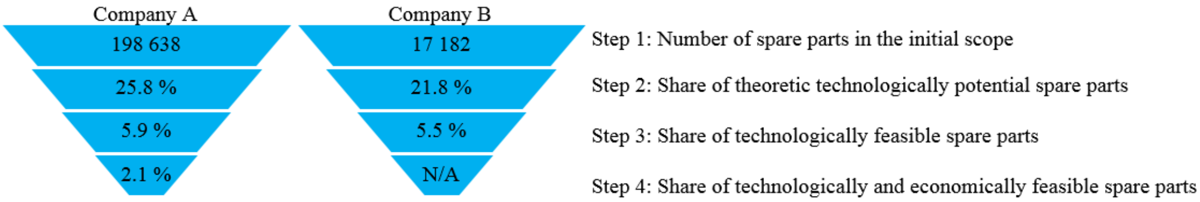


*Figure 1. Results from the case studies with company A and B.*

The large difference between step 2 and 3 comes from excluding spare parts, which could be 3D printed in theory, but it would not make sense to produce these with 3D printing. This group consists mostly of bulk items (for example bolts, nuts etc.) and simple geometry parts such as sheet metal parts. In this analysis, these were excluded in step 3 as technologically not feasible and therefore the economic feasibility was not further assessed for these in step 4. Counterintuitively, this group may contain some parts, which would actually make a viable business case, if examined in more detail. The most common factor in the spare parts identified as technologically feasible is that they are complex geometry parts, typically cast/molded today. This indicates further economic benefit for 3D printing, as expensive molds related to the spare parts could be eliminated. On the other hand, this study does not consider the possible need of post-processing or other finishing after 3D printing to meet tolerances or other specified part properties. This factor was not considered, as this information for the spare parts was not readily available. It is believed that if considered, this would render some parts unfeasible. These case studies and the one conducted by Knofius et al. (2016) indicate that regardless of the company, similar results can be expected.

## CONCLUSIONS

Based on the case studies in companies producing capital goods, it is estimated that up to over 20 % of the spare parts could be 3D printable in theory. This is reduced to around 6 % when parts with extremely simple or standardized geometries are excluded. Furthermore, around 2 % would also be economically feasible to 3D print today. To improve the accuracy and automate the identification process, more structured spare part data is required.

## REFERENCES

Deloitte. 2013. Driving Aftermarket Value: Upgrade Spare Parts Supply Chain. Deloitte China Auto Industry Spare Parts Management Benchmark Survey White Paper. 23 p.

Holmström, J., Partanen, J., Tuomi, J. & Walter, M. 2010. Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment. Journal of Manufacturing Technology Management, 21(6), pp. 687-697.

Knofius, N., Van der Heijden, M. & Zijm, W. 2016. Selecting parts for additive manufacturing in service logistics. Journal of Manufacturing Technology Management, 27(7), pp. 915

# III SMART MACHINES AND ROBOTICS

# 11. AWARENESS IN HUMAN-ROBOT INTERACTION FOR COLLABORATIVE TASKS

Alexandre Angleraud, Roel Pieters
Tampere University of Technology, Laboratory of Automation and Hydraulics
alexandre.angleraud@tut.fi

## ABSTRACT

A human and a robot working in pair produces a better and faster result than if they worked individually [1]. This collaboration is particularly adapted to explicit tasks which makes it a great asset for manufacturing lines. However, these interactions come with challenges such as strict time constraints in planning, advanced perception abilities, and of course, an absolute need for safety. More practically, this means that human and robot need to be aware of each other in order to make the collaboration possible. To investigate these novelties in human-robot interaction, we propose to build a demonstrator composed of one or two robotic arms reproducing an industrial context with a collaborative task to perform. This demonstrator will be equipped with different sensors allowing it to be conscious of its environment and a display system that will enable the communication with a human agent. By developing a cognitive system on top of this system we want to showcase the different improvements that it could bring upon the manufacturing world.

## CONCEPT

Although robots are already present in our industries, their use is limited to a restricted number of tasks and it is still hard to change and reprogram them for another set of actions. Moreover, in certain cases, humans just tend to perform better than robots at a specific task. For these reasons, research about cobots, i.e., robots meant for interaction and collaboration with humans, is an ongoing topic all around the world. Such systems have the opportunity to mix the best from the robot side but also from the human side and in this sense, cobots could be a way to rethink our industries, as part of the industry 4.0 movement [2].

However, two keys for this change to happen are the cost and the ease of use of the final system. We can already take lessons from other ongoing projects such as the two robots of Rethink Robotics in the USA, Baxter and Sawyer [3]. The first one, Baxter, is a two robotic arms solution for the manufacturing lines featuring force sensing and 7 DoF for each arm as well as a safe behavior near humans. As for Sawyer it offers the same flexibility but is composed of only one arm having a longer reach and taking less space than Baxter. They both use a software called Intera which consists in a train-by-demonstration interface for the ease of deployment. We can also think about the German project iMRK conducted in collaboration with Volkswagen [4] which resulted in a dual arm manipulation platform that could be controlled with human gestures. This shows that it is possible to produce robots for collaboration with humans. The next challenge is now to make the software evolve in a way that makes robots able to handle more tasks while keeping in mind the importance of having an intuitive interaction.

On a more technical level, previous works with reasoning through ontologies and collaborative robotics include [5] in which a framework has been developed to tackle the human activity recognition challenges that we could need in the process of teaching new tasks to the cobot. In [6], human activity recognition is also addressed with a focus on how to handle the different styles that could be encountered among humans when doing the same kind of action. This work brings the idea of really understanding what is being demonstrated. More recently, in [7] learning is considered from the perspective of memory skills to take into account the previous executions of a task. Our ideas are similar but aim at developing the potential interactions in the reasoning process whereas the described works were investigating automated solutions from artificial intelligence. Of course, one of our option would be to build an hybrid system taking advantage of both sides.

The object of our research is the construction of a demonstrator to investigate collaborative tasks between humans and robots through various interactions with a certain degree of awareness from the robot. The challenges addressed here are the following. First we want to develop the existing solutions for the perception interface that is needed to gather enough information about the environment. Our second objective is to rethink the interface between the robot and human agents allowing an efficient exchange of information adapted to the industrial environment in which the robot will be deployed. Finally, we want to have a software that can use ontologies to build a knowledge base about the different components of the environment and bring awareness in the collaboration between the human and the robot. This would allow us to take into accounts the task to perform and plan an efficient way to perform it using the different agents available. This software would also contain a way to enable humans to teach a task in an intuitive way using the latest technologies such as augmented reality for example.

A transversal goal in this work concerns the safety issues that occur during the collaboration between a human and a robot. Recently, standards have been established and we thus have precise criterias to qualify the robustness of our system [8]. As an example, the ISO/TS 15066 specifies the following : "safety requirements for collaborative industrial robot systems and the work environment, and supplements the requirements and guidance on collaborative industrial robot operation". Furthermore, to ensure the operationality of our product, testing is also an important part for us and our future partners. In [9] is described an approach for this, to allow more transparency in the testing process.

To validate our research we will mainly use the Franka Emika arm and its 2-fingers gripper even though using a second arm to allow more potential applications is also considered. In a first time the product will be developed in collaboration with a limited amount of industrial partners but enlarging this number would be a goal for the next part of our research plan.

When working with robots everyday, it is easy to forget "'What can I do with this robot ?'' as explained in [10] by an engineer of the Robotiq company. However, here is how he classifies the different applications of collaborative robotics. First would be machine tending, second packaging and finally material handling. If these terms can be representative of a lot of different tasks, the precise use cases and how to adapt the system in the best way according to its purpose is something that we will discuss with our industrial partners.

## GOALS

By building this demonstrator our main goals are as follows. First, to make progress in what we believe could increase the performances of the manufacturing environment. Second, to boost the cooperation between academia and industry, especially towards SMEs. As a result, by having ways to produce faster and better, companies having part of their activities in other countries to reduce the productions costs could be able to come back to a local production. The possible applications are wide, as the industry presents an important amount of tasks that could be affected by human-robot collaboration.

## REFERENCES

[1] Frank Tobe (30 Dec 2015). Why Co-Bots will be a huge innovation and growth driver for robotics industry. Retrieved from https://spectrum.ieee.org/automaton/robotics/industrial-robots/collaborative-robots-innovation-growth-driver

[2] Cencen, Argun & Verlinden, Jouke & Geraedts, Jo. (2016). Qualifying the performance of human-robot coproduction at a relabling station.

[3] Duhamel et al. “Rethink Robotics - Finding a Market” Stanford CasePublisher 204-2013-1. 20 May 2013.

[4] José de Gea Fernández, Dennis Mronga, Martin Günther, Malte Wirkus, Martin Schröer, Stefan Stiene, Elsa Kirchner, Vinzenz Bargsten, Timo Bänziger, Johannes Teiwes, Thomas Krüger, Frank Kirchner (2017). iMRK: Demonstrator for Intelligent and Intuitive Human-Robot Collaboration in Industrial Manufacturing

[5] Karinne Ramirez-Amaro, Michael Beetz and Gordon Cheng, Understanding the intention of human activities through semantic perception: observation, understanding and execution on a humanoid robot. Advanced Robotics 29 (5), 2015, 345-362

[6] Karinne Ramirez-Amaro, Emmanuel Dean-Leon, and Gordon Cheng, Robust Semantic Representations for Inferring Human Co-manipulation Activities even with Different Demonstration Styles. 15th IEEE-RAS International Conference on Humanoid Robots, 2015.

[7] Ferenc Balint-Benczedi, Zoltan-Csaba Marton, Maximilian Durner, Michael Beetz, "Storing and Retrieving Perceptual Episodic Memories for Long-term Manipulation Tasks", In Proceedings of the 2017 IEEE International Conference on Advanced Robotics (ICAR), Hong-Kong, China, 2017. Finalist for Best Paper Award

[8] Roberta Nelson Shea and Seungmin Baek (11 Nov 2016). Demystifying cobot safety : The four types of collaborative operation.
Retrieved from : https://blog.universal-robots.com/demystifying-cobot-safety-the-four-types-of-collaborative-operation

[9] Florian Weisshardt, Jannik Kett, Thiago de Freitas Oliveira Araujo, Alexander Bubeck, Alexander Verl, Enhancing Software Portability with a Testing and Evaluation Platform, Verband Deutscher Elektrotechniker e.V. -VDE-, Berlin: ISR/Robotik 2014, Joint Conference of 45th International Symposium on Robotics and 8th German Conference on Robotics. Proceedings. CD-ROM : 2 -3 June 2014, Munich, Germany.

[10] Mathieu Bélanger-Barrette (28 Oct 2015). 3 Best Collaborative Robot Applications. Retrieved from https://blog.robotiq.com/3-best-collaborative-robots-applications

# 12. AN OPEN-SOURCE, CONFIGURABLE IOT PLATFORM FOR REMOTE MONITORING OF SMART MACHINES

Ananda Chakraborti, Olli Usenius, Henri Vainio, Jussi Aaltonen, Kari Koskinen
Mechatronics Research Group, Mechanical Engineering and Industrial Systems, TUT
ananda.chakraborti@tut.fi

## ABSTRACT

Industrial Internet of Things (IIoT) and Cyber Physical Systems (CPS) have brought forth several connected devices with web-based data collection and monitoring platforms, which can extract machine data from sensors and provide valuable insights to the working of smart machines. Nowadays, use of such IoT platforms are getting more common in mobile industrial machines and manufacturing systems. However, no open-source, fully configurable IoT platform exists which can be easily integrated with the control system of any mobile machinery including machines with legacy systems to remotely monitor machine specific details in real-time. The main contribution of this article is to provide systematic guidelines in integrating various enabling technologies to develop such a platform, which collect, store and process data from mobile machineries to gain insights on its condition and represent information with end user devices.

## INTRODUCTION

Industrial Internet of Things philosophy has resulted in a rapidly growing ecosystem of open source IoT platforms for monitoring physical processes in industrial systems and mobile machineries. The open source nature of these platforms has attracted large communities of developers, enthusiast and businesses to contribute and enhance features of these platforms. However, adoption of these platforms by industries are rare because of the complexity in integrating various heterogeneous components to have seamless interoperation between real and virtual environments (Joseph Boman, 2014). These heterogeneous components are different hardware and software used in developing the platform. It is challenging to develop a messaging mechanism to communicate between these heterogeneous components with cross-platform technologies in autonomous industrial systems (Zhaozong Meng, 2016). The rest of the article is organized as follows. First the enabling technologies are introduced which are leveraged to build the platform. Then the platform and its capabilities are discussed and finally the conclusion is drawn.

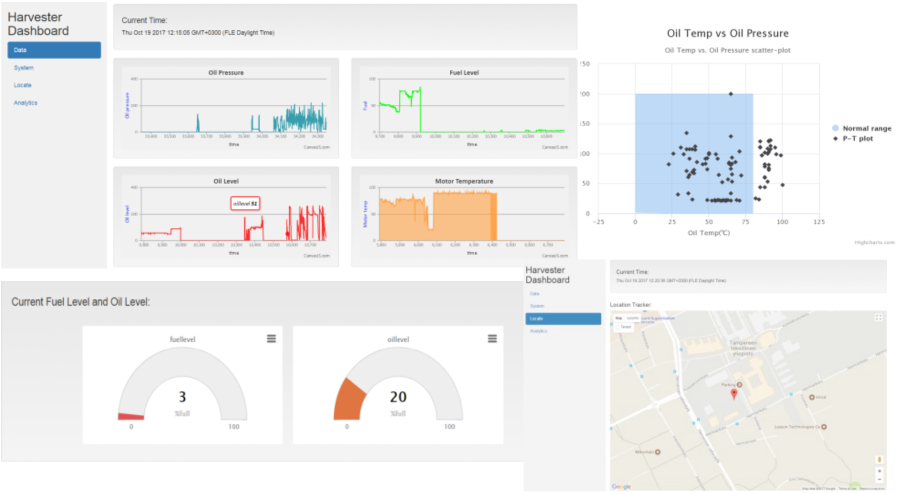
## ENABLING TECHNOLOGIES

IIoT depend on enabling technologies like smart sensors, embedded devices, communication and connectivity protocols, public and private cloud and data analytics. Smart sensors help in IoT sensing which means gathering data from the physical environment and sending it to a data warehouse or cloud where this data is processed. In industrial mobile machineries, interchange of digital information between sensors and electronic control units is done with serial communication protocol ISO 11898 (Controller Area Network) (ISO, 2006). Embedded devices are critical to IIoT platform operation. Sometime these embedded devices are Single Board Computers (SBCs) with built-in TCP/IP and security functionalities to gather, process, and send data to remote storage (Ala Al-Fuqaha, 2015). Connectivity protocols put the heterogeneous components together. The connectivity protocol can be wired or wireless. Example of wired connectivity protocol is IEEE 802.3 (Ethernet) (Healey, 2017). Examples of wireless connectivity protocols are IEEE 802.11 (Wireless Local Area Network) (Stephens, 2017), BLE (Bluetooth Low Energy), Zigbee, Low Power Wide Area Network like LoRA and SigFox or Cellular technologies like GSM, 3G, LTE etc. Communication protocols enables messaging between different hardware and software components. There are two communication patterns widely used between components in IoT platforms for real-time data exchange. They are Request-Response model (e.g. HTTP) and Publish-Subscribe model (e.g. MQTT) (Laurent Pellegrino, 2013).

Open source software components enable easier interoperability between the platform and the physical device. NodeJS is an open-source cross-platform JavaScript runtime environment, which is a popular platform for server-side development. NoSQL database allows storage and query of unstructured data from different devices. IoT platforms are capable of doing remote monitoring because of data collection strategy from sensors and storing them in cloud repositories or remote databases. Use of public cloud services offered by popular cloud service providers can provide on-demand pay-per-use data storage, analytics, devices and data management functionalities but at the cost of security. Private clouds on the other hand provide highest degree of control over performance, reliability and security. However, private cloud services are built by organizations for their own usage (Qi Zhang, 2010). Computationally intensive analytics are more expensive on private cloud. Security is an increasing concern for CPS. Modern CPS are pervasively monitored systems capable of networking with each other. These systems are resource constrained and safety critical. Hence, the threat is not just from external cyber-attacks trying to compromise information security but also within the system like data integrity.

## THE PLATFORM

This cross-platform technology brings together heterogeneous hardware and software. Process data is collected from in-built sensors of the smart machine with CAN Bus based controller. This controller uses low level firmware developed with C following MISRA C guidelines (C, 2016) for safety critical applications. It supports standard TCP/IP protocol to communicate with remote server. GSM device is used as a gateway. GSM has longest range and reasonable data rate in cellular networks suitable for near real-time remote monitoring applications in mobile machineries. The firmware post data from the device to a single-server running on a public network instance over HTTP. The server-side development is done with NodeJS. An open source NoSQL database runs as a service in the server instance. The platform remotely monitors process data from the smart machine as well as display historic data from the smart machine sensors. The platform also tracks and displays the location of the machine. The platform is capable of doing simple analytics such as regression analysis of machine data, online in real-time. Figure 1 shows a snapshot of the platform and its capabilities.



Current Time:
Thu Oct 19 2017 12:15:06 GMT+0300 (FLE Daylight Time)

Current Fuel Level and Oil Level:

Current Time:
Thu Oct 19 2017 12:20:36 GMT+0300 (FLE Daylight Time)

Location Tracker:

Figure 1. The open source IoT platform

As standard open source technologies are used to build this platform, it is fully customizable and configurable. It is also easy to add new features to this platform and remove unwanted components.

## CONCLUSION

Because of the simplicity in hardware-software integration and communication, this platform can be easily installed, configured and put to use in any mobile machinery or industrial system with CAN Bus based control system. This platform can be beneficial for fleet owners who want to monitor their machines as well as other industrial service providers such as maintenance or logistic services. Smart machine platforms like this can also serve as test-bench for researchers to study and integrate future technologies such as AI and human-machine interaction with industrial machineries.

## REFERENCES

Ala Al-Fuqaha, M. G. (2015). Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. IEEE COMMUNICATION SURVEYS & TUTORIALS.

C, M. (2016). MISRA C Guideline. UK: HORIBA MIRA .

Healey, A. (2017). IEEE 802.3 ETHERNET WORKING GROUP. IEEE.

ISO. (2006). Road vehicles — Controller area network (CAN) — Part 3: Low-speed, fault-tolerant, medium-dependent interface. ISO.

Joseph Boman, J. T. (2014). Flexible IoT Middleware for Integration of Things and Applications. 10th IEEE International Conference on Collaborative Computing. Maimi, Florida: IEEE.

Karl Koscher, A. C. (2010). Experimental Security Analysis of a Modern Automobile. IEEE Symposium on Security and Privacy. IEEE.

Laurent Pellegrino, F. H. (2013). A Distributed Publish/Subscribe System for RDF Data. International Conference on Data Management in Cloud, Grid and P2P Systems (ss. 39-50). Berlin : Springer.

Liikanen, E. (2003). Commission recommendation. Retrieved 9 17, 2016, from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32003H0361&from=EN

Mark Yampolskiy, P. H. (2012). Systematic analysis of cyber-attacks on CPS-evaluating applicability of DFD-based approach. Resilient Control Systems (ISRCS). Salt Lake City, USA: IEEE.

PratimRay, P. (2016). A survey of IoT cloud platforms. Future Computing and Informatics Journal, 35-46.

Qi Zhang, L. C. (2010). Cloud computing: state-of-the-art and research challenges. Journal of Internet Service Application, 7-18.

Quintana, V., Rivest, L., Pellerin, R., Venne, F., & Kheddouci, F. (2010). Will Model-based Definition replace engineering drawings throughout the product lifecycle? A global perspective from aerospace industry. Computers in Industry, 2010(61), 497-508.

Ruemler, S. P., Zimmermann, K. E., Hartman, N. W., Hedberg, T. J., & Feeny, A. B. (2016). Promoting Model-based Definition to Establish a Complete Product Definition. Journal of Manufacturing Science and Engineering, 2016.

Stephens, A. (2017). IEEE 802.11TM WIRELESS LOCAL AREA NETWORKS. IEEE.

Xiao-Hong, L. (2014). Research and Development of Web of Things System Based on Rest Architecture. Intelligent Systems Design and Engineering Applications (ISDEA). Hunan, China: IEEE.

Zhaozong Meng, Z. W. (2016). A Data-Oriented M2M Messaging Mechanism for Industrial IoT Applications. IEEE Internet of Things Journal, 236 - 246.

# 13. SAFETY CONSIDERATIONS IN THE DESIGN AND VALIDATION OF AUTONOMOUS MACHINE SYSTEMS

Eetu Heikkilä, Risto Tiusanen, Heli Helaakoski
VTT Technical Research Centre of Finland Ltd, Machine Health
eetu.heikkila@vtt.fi

## ABSTRACT

The advances in robotics, artificial intelligence, and communication technology are making industrial applications increasingly autonomous. For manufacturing companies this means transformation towards digitized enterprise that requires the development of core elements, such as building the data ecosystem, choosing the right techniques and tools, integrating technology into workplace processes, and adopting an open, collaborative culture. The rapid introduction of new technologies, combined with increasing human-machine interaction, brings along new and modified safety risks. For most industrial machine systems, the lack of existing standards and best practices further complicates the design and validation of these applications. In this paper, we identify the focal challenges in the design process of safe autonomous machine systems from a systems engineering perspective. As a result, the methodology and tools to be used in various phases of the design process are discussed. The needs for extensions to the systems engineering approach are also considered.

## INTRODUCTION

Increasing autonomy is a global trend in industry, with industries like transportation and manufacturing leading the way in the change. Autonomous systems are seen as means to increase productivity, cost efficiency and safety – not only by reducing the work done by humans, but also by enabling completely new business models. The concept of autonomy, however, has no single agreed definition and it is common that the terms “automation” and “autonomy” are used interchangeably. Autonomy, however, goes beyond automation by adding self-governing behavior and requiring intelligent decision-making abilities (NFA, 2012). The concept of autonomy also involves operation in complex domains, often in co-operation with humans. Autonomy is not a definite system characteristic. Instead, the transformation towards more autonomous systems is an incremental process and various autonomy level categorizations are available in different fields to demonstrate the gradual change. In these categorizations, the autonomy levels usually range from fully human operated to fully autonomous, with several semi-autonomous levels in between. In this paper, we focus only on high levels of autonomy, where the system operates autonomously with possible human supervision, but without the need for human interference in the majority of operational scenarios. Additionally, we focus on the safety risks in the intended performance of these systems, while cyber security threats are excluded in this context.

Increasing autonomy is not a limited to increasing the autonomy levels of individual devices. Instead, in many industries, it can cause disruption in the entire business by enabling the usage of novel approaches, such as by replacing heavy machinery with fleets of lighter devices. The resulting changes in the ways of working bring along new and modified safety risks. While general guidelines for safety considerations exist (e.g. IEEE, 2016), detailed standards and legislation are only slowly becoming available in limited applications, such as in the automotive industry – but also in limited industrial applications, such as. earth-moving machinery and mining (ISO17757:2017). Instead of the traditional prescriptive nature of standards, however, the new standards focus more on providing general performance guidelines (Danks & London, 2017). Thus, the technology developers bear an increasing responsibility for ensuring the safe operation of autonomous systems. This further increases the importance of a systematic design and validation approach.

## CHALLENGES IN DESIGN AND VALIDATION

The challenges in design and validation were studied by following a systems engineering V-model, which is a typical method to facilitate a top-down design process of a complex system. Several versions of the model exist for different purposes, but generally they represent the system development process moving from concept development towards more detailed design, implementation, and testing phases. In Figure 1, a simple V-model is presented with focal challenges brought along by increasing autonomy described in each step.

In the design of complex autonomous systems, the focus of activities is likely to concentrate towards the earliest stages of the design process. Organizations are putting increasing effort to understanding the risks involved in the earliest possible phase. This sets increasing demand for high-quality system description and requirements management methods. For autonomous systems, the system definition needs to be broader than in traditional system design. The definition needs to include the relevant information regarding the operating environment, stakeholders involved in the operation, and the different interfaces through which the system interacts with its environment. The requirements for the autonomous system's performance within all relevant situations need to be documented. For example, a Concept of Operations approach (see e.g. Osborne et al. 2005) can be used to produce a comprehensive description.

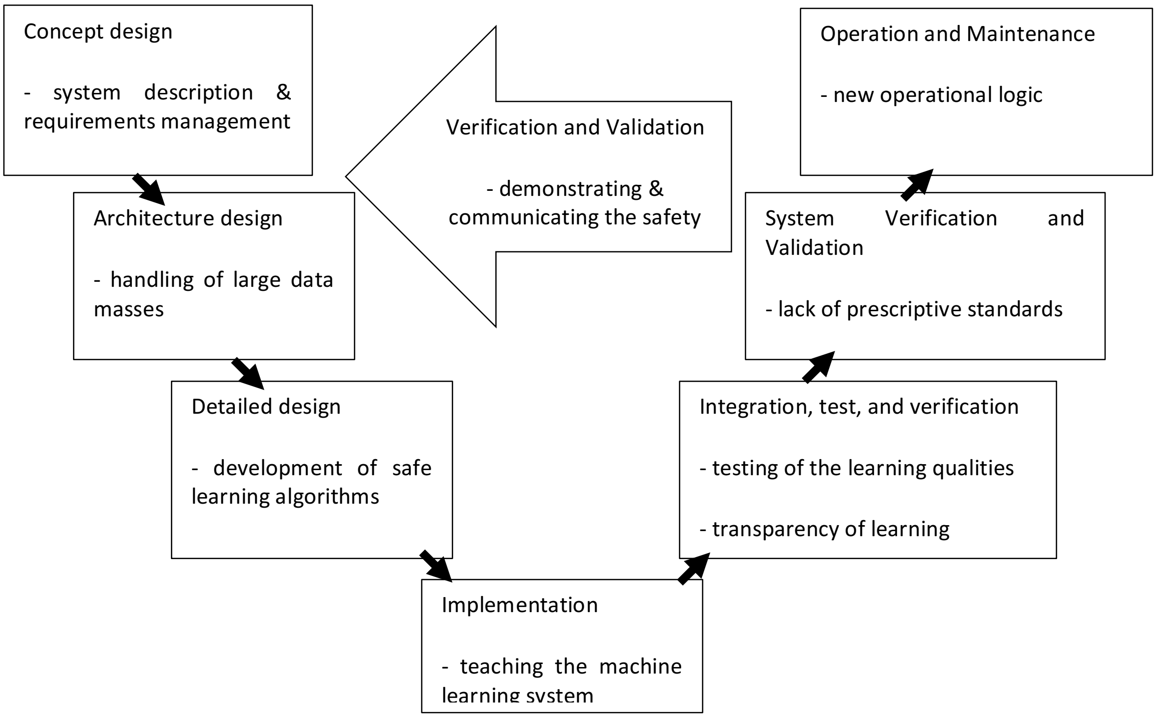


*Figure 1. A systems engineering V model (adopted from Osborne et al., 2005), with selected focal challenges for design and validation of autonomous systems.*

In the architecture design phase, the largest challenges are set by the large data amounts that need to be created and processed reliably to enable autonomous operation. This involves also the planning of how the data is used to teach the autonomous system by using machine learning methods. The learning capabilities of the autonomous system also need to be considered throughout the rest of the development process. This includes validation of the system's learning in various scenarios, which is likely to increase the need for advanced simulator testing. The transparency of the machine learning principles adds further challenges, as the developer may be unaware of the details of the actual machine learning process. To address these needs, certain expansions have been proposed to the V-model to incorporate the adaptive and learning characteristics. For example, Falcini & Lami (2017) propose a "W-model" to account for the effects of machine learning capabilities in autonomous systems. In the W-model methodology, a parallel process is introduced to facilitate data-driven training and validation of the machine learning application.

In the verification & validation phase, the lack of prescriptive standards sets increasing requirements also for the safety communication. A goal-based approach has been proposed as a method to communicate the relationship between the system requirements and safety validation results (Heikkilä et al., 2017). Finally, in the operation phase, the role of well-facilitated change management procedures is likely to increase when modifications are introduced into the system.

## CONCLUSIONS

The increasing autonomy in machine systems imposes increasing demands on the design and validation processes. Focal challenges for design and validation were identified as follows: quality of system description and requirements management, design & validation of safe and transparent machine learning, and safety communication with respect to the system requirements.

While individual tools are available for managing these individual aspects, and extensions have been proposed to the V-model approach, a holistic approach for the design of autonomous systems has not yet been developed. Development of such methodology is seen as an important area for future research to ensure the safe and sustainable introduction of increasingly autonomous applications. A comprehensive methodology could also be incorporated into a broader future framework for the assessment of entire lifecycle of autonomous systems.

## REFERENCES

Danks D., London A. 2017. *Regulating autonomous systems: Beyond standards*. IEEE Intelligent Systems. Vol. 32:1. IEEE.

Falcini F., Lami G. 2017. *Deep Learning in Automotive: Challenges and Opportunities*. Communications in Computer and Information Science, vol 770. Springer.

IEEE. 2016. *Ethically Aligned Design: A Vision for Prioritizing Wellbeing with Artificial Intelligence and Autonomous Systems, Version 1*. IEEE.

ISO17757:2017. *Earth-moving machinery and mining – Autonomous and semi-autonomous machine system safety.* ISO.

Heikkilä E., et al. 2017. *Safety Qualification Process for an Autonomous Ship Prototype – a Goal-based Safety Case Approach*. Marine Navigation: Proceedings of the 12th International Conference on Marine Navigation and Safety of Sea Transportation (TransNav 2017).

NFA Norwegian Society of Automatic Control. 2012. *Autonomous Systems: Opportunities and Challenges for the Oil & Gas Industry.* NFA.

Osborne L. et al., 2005. Clarus: Concept of Operations, Washington D.C., USA:Federal Highway Administration.

# 14. SIMULATING THE DRAG COEFFICIENT OF A SPHERICAL AUTONOMOUS UNDERWATER VEHICLE

Arttu Heininen, Jussi Aaltonen, Kari T. Koskinen
Tampere University of Technology, Mechanical Engineering and Industrial Systems
arttu.heininen@tut.fi

## ABSTRACT

In this paper, an AUV pressure drag simulations with different velocities are presented. The AUV’s main hull is spherical but its instrumental components extend out of the hull, and interfere with the flow. A pressure drag coefficient of a sphere was simulated to decide the used turbulence model (SST k-ω), by comparing simulation results to those found in literature. Then, simulations were done with different velocities to understand the behaviour of the AUV drag coefficient. These results can be used to improve the control system of the AUV and are an important factor in the AUV energy consumption.

## INTRODUCTION

One of the most important design factors of an autonomous underwater vehicle (AUV) is its shape. Shape affects directly to the drag coefficient. Along with other hydrodynamic derivatives, the drag coefficient dictates the AUV motion and energy consumption while moving. The larger the drag the more energy is required for a constant motion. This is the reason why there are plethora of torpedo-shaped AUVs found in the literature.

Conventionally, the drag coefficient is measured using a tow-tank. At present, the drag coefficient can be simulated using computational fluid dynamics (CFD). The simulation usually requires validation, so both the measurements and simulation are used together. However, in the early design stage, simulation provides information that is not available otherwise and this reduces the amount of required prototypes and measurements.

Usually the flow around an AUV is turbulent. Turbulence is often modelled using so-called turbulence models. In this paper, it is shown how an early stage simulation process could be done by choosing a turbulence model and then calculating the drag coefficient of an AUV.

## CHOOSING THE TURBULENCE MODEL

The drag coefficient, $C_d$, of a sphere can be estimated using equation [1, p. 624]:

$$C_d = \frac{24}{\mathrm{Re}} + \frac{2.6\left(\frac{\mathrm{Re}}{5.0}\right)}{1+\left(\frac{\mathrm{Re}}{5.0}\right)^{1.52}} + \frac{0.411\left(\frac{\mathrm{Re}}{263\,000}\right)^{-7.94}}{1+\left(\frac{\mathrm{Re}}{263\,000}\right)^{-8.00}} + \frac{0.25\left(\frac{\mathrm{Re}}{10^6}\right)}{1+\left(\frac{\mathrm{Re}}{10^6}\right)} \qquad (1)$$

where $Re$ is the Reynolds number [1, p. 622]. For a sphere with a diameter of 0.6 m the drag coefficient is 0.28, with flow velocity of 2 km/h, which is the AUV target velocity. When the flow velocity is fast enough, flow is separated from the surface of the sphere. According to [2, p. 92] SST k-ω turbulence model is suitable for separating flows. Using this turbulence model, a simulation was performed for the sphere with the same velocity as above, shown in Figure 4.

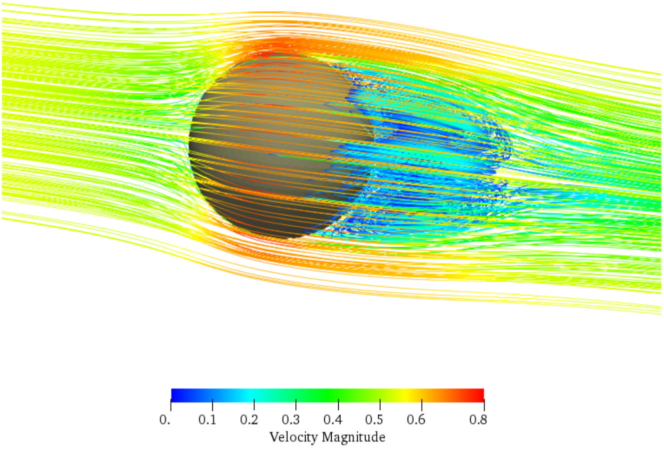


*Figure 4. A separated flow around a sphere*

The drag force is calculated from the pressure field around the sphere, and the pressure field from the velocity field. The drag coefficient is:

$$C_D = \frac{F_D}{\frac{1}{2}\rho V_\infty^2 A_P} \tag{2}$$

and from the simulation it is 0.29, which is close to the one calculated earlier. In this case, the SST k-ω turbulence model performs sufficiently.

## THE DRAG COEFFICIENT OF THE SPHERICAL AUV

The AUV has cylindrical instruments out of the spherical main hull. These instruments affect the drag coefficient by disturbing the flow, and are shown in Figure 5, which also shows the CFD grid that was generated. The grid has 978 000 volumes and most of those are near the AUV to capture the flow field in detail. Using this grid, simulations were run with different flow velocities. The drag coefficient was calculated for each case.

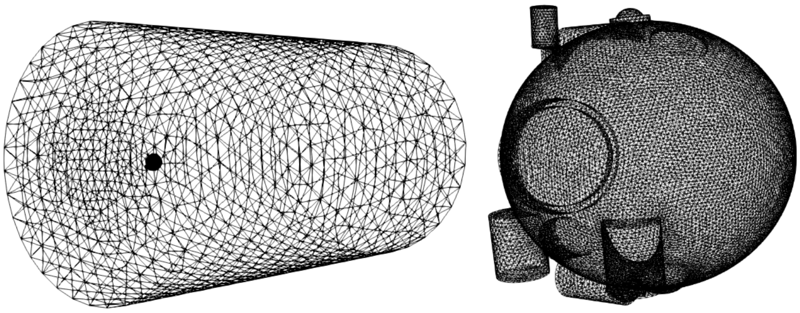


*Figure 5. The grid generated for the AUV.*

After the initial seconds of the simulation, the drag coefficient tends towards to a single value. The protruding instruments cause some variation, and therefore, a time average was taken between certain time steps of the simulation. The results are shown below.

*Table 2. Drag coefficients for different velocities.*

| Velocity: | Drag coefficient: |
|---|---|
| 1.0 km/h | 0.35 |
| 1.5 km/h | 0.33 |
| 2.0 km/h | 0.30 |
| 3.0 km/h | 0.42 |

Velocity field and vortices around the AUV (2 km/h) are shown in **Virhe. Viitteen lähdettä ei löytynyt.**. Changing velocity changes also vortices that the protruding instruments causes.

Figure 6 shows the Equation 1 plotted with the simulated values marked. It can be seen that the AUV drag coefficient behaves closely to that of a sphere. More simulations and measurements to validate these simulations are required to fully understand the hydrodynamics of the AUV. Grid independence must be studied, as the boundary layer grid around the AUV used here was designed for the target velocity and might not be suitable for other velocities. Also, there are other hydrodynamic derivatives that need to be studied.

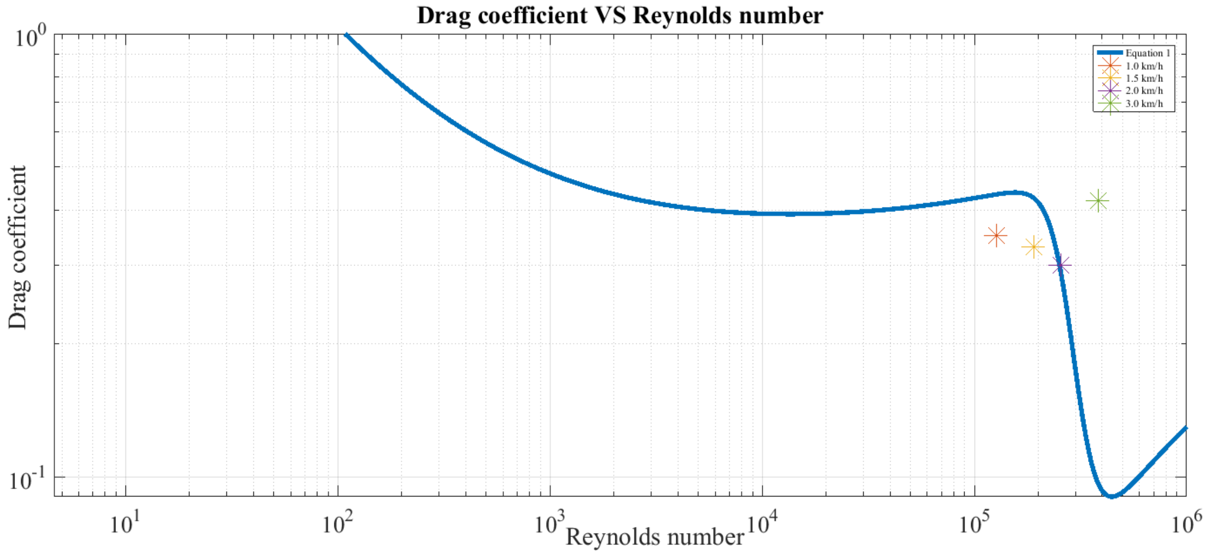


*Figure 6. Equation 1 and the simulation results.*

## CONCLUSION

The simulated drag coefficient of the AUV is in close agreement with that of a sphere. The turbulence model chosen proved to work well for this application. However, more information from simulation and measurements are required to fully understand how the flow develops around the AUV. In the early design stage, when measurements are not available, simulation is a useful tool to aid the design process. The information gained here can be used to develop the AUV control system and to calculate the required batteries inside the AUV, as the energy consumption during movement is directly proportional to drag.

## REFERENCES

[1] Morrison, F., A., An introduction to fluid mechanics, Cambridge University Press, New York, USA, 2013.

[2] Versteeg, H., K., Malalasekera, W., An introduction to computational fluid mechancics, Pearson Education Limited, Harlow, England, 2007.

## 15. AUTONOMOUS AND COLLABORATIVE OFFSHORE ROBOTICS

Jose Villa Escusol, Jussi Aaltonen, Kari T. Koskinen
Mechanical Engineering and Industrial Systems
Tampere University of Technology
jose.villa@tut.fi

### ABSTRACT

Autonomous robotic systems are becoming increasingly important in many industries. Many different industries include work and tasks that could be done faster and more safely without any human interaction. These tasks vary from underwater mining and maritime to borderline guarding. This research opening is creating the basic methodology for an autonomous offshore robotic system and open demonstration in a working environment. The autonomous robotic system includes collaborative features between aerial subsystems (Unmanned Aerial System/Drone) and waterborne subsystems (Autonomous Surface Vessel and Autonomous Underwater Vehicle) to carry out inspections or other actions without a need for any kind of human interaction. These research results of the new cooperation principles will provide possibility to find new business opportunities in the autonomous maritime ecosystem.

### INTRODUCTION

In this paper, the research opening “Autonomous and Collaborative offshore robotics” is going to be explained. The main objective of the research opening is to develop novel collaborative methods between a complete autonomous robot system. Additionally, this robot system operates in an offshore environment and covers all three possible scenarios (air, water surface and underwater) by an Unmanned Aerial System (UAS), an Unmanned Surface Vessel (USV) and an Autonomous Underwater vehicle (AUV) respectively. The ultimate goal is a complete demonstration of the offshore system in an open-real environment.

The research opening will focus on developing methodology for shared intelligence, including system and mission control, situational awareness and evolving capabilities tasks. In addition, offshore field testing and building a demonstration will be highly focused in this research.

### IMPLEMENTATION

The accomplishment of the research opening is the demonstration in a complete autonomous operation of the offshore robotic system consisting of an UAS, an USV and an AUV, all working in collaboration. The USV is used as an autonomous launch and recovery platform, and as a docking unit, where the UAS/Drone and AUV batteries can be recharged and the data they have acquired can be uploaded to cloud storage. The USV docking station system is able to process data, monitor and control operations to enable more reliable, faster and more efficient data uploads. Furthermore, the data consistency can automatically be evaluated by the given if missions need to be repeated in any possible scenario. The UAS is used as a sensor platform for the USV. This gives the system a completely new perspective and a lot more range for many sensors that can not be installed in the USV. Moreover, the UAS gives the USV some short range for mapping capabilities. Finally, the UAV is used as an autonomous underwater explorer. This subsystem is able to operate in inspection-class or research-class missions.

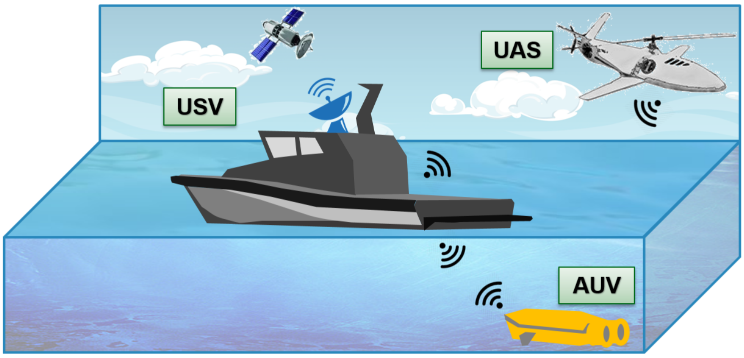


*Figure 1. Schematic of the aCOLOR system*

Apart from the ultimate goal of the complete demonstration, the main point is the shared intelligence research. This shared intelligence comprises:

- System and mission control: Formed by low-level control of each robot subsystem, the working principles of each vehicle to work autonomously and in collaboration, and mission planning, navigation and sensor data obtaining.
- Situational awareness: Sensor data obtaining and obstacle avoidance of the three subsystems.
- Evolving capabilities: Ability to develop when the robotic system makes common activities. The system works faster as it already learnt how to face comparable tasks. It comprises artificial intelligence, situational awareness and mission control.
- Demonstration: Includes the implementation of the autonomous and collaborative features and a pilot scale test and demonstrations in close and open-real environment. Concerning about the needed infrastructure for the Pilot and Demonstration phases, field testing, piloting and demonstrations will utilize existing research and development (R&D) infrastructure.

*Figure 2. Existing R&D infrastructure (Alamarin-Jet Oy)*

Regarding the research cases, response to unknown environments, such as river environments or no satellite data, situation awareness (monitoring the position and working conditions of all subsystems), common missions, such as search and rescue of the subsystems, and redundancy of the system (replacement radar with vision features) have to be researched in this offshore robotic system. Furthermore, according to end-user cases, e.g. underwater mining, various activities including mapping or equipment maintenance can be studied and tested in this research.

## SOCIETAL IMPORTANCE

These research results of the new cooperation principles will provide possibility to find new business opportunities in the autonomous maritime ecosystem. The results will also enable to make current operations safer and more efficient in demanding environments. Autonomous robotic systems are becoming increasingly important in many industries. In this research opening, the multi-component offshore robotic system can answer needs of many different industries such as ocean/sea transportation (e.g. emerging autonomous shipping), underwater mining, offshore renewable energy or needs of public authorities (customs or border guard).

## CONCLUSIONS

This research opening creates a technological and methodological basis for unmanned systems required in several applications services needed in the future maritime industries. As the USV used in this research opening works as an autonomous carrier platform, docking unit and communication relay station, there is no need for any kind of human-being interaction, making every activity more efficient and safer.

In general, offshore inspections and many other offshore operations still remain very labour intensive and expensive activities, typically requiring at least support surface vessels being manned. According to that, this research contributes in making any marine and offshore inspection operations autonomous in any scenario (air, water surface and underwater).

## 16. FUNCTIONAL HIERARCHY IN AUTONOMOUS ROBOT

Soheil Zavari,Tuomas Salomaa, Jose Villa Escusol, Jussi Aaltonen, Kari T Koskinen Mechanical Engineering and Industrial System Tampere University of Technology soheil.zavari@tut.fi

### ABSTRACT

The process of design and manufacturing of the UX-1 concern with considering a variety of design requirements for the purpose of creating an autonomous explorer robot. However, due to restricted and harsh operating environment, the non-functional requirement such as space and weight highly determine overall design and operation of the system, and therefore the process of developing and building the robot comes with several trials and challenges. Hence the implemented FEM analysis demonstrates the optimize solution by considering the non-functional requirement which in turn directly effect on the design and properties of the robot.

### INTRODUCTION

The process of design and development of autonomous robot interacts with numerous parameters that need to be fulfilled and evolve during the process of design. Although robots are designed and developed for the different purpose, some common grounds fundamentals need to be taken to account. Despite the fact that design requirements, general hierarchical decomposition has been the topic of system engineering in mechanical design, there have been few research (refer to [1] and [2]) in robotic due to interacting with complex systems. In following the main requirements of the UX-1 (refer to [3]) is categorized and it is described that how Non-Functional Requirement (NFR) parameters can effect on multiple functionalities of the system. Later general hierarchy for an autonomous robot is shown, while there could be an interaction between parameters at different levels or the same level.

Since the design of an autonomous underwater robot interacts with multiple disciplines, evaluating the requirement of the system [refer to 4] become complex. In this work, there are requirements which are not directly related to the technical design of the system. However, they affect to a high degree on the system indirectly. For instance, adaptability and portability in the context of robot operating environment (mines channels and tunnels) effect on the modeling and design of the robot. However, there is no unit or mathematical relation to measuring the effect exactly. But Analytic Hierarchy Process (AHP) is one method in order to evaluate and verify the design method

### REQUIREMENT CATEGORIZATION OF THE SYSTEM

The following table demonstrates the NFR and FR parameters prior or during the development phase of the project.

*Table 3: Requirements Specification*

| Functional Requirement | Non-Functional requirement |
|---|---|
| Speed 2km/h | End users (stake holders) |
| 5 hours of operation | Pilot sites (internal stakeholder) |

| | |
|---|---|
| Operating depth of 500 m | Degree of freedom |
| Manoeuvre in vertical shafts and tunnels | Weight and volume (size) |

One of the crucial non-functional requirement of the system is the vertical stability of the robot in the water, which can be derived directly from the buoyancy and weight of the robot. As the robot is completely buoyant, then the weight of robot would be maximum 107 kg. Therefore the difference between two parameters determine criteria which further can evaluate the operation of the robot. In our case, it is decided that robot must be completely buoyant and therefore the robot weight is exactly 107 kg.

## GENERAL HIERARCHY DECOMPOSITION OF THE SYSTEM

The decompositions in this paper follow the general hierarchical decomposition. It should be noted that the robot includes multiple complex functions however for the purpose of decomposition one objective can include several functions. In brief, the main goal of the robot can be condensed to 'Autonomous vehicle for extracting mineral information' which would be on top of the hierarchy. Follwing, several concepts can be extracted from the former statement, which lead to several subsystems. Solely, by considering the mechanical aspect of the project, the main functionality of the system as an autonomous robot forms the main various level of hierarchy as maneuverability, structure, feedback, and power. Each layer can relate to another layer one way or both way.

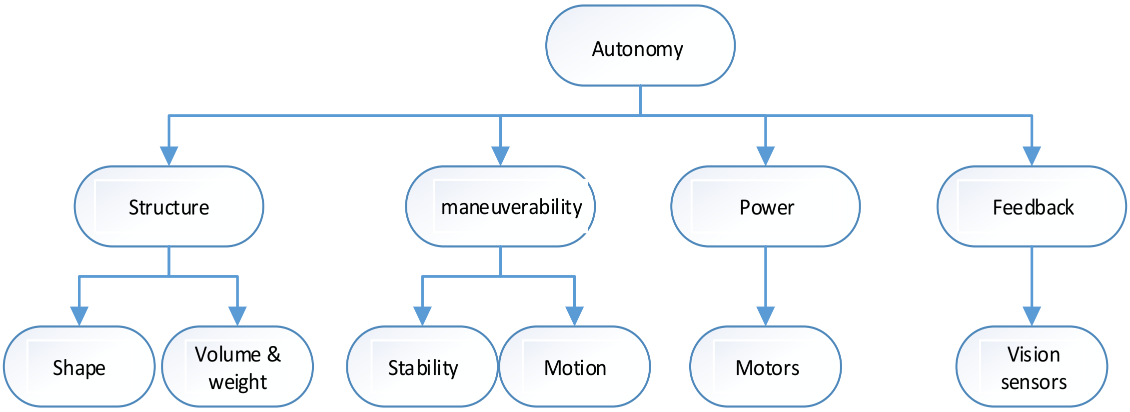


*Figure 7: General Hierarchy Decomposition*

The degree of freedom as functional requirement of the robot indicates the properties of the system. In this case heave, surge, heading, pitch, roll, and sway are the common degree of freedom for an underwater vehicles. The decomposition of maneuverability demonstrates the necessary degree of freedom which is horizontal and vertical motion (surge, heave), which can be operated independently (decoupled system), and therefore it demonstrates specific function of the system. On the other hand, degrees of freedom such as sway, roll, and pitch motion is not prioritized, and therefore they don't directly effect on accomplishing the goal of the project. Hence, the roll and sway motion is added into the system only after finding an optimized solution for thrusters configuration that supports maneuverability requirement (The functional analysis can determine the relation between sway and surge (or heave) motion that can be deliver as mathematic function. Indeed, further decomposition from feedback system, indicates that the robot must have pitch angle motion, which leads to the design of pendulum system.

## REQUIREMENT AND DECOMPOSITION

Figure 2 demonstrates how the non-functional requirement of the system effect on the hierarchy. For instance, since the site entrance tunnel is limited, the maximum robot size is required as 60 cm in diameter and consequently it indirectly effect on volume and weight as two major functional parameters of the robot. These parameters determine the robot stability which is sub level hierarchy decomposition of maneuverability. Simultaneously, the volume can determine the shape of the robot which in turn is sub level hierarchy decomposition of the structure. On the other hand, the figure indicates the flow direction in which NFR can determine the sub-functions and not the other way around.

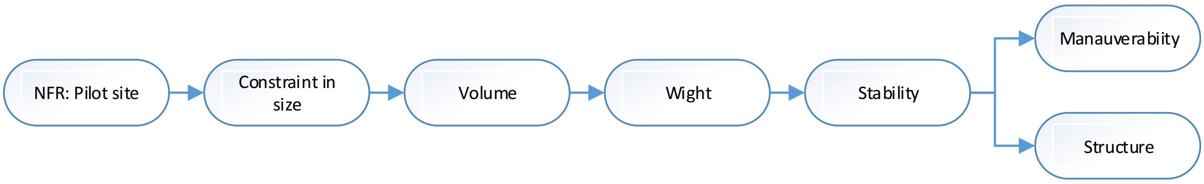


*Figure 8: NFR to Hierarchy*

## CONCLUSION

Since during the process of design, numerous parameters need to be taken to account, this paper aim to analyzed the requirements of the project in order to find the relationship between parameters. As future work AHP method can be applied to verify the final solution and design of the robot.

## REFERENCES

[1] Yamashita, Yuichi, and Jun Tani. "Emergence of functional hierarchy in a multiple timescale neural network model: a humanoid robot experiment." PLoS computational biology 4.11 (2008): e1000220

[2 ] Kirschman, C. F., G. M. Fadel, and C. Jara-Almonte. "Classifying functions for mechanical design." TRANSACTIONS-AMERICAN SOCIETY OF MECHANICAL ENGINEERS JOURNAL OF MECHANICAL DESIGN 120 (1998): 475-482.

[3] Zavari, Soheil, et al. "Early stage design of a spherical underwater robotic vehicle." System Theory, Control and Computing (ICSTCC), 2016 20th International Conference on. IEEE, 2016.

[4] Morita, Toshio, Hiroyasu Iwata, and Shigeki Sugano. "Human symbiotic robot design based on division and unification of functional requirements." Robotics and Automation, 2000. Proceedings. ICRA'00. IEEE International Conference on. Vol. 3. IEEE, 2000.

## LIST OF AUTHORS

1. Aaltonen Jussi
2. Ahonen Toni
3. Ahonen Toni
4. Angleraud Alexandre
5. Anttila Juha-Pekka
6. Auerkari Pertti
7. Chakraborti Ananda
8. Coatanéa Eric
9. Hakala Timo J.
10. Halme Jari
11. Hanski Jyri
12. Heikkilä Eetu
13. Heininen Arttu
14. Helaakoski Heli
15. Hosseini Mohammad
16. Kivikytö-Reponen Päivi
17. Koskinen Kari T.
18. Kujanpää Veli
19. Laukkanen Anssi
20. Leino Simo-Pekka
21. Mokhtarian Hossein
22. Niemi Arto
23. Paris Henri
24. Penttinen Jussi-Pekka
25. Pieters Roel
26. Puukko Pasi
27. Raunio Kalle
28. Reijonen Joni
29. Riipinen Tuomas
30. Saarela Olli
31. Salomaa Tuomas
32. Tiusanen Risto
33. Tuurna Satu
34. Usenius Olli
35. Vainio Henri
36. Vainio Henri
37. Valkokari Pasi
38. Vihinen Jorma
39. Villa Escusol Jose
40. Yli-Olli Sanni
41. Zavari Soheil

**#SMACCFinland**

**www.smacc.fi**

TAMPERE
UNIVERSITY OF
TECHNOLOGY

VTT
TECHNOLOGY FOR BUSINESS