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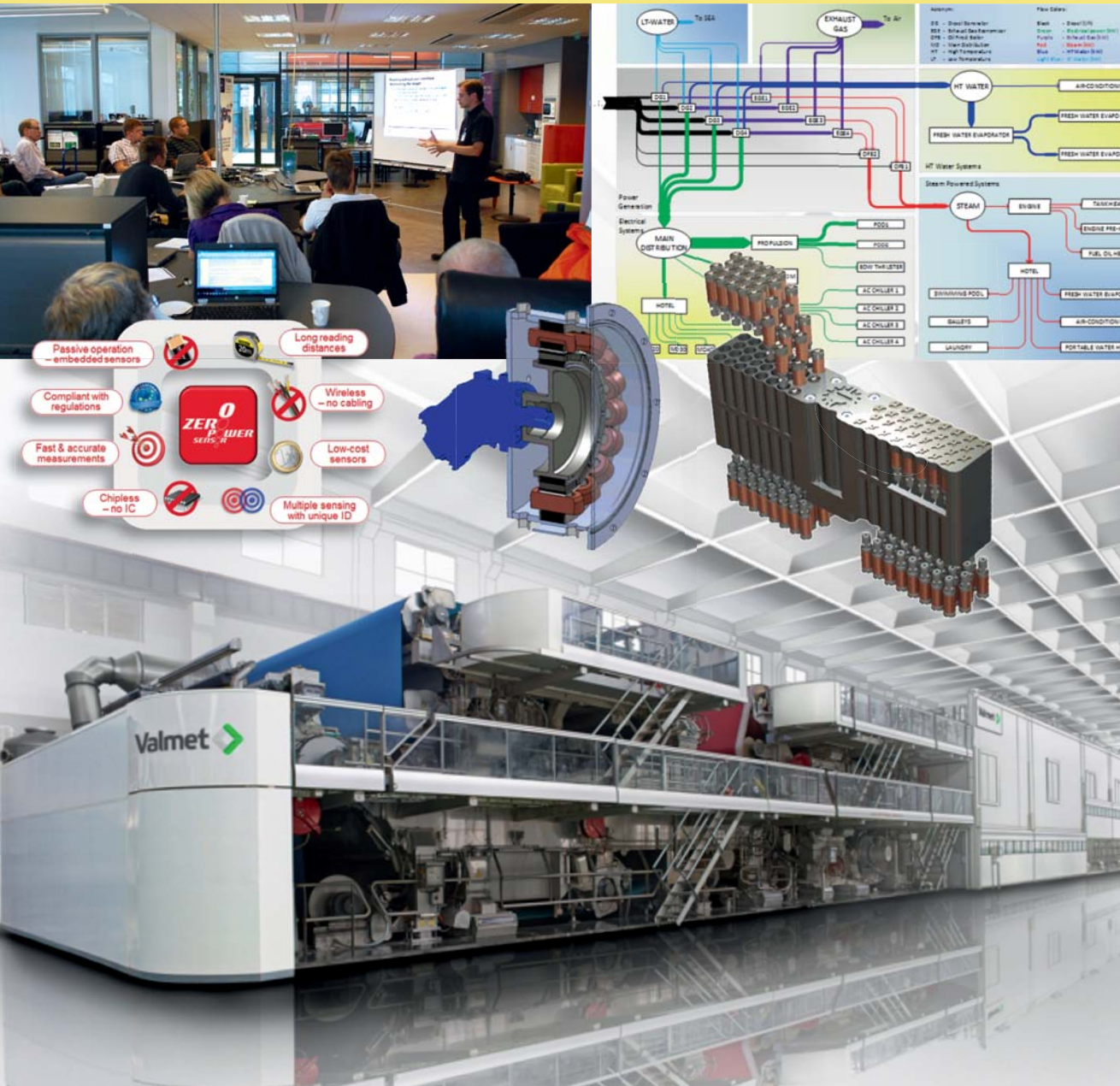
FINAL REPORT 2/2014

FIMECC PUBLICATIONS SERIES NO. 2

Energy and Life-cycle Cost Efficient Machines

2009-2014



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Better Together

Creating something radically new implies that things will be done in a different way. This new way of working towards greater targets is an exciting journey, and with the right partners often the most enjoyable one can make. This ideology forms an undisputed part of FIMECC: creation of the winning teams, giving them the most challenging problems to solve, and harnessing them with the best methods for their journey.

From its inception, FIMECC has endeavoured to find the best people and to develop new ways of working in order to overcome the most challenging industrial problems. Although not the easiest of tasks, the work has undoubtedly been exhilarating and beneficial, as we can see through the results in this final report of the Energy and Life Cycle Cost Efficient Machines EFFIMA programme.

Apart from producing excellent results, the FIMECC EFFIMA programme has also played a critical role in the creation of FIMECC's operations and methodologies. Along the way, these methods have conjoined the efforts of FIMECC EFFIMA partners and turned the consortium into an acknowledged ecosystem, with a unique culture of solving things together. I would like to thank the whole consortium, and especially the programme manager, Ismo Vessonen, for the great results achieved and the pioneering work you have performed in building such a creative ecosystems with an effective operations.

These operations will be transferred to FIMECC's forthcoming programs and develop further. Still the most important result of the programme is the co-operation and knowledge sharing culture the programme has created. This culture and the co-operation network will live among the consortium partners long time after the programme and will have a wider impact on industry – it will be the glue through which effective innovation ecosystems are created also in the future.

Culture lives on!

Dr Kalle Kantola
CTO
FIMECC Ltd

Nurturing the Seedlings of Co-creation

Times were exciting for the Finnish research community at the turn of 2008/2009. The world was in the middle of a severe financial crisis, and we in Finland were preparing several programmes of a totally new type that were about to give Finnish business life a leading role in the planning and implementation of these research efforts – these were the 1st generation SHOK programmes.

One of the first FIMECC programme initiatives, "Energy and life cycle cost efficient machines – EFFIMA", was about to start, gathering together an initial group of companies (24) from the Finnish machine-building industry and all major research institutes (9) with activities in the field. The main target was to develop new technology and solutions that enable machines and systems with dramatically lower life-cycle costs – especially lower energy consumption – compared to what was considered to be state-of-the-art internationally. Under this common denominator, we defined three key targets that would form the work package structure of EFFIMA, and under which the projects and their results are presented in this publication:

WP1: Low energy consumption and environmental emissions

By 2020, Finnish machine industry products are low emission systems with up to 50% lower energy consumption compared with that in 2008

WP2: Technologies for Life-Cycle Cost Management

By 2020, sustainable and profitable life-cycle management is a world-famous and inimitable brand for Finnish machine industry companies

WP3: Efficiency by means of human-compatible multi-machine systems

By 2020, Finland is the leading country in producing efficient multi-machine systems consisting of automatic or semi-automatic machines

At the beginning of the programme, the new, unproven programme concept, the prevailing economic situation, and the somewhat heterogeneous project and application area structure of FIMECC EFFIMA (involving companies from marine, mobile work machine, process machine and other industries) all posed challenges at every level of programme execution. But challenges are made to be tackled!

In the preparation phase of FIMECC EFFIMA, the inherent heterogeneity of the programme was also seen as an opportunity. Here one could learn from one another, and transfer proven concepts from one application domain to another without the burden of competition. In recognition, several steps were taken to ensure this would be realised in practice.

Projects were first asked to prepare a concrete co-operation plan with other relevant projects within FIMECC EFFIMA and other FIMECC programmes. A common environment for validating research results (e.g. GIM machine in TUT) was found to be one way of bringing together and integrating the activities and outcomes of different projects. Some projects decided to form a common steering group for their activities.

FIMECC EFFIMA adopted rather interactive working methods. All programme events were organised as interactive "marketplaces", initially for projects to communicate to each other the research plans and desired outcomes of their research efforts. The focus of these events later transferred naturally to the results and their impact on business and science. Arranging opportunities to discuss and spar face-to-face is vital for gaining the full spectrum of possible implications of all those ideas and results!

Research under the SHOK programmes is industry-driven, and requires an understanding by all participants of the business drivers and background behind the research questions. Evidently, this helps in targeting research work to meet the actual need, but a further purpose is to reveal existing bottlenecks or "eternal problems" that call for science-based solutions. To this end, FIMECC EFFIMA launched its "Impact Day" concept, involving half- or full-day events arranged at the business premises of an attending company where the real machines were available. Besides examples of research topics, special emphasis was placed on presenting intended and achieved impacts in the companies involved. These facilitated identification of common denominators in competence and technology needs, and served as starting points for new co-operation.

FIMECC EFFIMA also carried out pioneering work in developing the FIMECC Factory concept. FIMECC EFFIMA's largest project, Famous, which focuses on predictive and adaptive automation for mobile work machines, was arranged in its entirety to make use of factory space in Hervanta, Tampere. To promote networking and sparring of ideas, the project applied a working procedure that involved scheduled common work days in the Factory premises with a predefined agenda. These events were arranged separately for the three main work packages and the whole project. Several technology demonstrations were set up in the Factory, and some were available for try-outs over a longer period of time. Project management services for Famous were bought from Hermia Group, whose experts did a great job in coaching this rather complicated, multi-party effort into a fruitful research entity.

In terms of "customer satisfaction", FIMECC and the FIMECC EFFIMA programme have been success stories. Purely in the positive sense, companies have "voted with their feet", and increased their investment in research work continuously despite the economic challenges. In the case of FIMECC EFFIMA, this has meant a gradual growth of the initial company group to 38 companies, and of their total budget from EUR 13.3 million to EUR 20.5 million. Through increased research institute work contributions, this enables a total programme budget of EUR 39.7 million.

FIMECC's and FIMECC EFFIMA's implementation of the SHOK concept is proof of what can be achieved with committed, target-oriented and enthusiastic teamwork. All begins at the project level, where people clearly realise that this is "their" programme, and that their contribution is important for the project, for FIMECC EFFIMA and for FIMECC. As a result, those at this grass roots level of research activities have been tremendously co-operative and patient in their duties. The same applies to FIMECC EFFIMA project managers, and I am especially happy to see how well some younger researchers managed to fulfil this role.

It has fallen to us – the programme managers, the Programme Management Committees (PMCs), the FIMECC office, and Tekes as the main funding organisation – to nurture and channel this power and will for co-creation in the right direction. In spite of the challenges, this "conductor team" has run like clockwork. Once my work as programme manager is finished I shall miss this positive and active attitude permeating throughout FIMECC programme management and other events. I also express my gratitude to the FIMECC EFFIMA contact person at Tekes, Financial Manager Timo Laurila, for his continuous, committed and thorough support throughout the programme execution. After consulting him, it was always easy to decide on the right course of action.

This publication has been put together to illustrate the research results and impact of the FIMECC EFFIMA (2009–2014) programme, the first time co-operation of this intensity has been organised by the Finnish machine-building community. Our common journey has created many useful and tangible results that can be counted, categorised and evaluated from a number of different perspectives. Above all, the past five years has taught us important lessons about how this kind of common and open learning process works – the dos and don'ts of open co-creation.

When I was a youngster, my mother often told me: "You should become a gardener!" Well, instead of a gardener, I became an engineer and a researcher. But doing this programme manager's job has

certainly made me feel like a gardener of co-creation. FIMECC EFFIMA has taught me that building up a productive co-creation ecosystem is a time-consuming and laborious, and yet fruitful and rewarding task. I have learnt a few lessons about the meaning of selecting the right habitat and fertilisers, supporting weak seedlings, aligning the growth of healthy branches, cutting out wild branches, and even about the importance of talking to your plants! The most important lesson to keep in mind, however, is that although the stem should be healthy and strong, it is the rich harvest of fruits we are aiming at. In the case of the SHOK programmes, the fruit basket should be full of "the competitiveness of Finnish industrial life".

I sincerely hope that you like the fruits of FIMECC EFFIMA, and that the popularity of co-creation continues to grow, along with our skills in gardening it!

Ismo Vessonen
EFFIMA Programme Manager,
BDM, VTT Technical Research
Centre of Finland

STAKEHOLDERS' PERSPECTIVES

Metso Automation Oy

The FIMECC EFFIMA programme was one of the first programmes planned and successfully started in FIMECC, and definitely the first established by the machine-building community in the Intelligent Solutions area. It was not always that easy in the beginning to align the various ambitious targets and set the programme in motion. There were new practices and networks that needed to be created. But it was a rewarding task for all of us that were involved, and we succeeded! FIMECC EFFIMA grew to a network of 38 companies from the engineering industry and 9 top-class universities and research institutes.

Over the years of FIMECC EFFIMA a strong foundation has been created for a new way of working together in multi-disciplinary consortiums, for co-creation and open innovation, and for taking a common longer-term view to the horizon – our assignment being "How to make Finnish engineering and machine-building more competitive in the global arena!" This has been, and will be, a joint challenge to the whole community – equally important contributions are needed from already large global enterprises, from small companies still looking for their channels to the markets, and from research people who are expanding the technology and science base.

Our mission in FIMECC EFFIMA has been to develop new technologies and solutions that enable new machines, devices and systems with dramatically lower life-cycle costs and energy consumption. The bar for this a target is getting higher all the time, so the work is never finished. The FIMECC EFFIMA programme has brought a number of significant achievements and results in this area. The programme has also enabled the creation of new partnerships and research teams that will continue delivering high-class academic research, technology development and commercial applications after and beyond FIMECC EFFIMA. Another clear strength of this type of programme, with participants from different areas and businesses, is that we truly support and boost the adoption of proven solutions from one application domain to another where the technology or solution has yet to be tried.

The FIMECC EFFIMA programme has given extremely good support to many of the core research and development priorities of Metso Automation. The Zero Power Sensor Network (in the Intersync project) won the 2013 FIMECC prize. The team developed a solution for intelligent sensing where sensing is wireless and passive (no batteries). The concept nevertheless enables the reading of several sensors at the same time with communication distances of several dozens of metres, at high speed, with high accuracy, and using available frequencies.

This type of sensing and networking will be essential building blocks of the future Industrial Internet, and applications are not limited in any way to the industrial domain.

Digital hydraulics is another example of high-quality and novel technology development with strong Metso Automation relevance. The FIMECC EFFIMA projects developed both the base technology and the applications of digital hydraulics. The technology saves energy and space and improves robustness – all extremely important characteristics for future products.

In the Respo project, Metso Automation and partner companies developed automation technologies that give operators better means of controlling both individual machines and fleets comprising several co-operating machines. This was a good example of a new kind of development networking. And there are many other EFFIMA projects and results that are potential seeds for future further development, among others by Metso Automation.

Metso Automation is highly appreciative of the results, and the change in thinking and way of working, that being a member in FIMECC EFFIMA has brought. Co-operation with other companies and with new research partners has been eye-opening. We still have much to do to improve our open innovation, but we have started, and are on the right track! Metso Automation wants to thank all the people and participants it has had the pleasure to work with. We at Metso Automation – and, I believe, my colleagues in all the other FIMECC EFFIMA stakeholders – owe our most sincere thanks to the Finnish Funding Agency for Technology and Innovation (Tekes) and FIMECC Oy for their invaluable contribution and support – without them the programme would never have started. And the warmest thanks also to the excellent programme management – we would not have brought the programme to a successful conclusion without it!

The work continues. See you all on the Industrial Internet! That is what everyone is talking about – and with good reason. Many of our next major challenges and opportunities are there – and it is not only about technology, but even more about service development and new business models. Seems like a perfect topic for FIMECC!

Jukka Ylijoki
Vice President, R&D
Process Automation Systems

VTT Technical Research Centre of Finland and Tampere University of Technology

EFFIMA (Energy and Life Cycle Cost Efficient Machines) was among the very first FIMECC – or indeed SHOK – programmes in the country. Even during planning, the EFFIMA programme began to realise many of the SHOK programme expectations. These include genuine joint research and development among industrial companies and research institutes, such as VTT Technical Research Centre of Finland or the universities, and reaching high in technology while maintaining industrial relevance. Both VTT and Tampere University of Technology have been – and will continue to be – significant and constructive actors in FIMECC, having participated in writing the generations of FIMECC strategic agendas, and planned and managed programmes such as EFFIMA. Both have also been represented on the FIMECC Board, the FIMECC research council and several steering groups. While not the only major research partners, VTT and Tampere University of Technology have promoted the spirit of the projects and programmes by combining academic research potential with industrial interests in a host of practical ways.

Research and development for the machine industry has long been a cornerstone of the research portfolios of both VTT and TUT. Although national technology and research programmes have always been crucial when it comes to focusing resources on any one domain, during the 2000s researchers and companies felt that such programmes had tended to neglect the machine industry, and consequently welcomed the emergence of FIMECC and the FIMECC EFFIMA programme. The latter was based on 30–40 project ideas formed into a compact set of projects by the Intelligent Systems steering group. For VTT and TUT, this meant outstanding opportunities for many of their most potent research lines.

The decade-long success of wireless sensor networks had mostly been academic. For the FIMECC EFFIMA programme, VTT combined with Tampere University of Technology and the University of Oulu to form the extensive Intersync project along with some of the larger frontline Finnish machine-building companies. The early years of Intersync concentrated on development of what might be called 'established' WSN issues, such as low power consumption, sensoring methods, energy harvesting, and VTT's own WSN module platform, known as VTT Node. Invention of the 'zero-power' sensor gradually began to draw most of the attention of both companies and research. Calculations and laboratory measurements indicated that passive measurement elements could be monitored wirelessly over distances beyond 10 metres. The zero-power sensor quickly proved a successful and widely recognised outcome of FIMECC EFFIMA, although certain obstacles remain before it becomes an ultimate industrial flagship.

Research piloting of analysis and diagnosis algorithms goes even further back, but at the beginning of FIMECC EFFIMA the companies still felt they lacked practical means of benefiting from such an advance. The Tolkku project was thus set up to begin tailoring the algorithms and usage for industrial environments into a specific library known as Tolkku Toolbox. The closing FIMECC EFFIMA programme is now in a position to hand over a proven toolbox to the EFFIMA partners, and to subsequent SHOK programmes that intend to extend the emphasis from fault diagnosis to a much more challenging fault prognosis. Eventually, the machine industry will be capable of the accurate and reliable prediction of remaining useful lifetimes essential to optimised operations and maintenance, both for end-users and industrial service providers.

The Famous project has been highly significant during the latter half of FIMECC EFFIMA. VTT has great strengths in many kinds of safety-related applications. Famous gave VTT the opportunity to develop an effective, flexible, and adaptive worksite safety system. This would allow an increasing number of autonomous machines and machine groups to reside and operate with people at the same site more freely. VTT would also be able to derive significant benefit from its virtual technology laboratory and facilities in Tampere. Indoor positioning is another VTT topic under the Famous project. GPS technology is well known for positioning objects within direct sight of respective satellites, or in other words, objects residing outdoors. Although several technologies exist for indoor positioning relevant to various industrial applications, that known as ultra-wide band technology, thanks to the Famous project, proved highly accurate, eliminating disturbing signal echoing and other drawbacks.

Several innovative ways of connecting the academic and industrial worlds have been exploited during the FIMECC EFFIMA programme. One of these is the 'FIMECC Factory'. Here, project members meet each other regularly, the Famous project being a good example. The FIMECC Factory at Tampere is located in Hervanta, conveniently close to where Tampere University of Technology and VTT have research facilities. This opportunity has been made full use of during the research work, and both academia and industry have been encouraged by the experience of working together in this way. Another novel approach lies in the demonstrations carried out during the project, such as those for harbour and forest environments. First validated piece by piece in a VTT or university research installation, the full demonstration would then be performed in the FIMECC Factory or in an industrial environment arranged by the companies.

One of the research fields in FIMECC EFFIMA was energy efficiency, covered by the Neffi project. Using hybrid solutions, the main partners – Cargotec, ABB, Lappeenranta and Tampere University of Technology – achieved results that reduced energy losses by about 30%.

GIM (Generic Intelligent Machines), an Academy of Finland centre of excellence in research, participated in the FIMECC EFFIMA pro-

gramme to a remarkable extent. These academic results were implemented in the FIMECC EFFIMA programme's applied results, some of which have already appeared in company R&D processes. The quick path from academic results to useful company knowledge is clearly one of the programme's main strengths.

A new technology – digital hydraulics – was introduced to Finnish industry in two projects, DiHy and Digihybrid, with companies involved including Wärtsilä, Metso/Valmet and Norrhydro. Research was carried out on new digital hydraulic applications, with some results already finding their way into products. Academic co-operation between Tampere University of Technology, Aalto University and Åbo Akademi University has been extremely fruitful.

One of the most significant challenges of contemporary shipbuilding and marine logistics concerns the efficiency of marine energy and environment. VTT has a significant history of marine or shipbuilding research stretching back decades. Together with industry, VTT planned for FIMECC EFFIMA a practical yet challenging energy and environmental effects model and simulator, amounting to an effective combination of VTT's deep domain knowledge and modern mathematical or engineering tools. This resulted in the successful SEEE project.

FIMECC EFFIMA has proved an advantageous and successful means of developing science-based technology for the benefit of industry. VTT and the universities have learnt much from FIMECC EFFIMA about what it means to plan and carry out industry-relevant research. By the same token, the industry sector has learnt to recognise the advantages of SHOKs. Few of the practices in planning and managing such programmes existed when FIMECC EFFIMA began. Instead, the ecosystem found itself designing, trying out and elaborating on many practicalities, principles, processes and tools. VTT and Tampere University of Technology have been involved in the planning of most subsequent FIMECC and other SHOK programmes since FIMECC EFFIMA set out, and the experiences gained over the programme's lifetime have produced untold benefit. FIMECC is one of the strongest SHOKs today, well placed to cope with the challenges of the country in the aftermath of the remarkable mobile phone era: a new epoch in which machine industries are playing a growing role.

Olli Ventä
Research Manager, VTT Technical Research Centre of Finland

Kalevi Huhtala
Professor, Tampere University of Technology

FIMECC EFFIMA in a Nutshell

Company partners: ABB Oy, Arctic Machine Oy, Axco Motors Oy, Bronto Skylift Oy, Cargotec Finland Oy, Creanex Oy, maximatecc Oy, Deltamarin Oy, ELHO Oy, FIMA ry, John Deere Forestry Oy, Junkkari Oy, Kemira Oyj, Kone Oyj Konecranes Finland Oy, Konecranes Oyj, Metso Automation Oy, Metso Minerals Oy, Valmet Oyj, MeVEA Oy, NAPA Oy, Navitec Systems Oy, Norrhydro Oy, Novatron Oy, Nurmi Hydraulics Oy, Optofidelity Oy, Potila Tuotanto Oy, Rocla Oyj, Sandvik Mining and Construction Oy, Savant Simulators Oy, Suonentieto Oy, Technion Oy, Valio Oy, Valtra Oy Ab, Parker Hannifin Manufacturing Finland Oy, Wapice Oy, Vieskan Metalli Oy, Wärtsilä Finland Oy

Research institute partners: Agrifood Research Finland (MTT), Aalto University (AALTO), Lappeenranta University of Technology (LUT), Tampere University of Technology (TUT), University of Helsinki (UoH), University of Oulu (UoO), VTT Technical Research Centre of Finland, Åbo Akademi University (ÅAU), Turku University of Applied Sciences (TUAS)

VOLUMES

Duration	1.6.2009 – 30.9.2014
Budget:	39.6 M€
Company budget	20.5 M€
Research institute (RI) budget	19.1 M€
Number of companies original/final	24/38
Number of research institutes	9
Number of projects	12
People involved	~250
Company work	~1400 Man-months
RIs' work	~1500 Man-months

RESULTS

Number of publications:	210
Number of deliverables	410
Number of Doctoral Theses:	10
Doctoral studies with over 1 year EFFIMA contribution	9
Number of Master's Theses:	52
Number Invention Disclosures:	4
Number of Patents	2
Patents/patent applications based on EFFIMA knowledge but outside EFFIMA	36
Number of company R&D projects based on EFFIMA knowledge	~40
Volume of company R&D projects	> 10 M€
Researcher Exchange	72 Man-months
FIMECC Prize wins (elected by FIMECC members)	3
FIMECC Hightec Results publications	28

WORK PACKAGE 1:
Low Energy Consumption and Environmental Emissions

PROJECTS:

- Digital Hydraulics, Digital Microhydraulics – DiHy DiMi
- Digital Hydraulics, Marine Hydraulics – DiHy Marine
- Regenerative Hydraulic Hybrid with Digi-valve and Multi-chamber Cylinder Technology – Digihybrid
- Integrated Serial and Parallel Hybrid Drives in Working Machines – Neffi
- Ship's Energy Efficiency and Enviroment – SEEE

PROJECT NAME

WP 1 Low Energy Consumption and Environmental Emissions

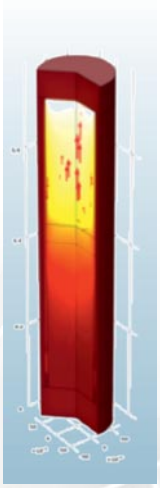
DiHy DiMi

Digital hydraulics provides an excellent tool for saving energy, space and trouble in different applications. And these altogether save MONEY.

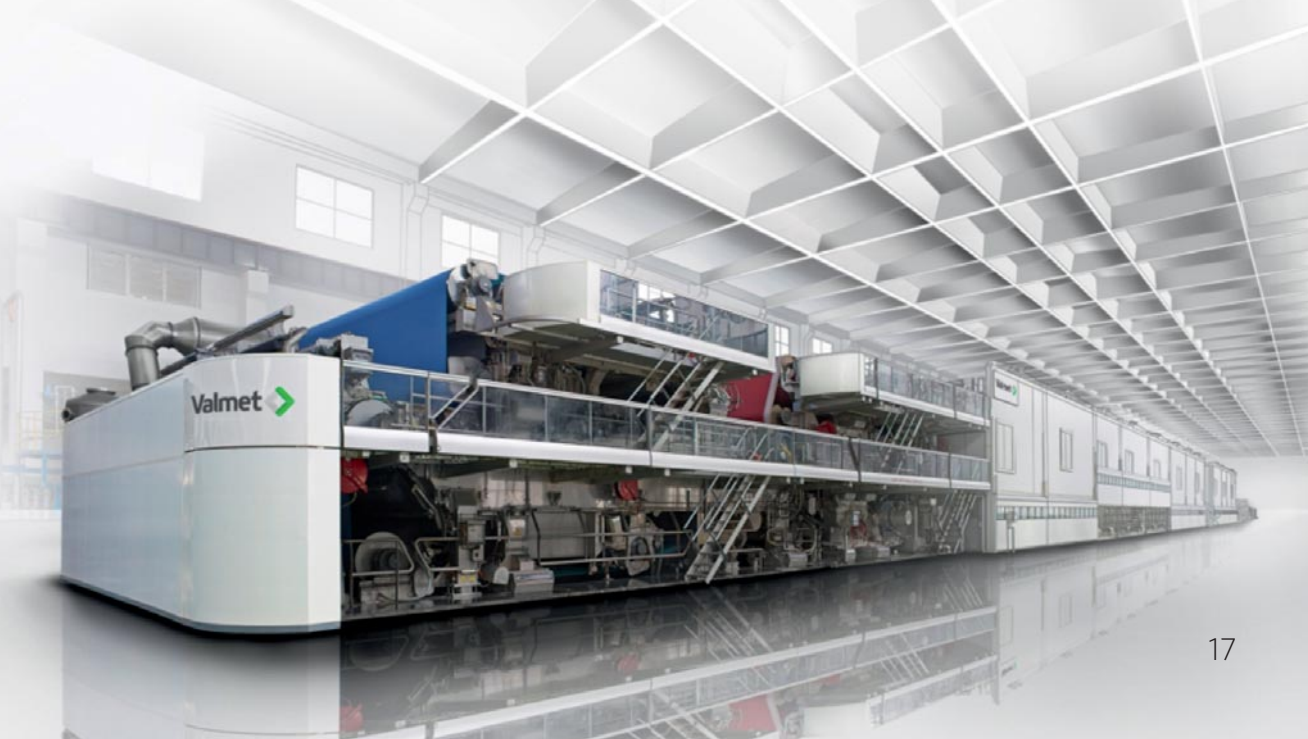
Digital Microhydraulics

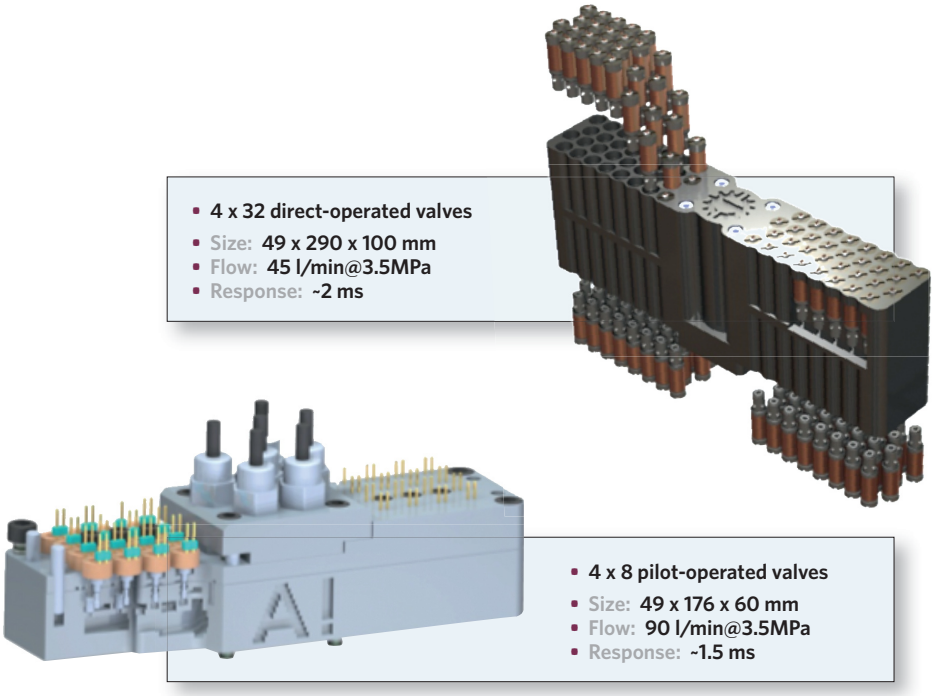
BIG things with SMALL components

Earlier implementations of Digital Valve Systems (DVS) have been clumsy, but the new microhydraulic concept changes everything. Even modernisation of hydraulic systems is possible with retrofitable digital microhydraulic four-way valve systems. Both direct- and pilot-operated microvalves were developed, manufactured and tested in the DiHy project, the test results showing that microhydraulic valve systems are suitable for most industrial hydraulic systems.



Energy efficient hydraulic pressure accumulators were also studied. Based on the results, efficiency can be improved significantly and the prediction is over 90% cycle efficiency. With the above value, hydraulic energy recovery and re-use becomes a very attractive solution in place of transforming energy between hydraulic and electric forms.





VALMET: Digital hydraulics in paper machine lines

A paper machine calender has two loading cylinders with movement and nip loading control. Both controls have to be very fast and exact, otherwise roll damage could occur. Digital hydraulic control has been proven to fulfil the above requirements. In particular, changing from flow to pressure control was extremely rapid and created no pressure overshooting. This is important because the calender must close as fast as possible, but pressure overshooting can damage the roll cover.

During the tests it was noticed that while the calender was running under loading for several weeks, it was possible to stop the hydraulic power unit. The unit was then started only about once a day to recharge the pressure accumulators, resulting in an energy saving of about 98%. This function is already in use in customer projects.

The DiHy project also developed a control and hydraulic system suitable for paper mills, as well as a new booster card. Space requirements were reduced to a fraction compared to the first version.

A more suitable on/off valve for digital hydraulic applications was developed in co-operation with a valve manufacturer. The valve size was reduced significantly and made faster with a switching time of less than 4 ms.

Several customer projects have been sold all over the world, with the biggest delivery a multinip calender with about 1,500 digivalves.

TUT+AALTO: Compact design digital hydraulics

The results of the DiHy project show the possibility of compact implementation of DVS. One important factor enabling compact manifold design is lamination technology. Two compact valve packages have been designed and manufactured in the project. The first one uses direct-operated on/off valves with small and equal volume flows, resulting in small steps in the movement velocity of an actuator. The second one uses pilot-operated on/off valves with bigger volume flows allowing faster movements. Both valve systems are suitable for the CETOP 3 mounting pattern.

The results put the advantages of digital hydraulics within reach of most industrial hydraulic systems. The potential for power loss reduction is huge. The novel valve packages raise the performance and fault tolerance of the valve systems to a new level.

Industrial relevance

"In modernisations it is important that the existing valve can be replaced without manifold changes. The matrix type valves have several advantages compared to traditional digital hydraulic solutions."

***Juhani Toppari**, Valmet Oy*

AALTO: Highly efficient hydraulic accumulators

Hydraulics are used in heavy duty machines and demanding industrial applications, such as paper machines. These systems have a lifetime of several decades and are designed for performance rather than energy efficiency. Many systems have high peak power, while average power demand is significantly lower. The use of hydraulic accumulators in the generation and recovery of high power peaks results in strongly downsized motors, as well as smaller and cheaper systems. The problem is that the efficiency of traditional hydraulic accumulators is poor, often below 70%.

The new hydraulic accumulator with 12 per cent unit improved cycle efficiency (up to 85%) has been developed in the DiHy project. The simulation results show that efficiency can further be improved, with a prediction of over 90% cycle efficiency. This makes hydraulic energy recovery and re-use an attractive solution because there is no need to transform energy between hydraulic and electric forms.

Industrial relevance

"In the short run, energy regeneration is gaining ground across hydraulic systems. For that reason it is important to improve the energy storage components. The improved hydraulic accumulators are a step forward to more efficient hydraulic regenerative systems."

***Juha Elonen**, Nurmi Hydraulics Oy*

PROJECT NAME

WP 1 Low Energy Consumption and Environmental Emissions

DiHy DiMi

CONTACT PERSON

ARTO LAAMANEN
MATTI LINJAMA
TAMPERE UNIVERSITY OF TECHNOLOGY

PARTICIPANTS (ORGANISATIONS)

TAMPERE UNIVERSITY OF TECHNOLOGY
AALTO UNIVERSITY
ÅBO AKADEMI UNIVERSITY
VALMET OY
METSO AUTOMATION OY
NURMI HYDRAULICS OY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

3.700 MILLION

Digital Microhydraulics

Main targets & motivation

The first generation of Digital Hydraulics has over 30% reduced losses, better controllability and good fault tolerance compared to traditional hydraulics. Some challenges are nevertheless posed by deficient on/off valve technology: the valve system, for example, is physically large, and switching times rather slow. This is something to be tackled in the second generation, and accordingly the main objectives of DiHy projects were:

Objective I:

Second Generation Digital Valve Packages

- 10 × speed
- 50% smaller
- 90% reduced control power

Objective II:

Up to 50% reduction of power losses with no significant system changes

- Programmable and multipurpose digital hydraulic control valves
- Energy-optimal control

Objective III:

Modular systems

- Reliable and modular control code
- Modular digital hydraulic solutions

Results

- Lamination technology was proven to be a good alternative and the technology successfully developed for this use
- Design and manufacture of two compact valve packages based on the lamination technology
  - The first uses direct-operated on/off valves with small and equal volume flows, resulting in small steps in actuator movement velocity
  - The second uses pilot-operated on/off valves with bigger volume flows, allowing faster movements
- The new compact valve packages make the advantages of digital hydraulics available for most industrial hydraulic systems, with huge potential for power loss reduction: novel valve packages also take the performance and fault tolerance of valve systems to a new level
- Design of a new type of control electronics for the compact valve package: this enables fast opening and closing times, low hold current and simple controllability
- The energy efficiency of valve-controlled cylinders can be increased significantly by using a digital valve system capable of independent metering, while the number of different control modes is increased further by pressurising the tank line: measurement results of a single actuator system show a 53–71% reduction in energy losses
- Extension of a digital valve system using a programmable pressure relief function realised with modular code: it was shown that use of the pressure relief function as a safety relief valve in actuator chambers requires fast acting (typically < 2 ms) on/off valves
- Development of a verification tool for checking (symbolically) that a Simulink model always fulfils contract specifications
- Implementation of metrics for measuring quality attributes, mainly complexity: these complexity metrics are also implemented as part of a verifier, allowing designers and project leaders to assess design quality of large models automatically and thus ensure that future work on the models can be carried out efficiently
- Development of a new hydraulic accumulator with 12 per cent unit improvement in cycle efficiency: the simulation results show that cycle efficiency can be further improved, with a prediction of over 90%, making hydraulic energy recovery and re-use an attractive solution that dispenses with the need to transform energy between hydraulic and electric forms

- Digital hydraulic control was proven to fulfil the requirements of paper machine applications such as calendar movement and nip loading control, with rapid change from flow to pressure control and no pressure overshooting: important because the calender must close as fast as possible but pressure overshooting can damage the roll cover
- Development of a new booster card by Valmet and Metso Automation, designed to be compatible with a commercial 16-channel binary output card: space requirements were reduced to a fraction compared to the first version.

Key publications

1. Paloniitty, M., Linjama, M. & Huhtala, K. (2014), Concept of digital microhydraulic valve system utilizing lamination technology. 9th International Fluid Power Conference (IFK 2014), 24-26 March 2014, Aachen, Germany. Vol. 1, pp. 302–313.
2. Lantela, T., Kajaste, J., Kostamo, J. & Pietola, M. (2014), Pilot-operated miniature valve with fast response and high flow capacity. International Journal of Fluid Power, vol. 15. iss. 1, pp. 11–18.
3. Juhala, J. & Pietola, M. (2011), Hydraulic Accumulator as Energy Storage, IMECE2011-63780. ASME 2011 International Mechanical Engineering Congress & Exposition, Denver, Colorado, USA, 11-17 November 2011.
4. Huova, M & Linjama, M. (2012), Energy efficient digital hydraulic valve control utilizing pressurized tank line. 8th International Fluid Power Conference Dresden, 26–28 March 2012, Dresden, Germany, pp. 111–122.
5. Boström, P. (2011), Contract-Based Verification of Simulink Models. In: Shengchao Qin, Zongyan Qiu (Eds.),13th International Conference on Formal Engineering Methods, ICFEM 2011, Lecture Notes in Computer Science 6991, pp. 291–306, Springer, 2011.

Number of publications: 28
Number of Doctoral Theses: 1
Number of Master's Theses: 5

Networks and international co-operation

The Department of Intelligent Hydraulics and Automation at Tampere University of Technology (TUT/IHA) is a member of ACCM (Austrian Center of Competence in Mechatronics), with the Institute of Machine Design and Hydraulic Drives/Johannes Kepler University (IMH, Linz, Austria) as the most important research partner. IMH has a deep understanding of fast on/off

valves and their control electronics. Co-operation has taken the form of information sharing, research mobility and common courses. Four international digital fluid power workshops have also been organised in Linz, Austria and in Tampere, Finland.

At the national level, TUT/IHA has developed solenoids for miniature digital valves in close co-operation with the university's Department of Electromagnetics, while laminated valve blocks have been developed together with the Department of Material Science.

Pontus Boström from ÅAU/DSLab visited Peter Müller's group at ETH Zürich for 10 months starting from June 2011. This co-operation provided valuable insight into state-of-the-art software verification tools and methods. ÅAU/DSLab has been involved in long-term co-operation with the University of Southampton and University of Newcastle on the formal development process for dependable control systems and their deployment in industry. This co-operation has provided valuable insight into dependability and formal methods.

Within the EU RECOMP project (2010–2013), ÅAU/DSLab has co-operated with Danfoss Power Electronics A/S on modelling safety-critical systems, which has provided insights into the requirements demanded by safety standards. With Tallinn University of Technology, ÅAU/DSLab co-operation concerned verification of real-time properties. A more recent co-operation partner is the Eindhoven University of Technology in the Netherlands. This co-operation explores internal and external quality for Simulink models.

Applications & impact

- Valmet has delivered several applications to paper machines, for example a multinip calender with about 1,500 digivalves
- Co-operating with a valve manufacturer, Valmet has developed a more suitable on/off valve for commercial digital hydraulic applications
- The results of new laminated valve packages make the advantages of digital hydraulics available for most industrial hydraulic systems, with huge potential for power loss reduction and a relatively simple retrofit
- Design of a new type of control electronics for the compact valve package, with control power reduced significantly by about 70%
- A predicted significant 90%-plus improvement in cycle efficiency for pressure accumulators, making hydraulic energy recovery and re-use a highly attractive solution that dispenses with the need to transform energy between hydraulic and electric forms.

"The DiHy project has provided Valmet with leading digi-hydraulic developer contacts. At the beginning of the task there was no acceptable technology in existence. Significant development has been carried out with control system hardware, software and hydraulics. Delivering a digi-hydraulic system to a paper machine involved Valmet needing to define requirements for each section. With these requirements achieved, several customer projects have since been delivered."

Juhani Toppari, Development Manager
Valmet Technologies Oy

"DiHy gave a great opportunity to our research group to perform high-level research on a relatively new research area. Our research expertise rose to a higher level during this project. The project also gave us a great way of meeting other partners and contacting new people. These contacts can be utilised in future research projects."

Matti Pietola, Professor
Fluid Power, Aalto University

PROJECT NAME

WP 1 Low Energy Consumption and Environmental Emissions

DiHy Marine

Digital Hydraulics Applied Research – Marine Hydraulics

Increasing hydraulic system modularity and design accuracy

Marine hydraulics is designed to meet special requirements that give it somewhat unique characteristics. The corrosive operation environment has a large temperature scale, and Arctic areas are estimated to have a significant role in the future of the shipping business. Modular ship-building creates its own challenges for hydraulic systems, as traditional centralised systems no longer meet the requirements of ease and quality of installation, and strong cost-orientation creates a constant requirement for more accurate and effective design methods. DiHy has resulted in an increase not only in Arctic competence but in the hydraulic system design accuracy essential for finding modular and energy-efficient drive solutions.

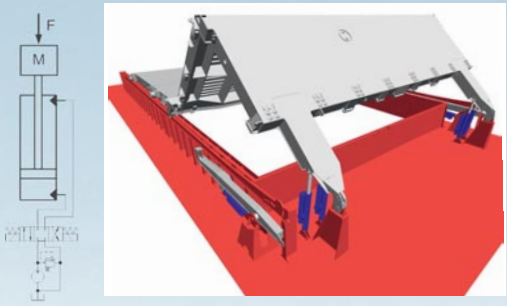


Figure 1. **Utilization of 3D CAD model in virtual design of hydraulic cargo hatch cover**

Figure 2. **Compact pump-controlled asymmetric cylinder drive**

3D Models in Virtual Design

- The CAD model contains exact information about a mechanism
- Mass, inertia, pivot points, lever arms, gear ratios
- Easy load model generation
- Easy implementation of changes
- Quick design
- Accurate system dynamics in a simulation environment.

Compact hydraulic drive

- No pipelines, minimal amount of oil
- Minimal power losses
- Easy installation
- No claims due to 3rd party mistakes.

Variable speed semi open loop system prototype

- Pump-controlled asymmetric cylinder
- Energy recovery with frequency converter
- Few components.

3D mechanical design benefits in marine hydraulic design

CAD models are able to describe mechanics with essential information, giving a wider analysis of the total system operation. A modular and numerically light simulation model – created with the help of a 3D CAD model, SimMechanics and SimMechanics Link tools – converts mechanical structure into dynamic actuator load, allowing the designer to perform a quick and accurate analysis of the interaction between load and hydraulic system. The best hydraulic system solution is ultimately chosen for the end product.

Industrial relevance

"New design methods developed in FIMECC's DiHy project have brought us new ways of achieving more accurate system design and analyses, thus increasing our competence in demanding customer-oriented projects and R&D actions."

***Mikko Sinivaara**, Cargotec Finland Oy*

CASE 1: Digital hydraulics in folding cargo hatch application, simulation study

The use of digital hydraulics increases the universal value of the hydraulic unit thanks to fully programmable valve control. Energy losses can be minimised by means of optimal valve combinations. Intelligent control enables effective use of accumulators in energy recuperation, and together with accurate virtual load design achieved a 90% energy recovery rate during simulated hatch closing. Combined use of accumulators and pump for lifting movement produced an efficiency of 83%. The accumulator temperature control necessary for optimal energy efficiency in the marine environment has been successfully researched in DiHy Task 1 with thermal insulated accumulators.

CASE 2: Semi open loop pump-controlled unit in folding cargo hatch application, experimental study

A semi open loop pump-controlled unit is an attractive choice because of its low number of components and energy transformation capability, and the added bonus of practically no active valve control. A semi open loop unit was selected for realisation and experimental research, achieving an energy recovery rate of 75% and efficiency of lifting movement comparable to a digital hydraulic setup. The frequency converter showed good torque and rpm response under demanding loading conditions.

Industrial relevance

" Commercialisation of a modular and energy-efficient local hydraulic concept is now under way. The extensive and innovative technology survey, including in-depth analyses of energy recovery and other characteristics, has given us a wide range of tools for future development."

***Marko Perukangas**, Cargotec Finland Oy*

PROJECT NAME

WP 1 Low Energy Consumption and Environmental Emissions

DiHy Marine

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
ESA MÄKINEN, SAMI KUKKONEN TAMPERE UNIVERSITY OF TECHNOLOGY **MARKO PERUKANGAS** CARGOTEC FINLAND OY	**TAMPERE UNIVERSITY OF TECHNOLOGY** **CARGOTEC FINLAND OY**	**2009 – 2013**	**1.020 MILLION**

Digital Hydraulics Applied Research – Marine Hydraulics

Main targets & motivation

Traditional marine hydraulic systems lack energy efficiency because of their central hydraulic design aspect, and are vulnerable to system failure and environmental pollution. The aim of this project was to apply compact design philosophy to hydraulic design with on-deck applications in order to overcome the downsides of current systems. The research targets were:

- Feasibility study and applications of digital hydraulics in hatch cover hydraulics
  - Benefits and energy-saving potential using digital hydraulics
- Environmental aspects
  - Energy-saving potential using digital hydraulics
  - Hydraulic system design guidelines for Arctic environment
- Modularity in shipbuilding
  - Modular hydraulic system technology survey
- Advanced design methods
  - Potential use of simulation to improve the hydraulic system design process.

Results

Handbook and guidelines established for Arctic environment and operation conditions

Technology surveys and simulations carried out for compact modular hydraulic power packs – comparison of digital hydraulics and variable speed pump-controlled hydraulics. Both cases presented have good energy efficiency and thus sufficient temperature control; a digital hydraulic setup can achieve the best overall efficiency with the help of accumulators and optimised valve control

New loading profiles based on mechanical design have brought significant accuracy and additional capability to the virtual design environment:

- Simulated loading profiles were verified by on-board measurements
- Stability assessment of different hydraulic circuit structures under varying load dynamics
- Optimal sizing of components to maximise energy efficiency
- Optimal control

Practical tests with the pump-controlled unit showed good dynamic response to challenging loading conditions when using the inverter to recover energy.

Key publications

1. Kukkonen, S. & Mäkinen, E. (2013), Hydraulics for High Inertia, Heavy Load Lifting Application – Comparing Different Options. The 8th International Conference on Fluid Power Transmission and Control (ICFP2013), 9–11 April 2013, Zhejiang University, Hangzhou, China.
2. Westerlund, S. & Mäkinen, E. (2012), Digital Hydraulic Cylinder Drive for Folding Cargo Hatches. The 7th FPNI PhD Symposium on Fluid Power, 27–30 June 2012, Reggio Emilia, Italy.
3. Westerlund, S., Mäkinen, E. & Sinivaara, M. (2011), Self-contained hydraulic module for cylinder-driven applications, The 12th SICFP, 18–20 May 2011, Tampere, Finland.

Number of publications: 3

Number of Master's Theses: 2

Networks and international co-operation

The project research was mainly concentrated on working with the main partner (Cargotec) and the possibility of international co-operation was not considered.

Applications & impact

The virtual design environment tools have provided faster and more accurate system design, capable of providing information on system dynamics and operation times not previously available

Surveys of hydraulic system demands in cold and harsh operating conditions have increased Arctic design competence

Optimising hydraulic design according to loading profile produced an efficiency rate of 75–90% with the compact hydraulic drives studied

Commercialisation is under way or has been partly achieved for the pump-controlled compact hydraulic power unit, although the digital hydraulic version has yet to be considered for production.

"Co-operation with research institutes has given our R&D team access to state-of-the-art technologies. The contacts created during the project will also enable future co-operation with research institutes once the project has ended. Project result highlights are the increased hydraulic system design competence provided by new design tools developed in the project, and studies related to the effects of Arctic conditions."

Marko Perukangas, Control System Engineer
MacGREGOR Finland Oy

"The DiHy Marine project has played a key role in the study of marine hydraulic energy-efficient and environmentally friendly drives. Apart from having good synergy with other research in the department, particularly digital hydraulics, the project has also opened up new research avenues, such as hydraulic-pump-controlled cylinder drives driven by frequency converter. The best part of the project has been concrete and close co-operation between the university and companies."

Esa Mäkinen, IHA Rauma Unit Manager
Tampere University of Technology

Regenerative Hydraulic Hybrid with Digi-valve and Multi-chamber Cylinder Technology

Variety of Challenging Applications – Versatile Digital Hydraulic Solutions

High energy efficiency with innovative multi-chamber cylinder technology

Energy efficiency has gained increasing attention in recent years because it affects operating costs and emissions, among others. Study was made of energy-efficient digital hydraulic systems, especially with multi-chamber cylinders, in very different applications in the Digihybrid project. While results showed improvement in energy efficiency, the reliability of digital hydraulic systems also stepped up to a new level through enhanced software and control electronics.

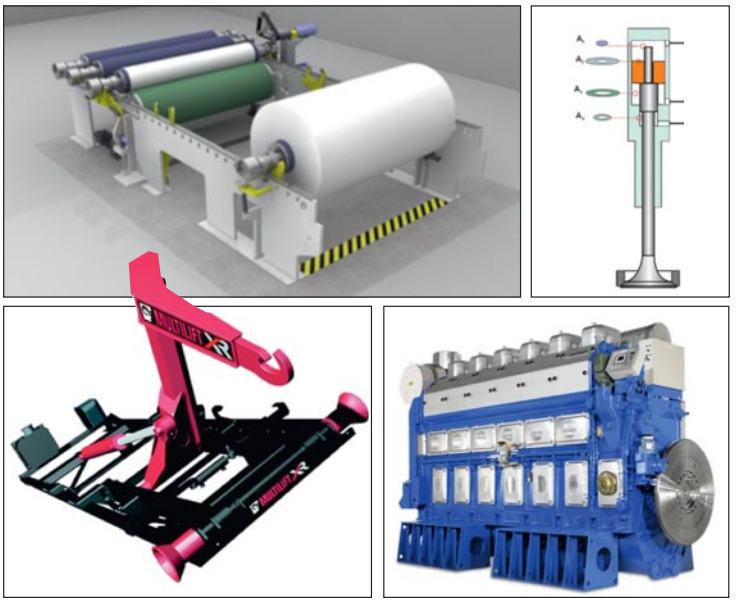


Figure 1. **A variety of challenging applications studied in the Digihybrid project**

Valmet: Energy recuperative digital hydraulic reel control – better control with fewer valves

During the reeling sequence, the reel drum is pressed down and then lifted up again. No energy is actually needed. However, there are frictions and some other losses that must be compensated. In a traditional system a hydraulic pump must run all the time, requiring cooling of the hydraulic unit and long piping to the basement from the machine level.

The Valreel Pro with regenerative function needs a hydraulic pump only once for about 30 seconds for each reel, while an accumulator is used to deliver peak powers. This means that the pump will be off for 99.2 % of the time. The hydraulic unit is also a fraction of the size of the conventional system, and can be placed in a small cabinet beside the Valreel Pro.

The selected system hydraulic circuits are simple and very cost-effective. Test results have shown that the performance of the system is excellent, with no complicated components.

Wärtsilä: Multi-area hydraulic actuator – flexibility and energy efficiency for VVT

A hydraulic multi-area actuator concept for variable valve timing (VVT) in internal combustion engines was invented and simulated. Multi-area actuators can be used when replacing traditional engine valve trains with fully or semi-hydraulic valve trains.

Although hydraulic VVT can offer very good flexibility for valve timing, the downside is high energy consumption. Elements of digital hydraulics can be taken into use when making a hydraulic valve train more energy efficient. A cylinder with multiple effective areas, energy recovery and fast valve technology are tools for achieving a very flexible valve train with reasonable energy consumption. The multi-area actuator with related hydraulic valve arrangement was patented by Wärtsilä.

ÅAU + VTT + TUT: Efficient and reliable control software

Development of efficient and reliable control software requires efficient development tools. Simulink has been used as one of the main tools in the project, due to the possibility of integrating controller development with simulation of the hydraulics. The reliability of software can be increased by measures to avoid faults or by tolerating faults in the software. A verifier for Simulink models has been developed for automatic checking of the model's correct functioning according to specifications. However, these types of tools have limited scalability.

In order to ensure reliability of large complex systems, a fault tolerance mechanism was developed based on using two versions of components together with a priority arrangement policy for real-time tasks. This allows for compensating faults in an advanced controller by using a small, verified backup controller. This arrangement can handle faults such as runtime errors and deadline misses in the advanced controller, while ensuring that real-time constraints are met for the system as a whole.

Deploying the safe and advanced controller on different hardware platforms also allows tolerating of faults in the hardware. Furthermore, this kind of architecture enables live upgrades of running systems.

Industrial relevance

"In large Simulink models it is important to have an automatic tool. This tool is easy to configure and verifies the absence of certain runtime errors. The verifier detects divisions by zeroes and matrix accesses outside bounds, and also suggests how the implementation can be simplified."

***Päivi Rintamäki**, Valmet Technologies Oy*

TUT: Energy-efficient pump-controlled multi-chamber cylinder – a new extension for the field of Digital Hydraulics

Energy-efficient multi-chamber cylinder technology requires often fairly large hydraulic accumulators, but in certain applications, e.g. a hook lift, there is no extra room for the accumulators. This led to the discovery of a novel technology in this project, and development of a pump-controlled multi-chamber cylinder. Based on the experimental measurements in a boom mock-up, energy loss reduction of 50% was observed when compared to traditional load sensing hydraulic cylinder control.

Industrial relevance

"Energy efficiency is a great sales argument in mobile applications nowadays. Our simulations showed the energy-saving potential of this system, and we believe we can gain a competitive advantage over our competitors by developing and implementing this system in future."

***Jari Laitervo**, Cargotec Finland Oy*

PROJECT NAME

WP 1
Low Energy Consumption and Environmental Emissions

Digihybrid

CONTACT PERSON

ARTO LAAMANEN
TAMPERE UNIVERSITY OF TECHNOLOGY

PARTICIPANTS (ORGANISATIONS)

TAMPERE UNIVERSITY OF TECHNOLOGY
ÅBO AKADEMI UNIVERSITY
VTT TECHNICAL RESEARCH CENTRE OF FINLAND
CARGOTEC FINLAND OY
VALMET TECHNOLOGIES OY
METSO AUTOMATION OY
NORRHYDRO OY
WÄRTSILÄ FINLAND OY

PROJECT DURATION

2011 – 2014

PROJECT VALUE (EUR)

1.417 MILLION

Regenerative Hydraulic Hybrid with Digi-valve and Multi-chamber Cylinder Technology

Main targets & motivation

The main research topic of the project has been energy-efficient hydraulic systems, including hydraulic energy storing and re-use. A multi-chamber cylinder approach, digital valve systems and hydraulic accumulators were the main tools for obtaining an 80 per cent reduction in hydraulic losses when compared to traditional systems. Control methods formed another important part of the research because all functionality is implemented by software. Control research includes systematic code development and validation, energy-optimal and high-performance control, and safety issues.

Results

- While a literature survey showed that hybridisation can be used to recuperate energy in case of negative work, an equally important feature is the possibility of levelling out the power demand from the prime mover and reducing its size
- Evaluation of the energy-efficient digital hydraulic system architectures showed that multi-chamber cylinder technologies have competitive energy efficiency

- A survey was carried out on requirement specifications for industrial and mobile applications: those in the Digihybrid project have very specific characteristics and only limited synergy
- Preliminary simulations of hook lift application with multi-chamber cylinder showed around 50–75% reduction in operation cycle energy losses
- A report was made containing information from relevant standards and from recommended risk analysis methods
- Development of a novel pump-controlled multi-chamber cylinder: a reduction in energy loss of 50% was observed in experimental measurements when compared to traditional load sensing hydraulic cylinder control
- Demonstration and documentation of a safe controller concept: despite an error induced in the communication chain, the fault-tolerant control system was able to continue operation
- Proposal for the third generation architecture of a digital hydraulics controller: one of the main features of the architecture is parallel computing possibilities with FPGA offloading reasonably powerful microcontroller
- Development and experimental testing of a fault-tolerant software platform for a digital hydraulics control system
- Development in conjunction with the EFFIMA's DiHy project of a verifier for Simulink models: the verifier can check automatically that the models always function correctly according to specifications
- Design of new regenerative digital hydraulic control systems for a paper machine reeler: the pump will be off for 99.2% of the time in the new system
- Study of commercial high-flow rate valves: results show that flow range of the digital valve system can be extended beyond 150 l/min with a reasonable switching time
- Development of a new digital hydraulic angular positioning device for engine application; manufactured and experimentally tested using three interfaces, results show that the turning actuator is a workable concept enabling the substitution of an electrical solution with digital hydraulics
- Theoretical analysis and simulations showed that digital hydraulic system is a promising method for controlling intake valves in engines
- Invention and simulation of a hydraulic multi-area actuator for variable valve timing for internal combustion engines: the actuator can be used to replace traditional engine valve trains with fully or semi-hydraulic valve trains.

Key publications

1. Huova, M., Ketonen, M., Linjama, M., Alexeev, P., Boström, P., Walden, M. & Sere, K. (2012), Simulations with Fault-Tolerant Controller Software of a Digital Valve. In: Arto Laamanen (Ed.), Proceedings of the Fifth Workshop on Digital Fluid Power (DFP12), Tampere, Finland, pp. 223–242, Tampere University of Technology, Finland.
2. Ostroumov, S., Boström, P. & Waldén, M. (2014), Deriving Efficient and Dependable Parallel Programs from Simulink Models. TUCS Technical Reports 1111.
3. Boström, P. (2011), Contract-Based Verification of Simulink Models. In: Shengchao Qin, Zongyan Qiu (Eds.), 13th International Conference on Formal Engineering Methods, ICFEM 2011, Lecture Notes in Computer Science 6991, pp. 291–306, Springer.
4. Niemi-Pynttäri, O., Laamanen, A., Linjama, M. & Huhtala, K. (2014), Parallel pump controlled multi-chamber cylinder. To be published in ASME/Bath in September 2014.
5. Hyöty, I. (2012), Commercial High-flow On/Off Valves for Digital Hydraulics. Proceedings of the Fifth Workshop on Digital Fluid Power (DFP12), 24–25 October, 2012, Tampere, Finland. pp. 189–208.

Number of publications: 16
Number of Master's Theses: 6
Number of patent applications/patents: 1

Networks and international co-operation

Digihybrid conducted co-operation with the Academy of Finland project "Energy Efficient Digital Hydraulic Hybrid Machines" (1/2011–12/2014). Different applications were studied in this project but some tasks were common, e.g. literature survey and energy-storing strategies.

Within the EFFIMA programme, Digihybrid and DiHy had similar research field and topics but employed a different approach. The Digihybrid and Intersync projects also had synergy with the safe controller platform. ÅAU/DSLab has co-operated with the Department of Intelligent Hydraulics and Automation at Tampere University of Technology (TUT/IHA) on design of reliable control software for digital hydraulics software. The co-operation has resulted in architectures for fault-tolerant control. Furthermore, the verification tools and methods, as well as quality metrics, for Simulink models developed in the project by ÅAU/DSLab have been tested on control systems from TUT/IHA.

Pontus Boström from ÅAU/DSLab visited Peter Müller's group at ETH Zürich for 10 months beginning in June 2011. This co-operation provided valuable insight into state-of-the-art software verification tools and methods. ÅAU/DSLab has been in long-term co-operation with the University of Southampton and University of Newcastle on the formal development process for dependable control systems and their deployment in industry. This co-operation has provided valuable insight on dependability and formal methods.

Within the EU-project RECOMP (2010–2013) we have co-operated with Danfoss Power Electronics A/S on modelling safety-critical systems, which has provided insights on requirements demanded by safety standards. In verifying real-time properties, the ÅAU/DSLab has co-operated with Tallinn University of Technology. A more recent co-operation partner is the Eindhoven University of Technology in the Netherlands. This co-operation explores internal and external quality for Simulink models.

TUT/IHA is a member of ACCM (Austrian Center of Competence in Mechatronics) the most important research partner being the Institute of Machine Design and Hydraulic Drives/Johannes Kepler University (IMH, Linz, Austria). IMH has deep understanding of fast on/off valves and their control electronics. Co-operation has taken the form of information sharing, research mobility and common courses. Four international digital fluid power workshops have also been organised in Linz, Austria and in Tampere, Finland.

Applications & impact

A new regenerative digihydraulic control system for a paper machine reeler was developed by Valmet and TUT/IHA. The system is already in commercial use.

A hydraulic multi-area actuator concept for variable valve timing in internal combustion engines was patented and studied. A cylinder with multiple effective areas, energy recovery and fast valve technology are tools for achieving a highly flexible valve train with reasonable energy consumption.

A safe controller implementation was developed using an embedded microcontroller platform running on the RT operating system. The safe controller algorithm was provided by TUT and ported first to VTT's 4th generation sensor node. Safe aspects to the model were provided by ÅAU/DSLab.

The new pump-controlled multi-chamber cylinder broadens the variety of digital hydraulic systems and offers an excellent option for certain type applications. With basic research still needed, this is not yet ready for commercialisation.

An improved code verification tool (VerSÅA) has been developed and two training days organised for EFFIMA participants. VerSÅA is an essential tool for improving reliability of the control codes in digital hydraulic applications.

"The project has enabled us to obtain a deeper understanding of digital hydraulics and where it could be used in our industry. The project produced several interesting inventions and ideas. We are convinced that these will have a positive impact on our future competitiveness. We also highly appreciate the opportunity the project has given us to collaborate with both industrial and academic partners."

Harry Särs, Chief Design Engineer
Wärtsilä Finland Oy

"The Digihybrid project provided us with an excellent environment for the development of our methods and tools in the design of reliable and safe control systems. We also had a great opportunity to evaluate these methods and tools in an industrial setting."

Marina Waldén, Adjunct Professor
Åbo Akademi University

PROJECT NAME

WP 1 Low Energy Concumption and Environmental Emissions

Neffi

Integrated Serial and Parallel Hybrid Drives in Working Machines

Energy savings and low emissions through hybridisation and a new integrated energy converter component

The results of Neffi provide knowledge, simulation tools and a new component for hybrid mobile working machines and other applications.

Neffi provided energy flow analyses of mobile working machines, hybrid system simulation and optimisation methods, generic analysis approach of energy recovery capability in various heavy working machines, simulation models of mobile working machines with energy flow and consumption analysis and combination table of several transmission and work hydraulics alternatives.

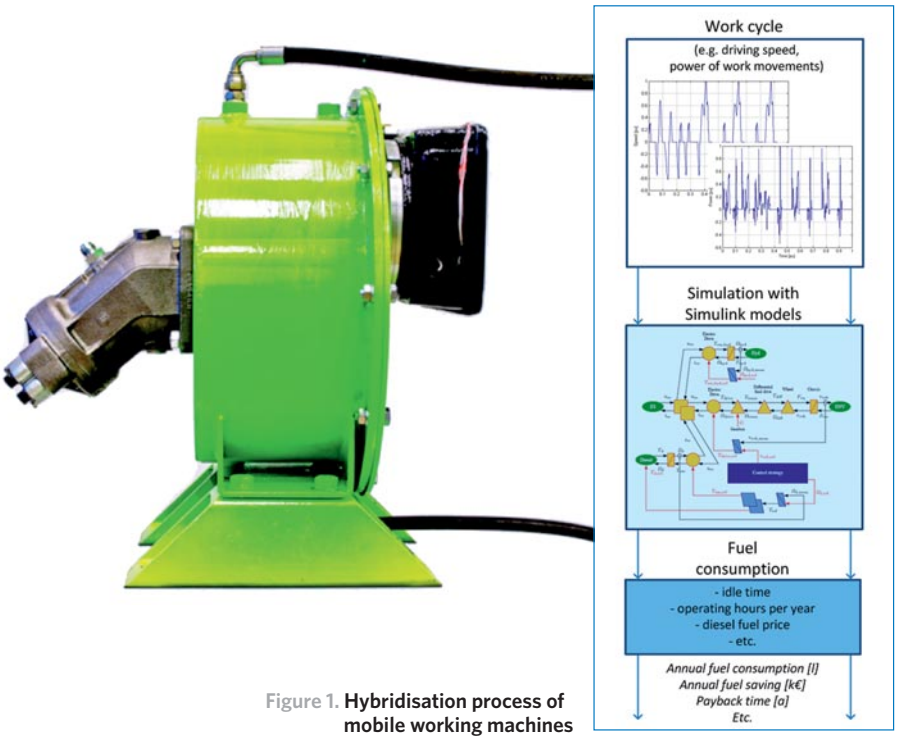


Figure 1. **Hybridisation process of mobile working machines**

IEHEC – Integrated Electro-Hydraulic Energy Converter

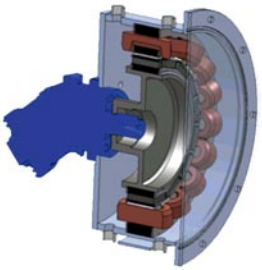


Figure 2.
IEHEC – Integrated Electro- Hydraulic Energy Converter

Energy savings can be achieved for example in cranes, excavators, reach machines and different stackers, where the potential energy can be recycled if the hydraulic machine could work as a hydraulic motor and drive the electrical machine in generating mode. In Neffi, a specially designed compact permanent-magnet synchronous electric machine was integrated into a bent-axis piston-type hydraulic machine for such motion control and energy recovery purposes.

The integrated design of prototype IEHEC (30 kW, 100 l/min @ 1500 rpm, 380 bar, 110 kg) offers high power-to-weight ratio. As a case example, energy saving in a long boom application by IEHEC was analysed by the researchers of LUT Energy, LUT Mechanical Engineering and TUT IHA. According to the results, energy savings up to 48% can be achieved. The IEHEC principle could be used in different sizes, and also in application areas other than mobile working machines.

Industrial relevance

"The IEHEC concept has proven to be interesting both scientifically and industrially. Laboratory tests have shown the good energy efficiency and controllability of IEHEC. Practical demonstrations are needed to prove the concept in reality. The future of energy-efficient mobile working machines needs such electro-hydraulic actuators as IEHEC."

***Heikki Salonen**, Product Manager, Cargotec Finland Oy*

Hybridisation process of mobile working machines

The hybridisation process of a mobile working machine commences by defining the work cycles and corresponding loads for all the main components of the machine. The work cycle should reveal the purpose for which the energy is consumed and whether there are energy recovery opportunities.

The hybrid system type will be selected on the basis of the working machine work cycle. The manufacturer must decide on how radical will be the changes it is ready to make to the machine. The components should then be sized. The difficulty in selecting the main components for a hybrid system is that there are, in principle, a huge number of possible combinations, despite the boundary conditions. An extra difficulty is imposed by the control of the system, as it is possible to apply several different control methods, resulting again in different energy efficiencies of the system. The fuel consumption of a work cycle can be estimated as the simulation result of the Matlab/Simulink models created, while the annual fuel consumption,

annual fuel saving and payback time can be defined, once the idle time, operating hours per year, diesel fuel price and additional costs of hybrid systems are known.

Industrial relevance

"The hybridisation process analysis in Neffi has helped ABB to understand how OEMs work in this segment. Typical power ranges and benefits of different hybrid solutions have also strengthened the selection criteria of customer demands in product development."

***Teemu Ronkainen**, Sales manager, ABB.*

Energy system modelling for a real-time product development simulator

At Cargotec, knowledge gained in early phases of Neffi has been used in modelling the energy system of a hybrid straddle carrier. The simulator in question is a real-time simulator built specifically for product development use. Models have been made using MATLAB/Simulink. In the simulator, the energy system model has been integrated on one side to a machine control system and on the other to the multibody dynamics simulation model.

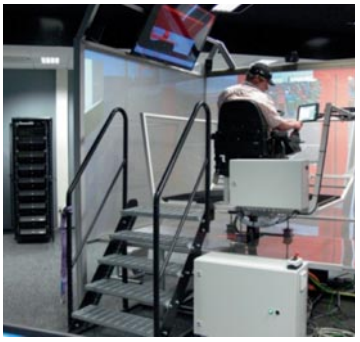


Figure 3. **Physical setup of the product development simulator**

It has been shown that the approach selected – building a separate energy system model with a well-known modelling and simulation environment – is a sound one. Parameters measured at engine and electric test laboratories for various components of the energy system can now be fed easily into the model. The machine behaviour can then be simulated to take account of the driver's actions, normally somewhat difficult to incorporate into off-line simulations. Connecting the energy system model to the true machine control system also makes it possible to observe the co-operation of energy system components and their control systems.

PROJECT NAME

WP 1 Low Energy Concumption and Environmental Emissions

Neffi

CONTACT PERSON

HEIKKI HANDROOS
LAPPEENRANTA UNIVERSITY OF TECHNOLOGY LUT

LASSE LAURILA
LAPPEENRANTA UNIVERSITY OF TECHNOLOGY LUT ENERGY

PARTICIPANTS (ORGANISATIONS)

LAPPEENRANTA UNIVERSITY OF TECHNOLOGY LUT

TAMPERE UNIVERSITY OF TECHNOLOGY TUT

CARGOTEC FINLAND OY

ABB OY

AXCO-MOTORS OY

PROJECT DURATION

2009 – 2013

PROJECT VALUE (EUR)

2.131 MILLION

Integrated Serial and Parallel Hybrid Drives in Working Machines

Main targets & motivation

- Energy flow analysis in mobile working machines
- Hybrid system simulation and optimisation methods
- Generic analysis approach for energy recovery capability in various heavy working machines
- New energy saving methods in working hydraulics
- Develop energy saving technology resulting in CO_2 emissions reduction in heavy mechanical / hydraulic working machines.

Results

- Simulation model for mobile working machine with energy flow and consumption analysis
- Simulation model for working machine with hydraulic CVT
- Combination table of several transmission and work hydraulics alternatives
- IEHEC – Integrated Electro-Hydraulic Energy Converter – prototype

Key publications

1. Immonen, P. (2013), Energy Efficiency of a Diesel-Electric Mobile Working Machine, Dissertation, Lappeenranta University of Technology, 6/2013, available: http://www.doria.fi/handle/10024 /90573
2. Ponomarev, P., Lindh, P. & Pyrhönen, J.(2012), Effect of Slot and Pole Combination on the Leakage Inductance and the Performance of Tooth-Coil Permanent-Magnet Synchronous Machines, IEEE Transactions on Industrial Electronics.
3. Åman, R., Handroos, H., Ponomarev, P. & Pyrhönen, J. (2013), Utilisation of Electro-Hydraulic Hybrid Actuator System in Off-Highway Working Vehicles. Proceedings of the 8th International Conference on Fluid Power Transmission and Control (ICFP 2013), held in Hangzhou, China, 9–11 April. World Publishing Corporation. [CD-ROM] pp. 232–236.
4. Heinikainen, O., Handroos, H., Pessi, P. & Salonen, H. (2011), The energy recovery potential in a heavy working machine, 12th Scandinavian International Conference on Fluid Power, SICFP, Tampere, Finland.
5. Tikkanen, R. (2012), Modifications and measurements of pump-controlled working hydraulics (in Finnish), Master's Thesis, Tampere University of Technology.

Number of publications: 14
Number of Doctoral Theses: 2
Number of Master's Theses: 4

Networks and international co-operation

The project was mainly concentrated on co-operation between the main participants. LUT and Eindhoven University of Technology (Prof. E. Lomonova) conducted co-operation in the form of journal publication.

Applications & impact

- The results provide knowledge, simulation tools and new components for hybrid mobile working machines and other applications
- Knowledge gained in the energy efficiency simulation tools that were created has been used by Cargotec in modelling the energy system of a hybrid straddle carrier in a real-time product development simulator
- LUT is looking for partners to put the IEHEC – Integrated Electro-Hydraulic Energy Converter – principle further into practice, creating new demonstration cases and business
- TUT is looking for partners to demonstrate hybridisation in a real mobile working machine.

"The Neffi project has shown an effective way of reaching energy saving and CO_2 emission reduction. Co-operation with universities and companies in field measurements and data analysis gave reliable information for energy systems development. Further development of energy system models created originally by university teams has given tools for selecting future energy system concepts. Participation in this project will certainly lead to improved international competitiveness in the future."

Heikki Salonen, Project Manager
Cargotec Finland Oy

"Several interesting results have emerged in the Neffi research at LUT. The integrated electro-hydraulic converter (IEHEC) is one of the hardware results enabling direct electric drive control for hydraulics. Energy flows in different heavy machinery have been studied, with special research focus on the roles of electric energy storages and electric machine types. Pavel Ponomarev's dissertation studied torque-dense electric machines, while Paula Immonen studied the energy efficiency of mobile machinery as a function of electric energy storage performance. Both theses can be regarded as results of the Neffi project at LUT."

Juha Pyrhönen, Professor
LUT Energy, Lappeenranta University of Technology

PROJECT NAME

WP 1 Low Energy Consumption and Environmental Emissions

SEEE

Ship's Energy Efficiency and Environment SEEE

Superior competitiveness for the Finnish Maritime industry through adaptation of energy-efficient and environmentally sound technology, novel design procedures and efficient operational aids.

A ship's energy efficiency is gaining increasing attention as one of the most significant factors influencing ship operating costs during the life cycle and the impact of marine transport on the marine environment.

The aim of the SEEE project is to turn this global attention on energy and environmental efficiency into an additional source of competitive advantage – by creating comprehensive tools, methodologies, procedures and practices that facilitate the innovation of new energy-efficient and low-emission solutions and concepts for ship design, building and operation.

CASE 1: Development of a Ship's Energy Flow Simulator

Typically the ship's power plant is dimensioned for the maximum theoretical auxiliary power consumption, in addition to certain 'margins on margins' for propulsion motors and diesel engines. An early design calculation tool was therefore created in order to discover an optimum power plant and to find more efficient ways of distributing and consuming the energy. This would not only enable more accurate estimation of a ship's environmental impact throughout its life cycle, but make it possible to design and operate ships in a more environmentally friendly way.

A Ship Energy Flow Simulator was developed, using Matlab, Simulink and Simscape within the physical multi-domain simulation framework. The aim was systematic modelling and simulation of ship main energy flows with respect to dynamic ship operating profiles and user-customisable model inputs and parameters.

Large component libraries of different physical domains have been developed ready for use, with easy application to transport and other complex energy process industries.

As a case study using the multi-domain simulation platform, the project group has been successful in developing a specific ship energy flow simulator for a modern cruise ship. The main ship energy systems were modelled at a system level to facilitate the physical interactions among different energy subsystems. The validation results have been positive in showing the feasibility and reliability of the energy flow simulation method. More importantly, the ship energy flow simulator gives valuable insights into how to design an energy-efficient ship power plant and to operate the vessel efficiently.

For example, as first tryouts, more accurate regulation of a valve in an energy recovery system has been proven to cut the annual fuel bill for a single cruise vessel by 50,000 euros. The return of investment is estimated at one year.

The Ship Energy Flow Simulator has significant business potential for ship energy system simulation and optimisation, simulation-aided ship system design and optimisation, and energy-efficient ship operation guidance and optimisation. Specifically, the developed simulator has seen successful use in partners' products/offerings and design processes. For example, ABB and VTT have tested and evaluated novel solutions for energy-saving in large container ships whose harvested energy is as high as 4–13% of ship main engine nominal power under typical operations.

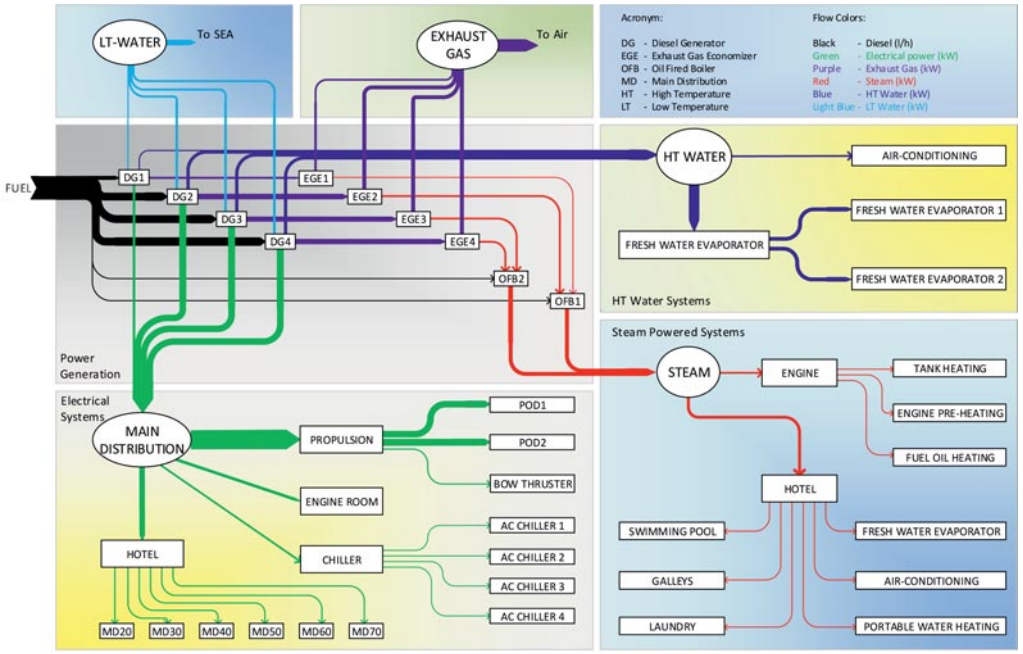


Figure 1. **Energy distribution within the case ship**

Industrial relevance

"The ship energy flow simulator has helped us to gain in-depth insight into the propagation of different energy flows throughout the ship. This information has been used in several development projects varying from energy harvesting to sophisticated control of different onboard subsystems. Overall, the simulator as a tool has enabled us to conduct fast prototyping of novel ideas and evaluation of the performance of a vessel with its current components."

*Dr **Juha Orivuori**, ABB Oy, Marine*

Deltamarin has verified that optimal boiler dimensioning and central cooler optimisation can result in big fuel savings in their bulk carriers.

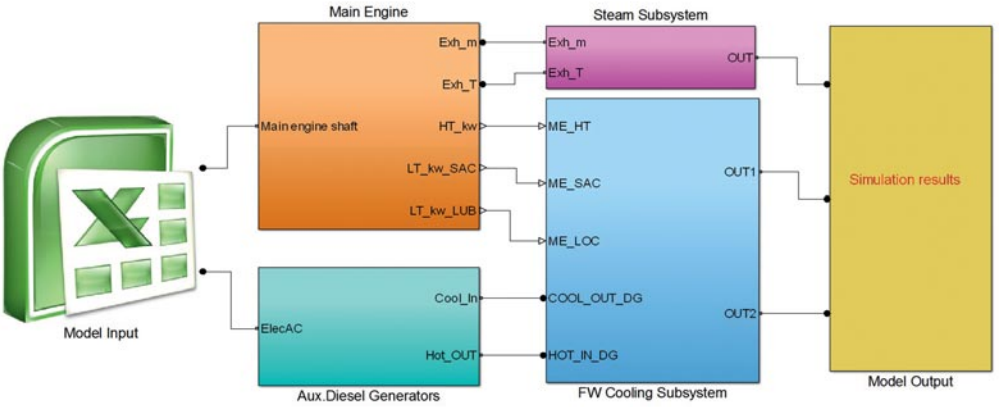


Figure 2. **Top level view of the bulk carrier ship energy flow simulation model**

Industrial relevance

"We have used the ship energy flow simulator in our most recent development projects to reach energy efficiency levels that will surpass those of our competitor's designs. Our customers have also been impressed with what we can do at such an early stage in the project."

Ms. ***Päivi Haikkola****, R&D Manager, Deltamarin Oy*

All the above-mentioned solutions can be deployed easily in different ship types.

Case 2: LCC/LCA Tool for ship concept evaluations

Alongside economic performance, the environmental/ecological aspect of performance is of increasing interest and importance, and requiring to be accounted for in ship design. This reflects both the greater demands being placed on the maritime sector by environmental regulations, and the positive marketing value of more sustainable technology perceived by the shipping industry.

The developed tool integrates assessment of life-cycle costs (LCC) and ecological impacts (LCA) with a common system specification capturing the behaviour of the ship and its various sub-systems, doing so in such manner that allows simulation of the effects of decisions made regarding vessel design and operation. The tool provides an analytic framework that provides efficient support for systematic comparisons of alternative vessel concepts, sub-system designs and ship-operating scenarios from both economic and ecological perspectives.

TOOL

- MS Excel & Visual Basic application
- enables comparison of various ship and machinery concepts and operating scenarios
- focuses on vessel-operating phase impacts
- predicts fuel consumption and costs, and exhaust gas emissions, of a vessel for the specified operating profile and associated operating modes
- indicates optimal engine loads in each operating mode regarding minimum fuel cost, or exhaust gas emissions (CO_2)
- enables calculations in the early conceptual design phase with scarce data, and more accurate calculations in later design phases when detailed data is available
- can also deal with gas and dual-fuel engines, gaseous fuels, scrubbers and catalysators for SOx and NOx reduction

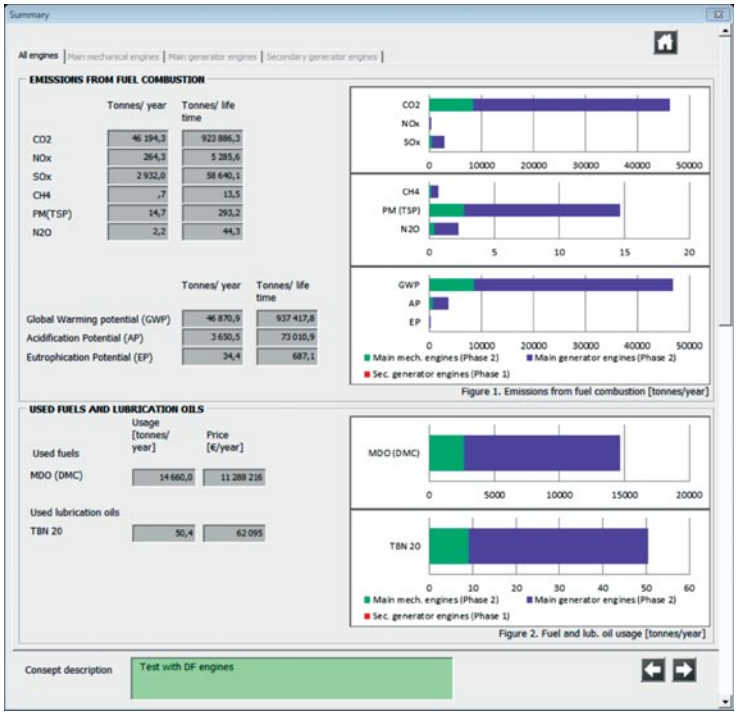


Figure 3. **Example of main LCC/LCA results provided by the tool**

Case 3: Tool for Obtaining Real Understanding on Vessel Performance

Understanding how the vessel performs in real operation is a cornerstone for optimising fuel efficiency and technical maintenance of the vessel. Traditional engineering methods can predict vessel performance accurately, but are developed for ideal conditions and thus only reliable under such circumstances. Current knowledge of vessel performance in actual operating conditions is not particularly extensive.

The Tool

Methods were developed that combine engineering methods with machine learning models in order to facilitate more accurate and self-learning models for the real-life performance of ships. Within the framework of the project, research was focused on developing suitable models that are applied to measured operational data from the vessel. Using such models requires a significant amount of computation power, leading to development of a framework allowing automatic analysis of the data in cloud environments. The results of the analysis are presented to the end user through a web-based business intelligence tool.

Part of the work was to establish an automatic and reliable data communication infrastructure for gathering data onboard and transferring it to the shore-based system, providing sufficient access for a globally distributed user base.

Validation of the results was carried out in co-operation with major organisations in the international maritime field (ship owners, operators, classification societies and shipyards).

Industrial relevance

"We have used the tool for a thorough evaluation of the overall model, from stem to stern. The tool brings us insight and simulation possibilities for enhancing the NAPA Voyage Optimisation model and NAPA for Design tools, giving us a more throughout view in our commercial applications, serving an integrated maritime market from design right through to operations."

***Jouni Salo**, Product Manager,*
Shipping Solutions NAPA for Operations

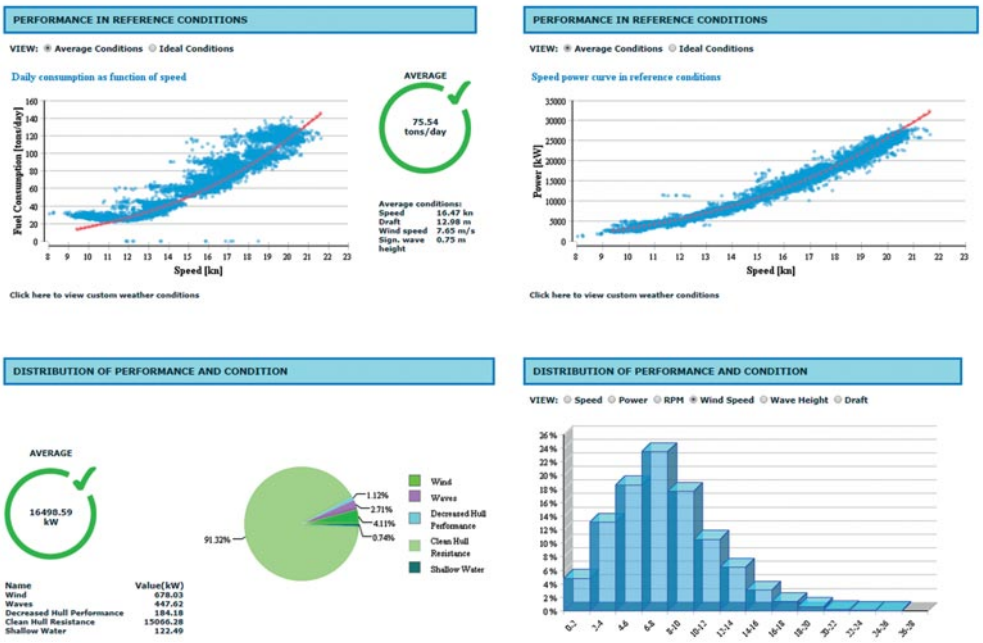


Figure X. **Example of ship performance report from the shore based system**

PROJECT NAME

WP 1 Low Energy Consumption and Environmental Emissions

SEEE

CONTACT PERSON

STEFAN WACKSTRÖM
ABB OY

SEPPO KIVIMAA
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PARTICIPANTS (ORGANISATIONS)

VTT TECHNICAL RESEARCH CENTRE OF FINLAND

TURKU UNIVERSITY OF APPLIED SCIENCES

ABB OY

DELTAMARIN OY

NAPA OY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

4.300 MILLION

Ship's Energy Efficiency and Environment SEEE

Main targets & motivation

- Develop an effective tool for LCA (life-cycle analysis) and LCC (life-cycle cost) evaluation
- Develop at least one verified measurement solution for long-term monitoring of emissions during operation (for example SO2 in relation to location, dwt, mileage, etc.) to help shipping companies cope with current and future legislation
- Create a transparent and extensive measurable environmental performance indicator system for shipping
- Develop systems for monitoring and analysing energy efficiency and emissions of a ship and fleet
- Develop knowledge-based expert systems for energy-efficient operation of a ship and fleet
- Achieve a comprehensive understanding of underwater noise produced by the ship, and its consequences
- Develop a prediction capability and simulation method for estimating underwater noise emission from a ship
- Measure ship's underwater emission and validate underwater noise prediction for a selected case.

Results

- Creation of the basis for the life-cycle model (methods and tools) for evaluating the life-cycle environmental and cost impacts of ships, and a LCC/LCA calculation software tool for the ship's operational phase
- Onboard Real Time Monitoring Tool for monitoring ship's performance during normal operation
- Shore-based fleet emission and performance monitoring tool with cloud-based architecture
- Analytics methods for estimating ship's performance using measured data, and for an automatic-learning ship model of an onboard optimisation system
- Optimisation tool for optimising ship's machinery, speed profile, and route in normal daily operation onboard the ship, involving extensive trial use with domestic and international shipping companies
- Methods for calculating optimum trim curves using CFD, developed and validated using model tests
- Infrastructure for onboard data collection and optimisation tools integrated with various data sources and communication systems
- Design of an environmental performance indicator for shipbuilding and ship-dismantling
- Ship Energy Flow Simulator, a system-level multi-domain simulation platform with high-level flexibility and reliability, easily adaptable for different ship types and even for other energy process industries
- ABB has been using the Ship Energy Flow Simulator in new concept designs.

Key publications

1. Hänninen, S., Peltoniemi, E., Tuominen, R., Kunttu, S. & Schabel, J. (2012), Ship's environmental footprint. International Conference on the Environmentally Friendly Ship, London, 28-29 February 2012. RINA, Royal Institution of Naval Architects. Papers, pp. 69–75.
2. Lappi, M., Hänninen, S. & Murtonen, T. (2012), Origin of particle emissions of a new IMO NOx Tier 2 category cruising ship compliant with European SOx emission control areas. 16th Conference on Combustion Generated Nanoparticles, Zürich, 25-27 June 2012. Eidgenössische Technische Hochschule (ETH) Zürich et al. Zürich, poster; extended abstract.

3. Zou, G., Elg, M., Kinnunen, A., Kovanen, P., Tammi, K. & Tervo, K. (2013), Modeling ship energy flow with multi-domain simulation, Proc. CIMAC.
4. Uosukainen, S, (2011) Foundations of acoustic analogies. VTT Publications 757.
5. Kariranta, R-J. (2010), Analysis of the Technical Performance of a Ship in Service. Master's Thesis Aalto University.

Number of publications: 7
Number of Master's Theses: 3
Number of Bachelor's Theses: 2

Networks and international co-operation

- Co-operation with shipyard and ship owner of the vessel used in the case studies
- Co-operation with domestic and international shipping companies in trialling the real time and shore based monitoring tools
- Participation in international conferences.

Applications & impact

- Life-cycle assessment model for shipbuilding. The study on shipyards' environmental impacts has brought know-how on the topic to the project consortium. The need for further research and practical application with actors of the industry was highlighted.
- LCC/LCA tool provides an analytic framework giving efficient support to systematic comparisons of alternative vessel concepts, sub-system designs and ship-operating scenarios from both economic and ecological perspectives.
- Emission measurements for one main and one auxiliary engine were realised during the sea trials of the case-study ship. The emission factors measured have been used in other research projects. VTT will develop and take into use continuous monitoring of exhaust volumetric flow rate.
- Onboard real time monitoring tool increases crew awareness of ship's performance and efficiency during normal operation.
- Shore-based monitoring tool with cloud-based architecture brings a monitoring solution to the global customer base and allows for scalable business development.
- The ship and fleet performance monitoring system offers the shipping industry a tool with automatic and accurate data on

ship's performance, fuel consumption and emissions. The system comprises methods developed for automatic data normalisation and analysis, providing users with reliable data on ship's and fleet's performance to enable the best possible decision-making.

- Voyage optimisation tool with a learning calculation model provides the shipping industry with an accurate tool for optimising voyages with regard to machinery, speed profile, and route for minimum fuel consumption and emissions. The system has been tested and adapted to new ship types, including tanker, container ship and bulk carrier. Study was also made of the special requirements for LNG carrier optimisation, and a dedicated LNG carrier version can be developed based on the results.
- New and quick methods for calculating ship's optimum trim curves, using CFD calculations instead of expensive and time-consuming model or full-scale measurements, will allow more and more vessels the opportunity of operating in optimum trim and saving propulsion energy.
- The successful co-operation within the project group is to be continued and expanded to a larger group, with a networked application to the Tekes MERI programme.
- The IPR for the Ship Energy Flow Simulator has been issued and is co-owned by VTT, ABB and Deltamarin.
- Measurement of ship's underwater noise during a cruise vessel's sea trial.

"The Effima project has been a substantial contributor to NAPA's ability to carry out extensive R&D activities in the field of marine energy efficiency. Several significant new concepts have been developed during the project, which has strengthened our position in the highly competitive global market."

Esa Henttinen, Executive Vice President
NAPA for Operations

"The SEEE project was an important milestone in research on the energy-efficiency of ships and ship systems in Finland. Novel methods and tools were developed for simulation of energy flows in ship systems, assessment of life-cycle operational cost and environmental impact of concept ships, and minimisation of energy consumption in operation through weather routing and engine combination. The tools were applied in the products of the participating companies, always the best measure of a successful project."

Seppo Kivimaa, Senior Principal Scientist
VTT Technical Research Centre of Finland

WORK PACKAGE 2:
Technologies for Life-cycle Cost Management

PROJECTS:

- Distributed Systems and Wireless Technologies for Industrial Applications – Intersync
- From Measurement Data to Information – Tolkku
- Forces and Vibrations as Fault Indicators– Fovi

fimecc

FINAL REPORT 2/2014

PROJECT NAME

WP 2 Technologies for Life-cycle Cost Management

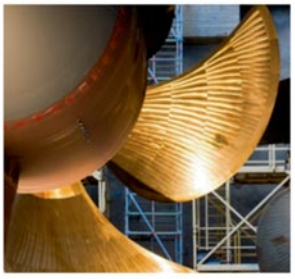
Intersync

Distributed Systems and Wireless Technologies for Industrial Applications

Energy-autonomous sensors for industrial condition monitoring

Maintenance-free wireless sensing solutions pursuing the strictest requirements of the industrial partners

- **High-performance sensor node & tool chain for distributed data processing**
- **Ultra-low-power sensors working maintenance-free for 10 years**
- **Zero Power Sensors for simple passive measurements with no internal power source**

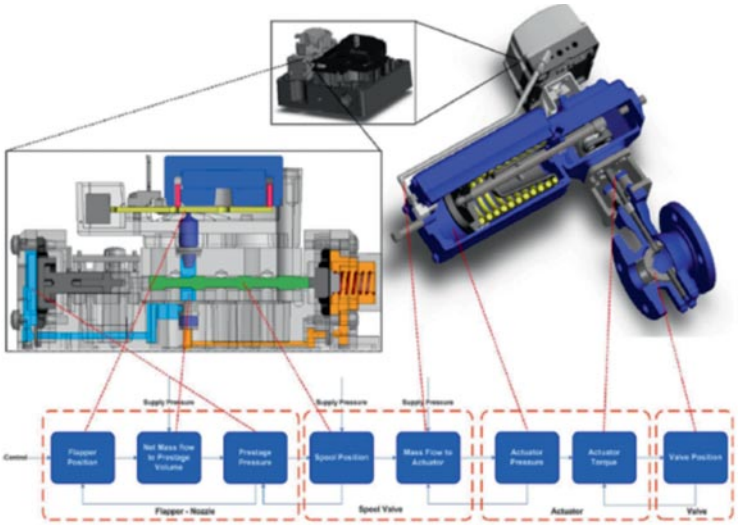


With Metso's intelligent control and automated on-off valve technology, process variability can be reduced to avoid production losses and upsets and bring down the consumption of fuel or raw materials.

A virtual valve model and simulator has been applied to state-of-the-art condition monitoring and diagnostics methods development.

Within the fault simulator it has been possible to model intelligent control valve dynamics analytically despite its inherent nonlinearities. These nonlinearities of the system have been identified and estimated by means of selected parameters. The derived models have been verified with measurements and the modelling error found to be acceptable for the fault simulations. Typical control valve faults have been simulated and an analysis made of the impacts on the flow control loop internal variables and control performance. The presented fault simulator can be used for fault detection and diagnosis as well as for robust control research and development.

Based on simulations and test bench test runs it is possible to detect and diagnose typical control valve faults before severe impact on flow control loop performance. This can be done with the on-line method, requiring low computing power, which was introduced in this study.



Wireless sensor networks for condition monitoring and real-time process automation is a promising technology for intelligent valves. The monitoring of solutions of critical components in harsh industry environments gives a new competitive edge. Of special interest is the monitoring of valve leakage or fugitive emissions with low-cost and reliable sensors.

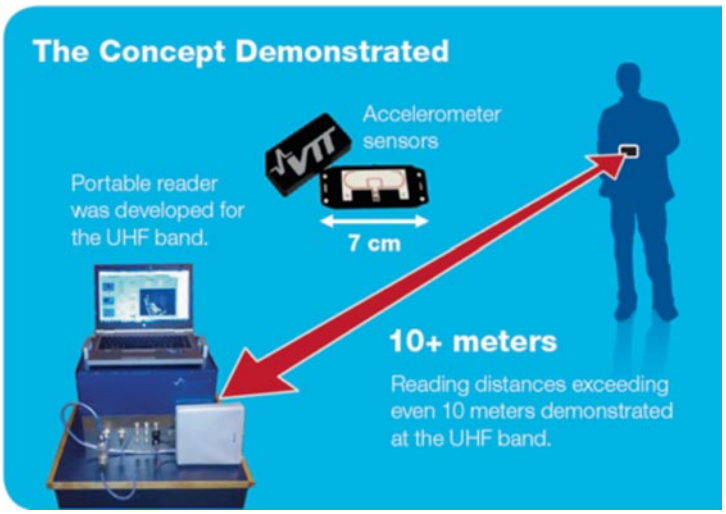
Innovative and novel wireless sensor technologies and solutions help to improve health and safety for workers, allowing plants to meet regulatory standards and to reduce product losses. Ultra-low-power usage provides 10 years of battery life, minimising the need for maintenance.

Industrial relevance

"The new wireless approach for leakage sensors can shorten and ease assembly and makes the physical interface more tolerant of tough handling. This kind of add-on approach could increase the usage of leakage sensors to many new kinds of valves. The same wireless approach can be extended in the future for other sensors such as strain and temperature. In the end this could lead to improved process efficiency, better energy management and reduced emissions into the environment."

***Joona Nikunen**, Research engineer, Metso Automation Oy*

The Zero Power Sensor Network technology developed at VTT is a solution for intelligent sensing, where sensing is wireless and passive. There are no batteries or cables, yet the concept enables the reading of many sensors at the same time, with communication distances of several tens of metres, high speed, high accuracy, and compliance with the frequency regulations.



The Competitive Edge

- Long reading distances
- Wireless – no cabling
- Passive operation – no batteries
- Low-cost sensors
- Multiple sensing with unique ID
- Compliant with frequency regulations
- Fast and accurate measurements

Industrial relevance

"The ZeroPowerNetwork research revealed a hidden world of fully passive sensing. Getting rid of cables, batteries and energy harvesters brings new and unforeseeable possibilities. This kind of research is definitely what SHOK research is meant for. New, out-of-the-box ideas that must be researched thoroughly before even the limits are known. This kind of work is not possible with one single company, but only through good co-operation. The future will tell whether it was worth it, but without research there will be no future."

***Joona Nikunen**, Research engineer, Metso Automation Oy*

PROJECT NAME

WP 2 Technologies for Life-cycle Cost Management

Intersync

CONTACT PERSON
VESA PENTIKÄINEN
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PARTICIPANTS (ORGANISATIONS)
VTT TECHNICAL RESEARCH CENTRE OF FINLAND
ABB OY
KONE OYJ
KONECRANES OYJ
METSO OYJ
TAMPERE UNIVERSITY OF TECHNOLOGY
UNIVERSITY OF OULU

PROJECT DURATION
2009 – 2014

PROJECT VALUE (EUR)
6.5 MILLION

Distributed Systems and Wireless Technologies for Industrial Applications

Main targets & motivation

- Maintenance-free wireless sensing solutions pursuing the strictest requirements of the industrial partners.
- Technologies developed for four company-specified use-case domains:
  1. Global networked asset management
  2. Distributed industrial condition monitoring
  3. Monitoring of critical components in harsh environments
  4. Service business by data analysis
- Multidisciplinary scientific team to cover all aspects of energy-autonomous wireless sensing:
  1. Multi-sensory distributed measurements
  2. Energy-autonomous sensor nodes
  3. Sensor technology
  4. Wireless communications
  5. Zero power sensor network
  6. Towards sensor node technology commercialisation

Results

Advanced methods and tools for energy-optimised measurement data analysis (developed in co-operation with the Tolkku project)

Platform technologies that enable development of wireless energy-autonomous sensor nodes

Zero Power Sensor Network concept enabling passive wireless sensing, with no batteries or power source at the sensor node

Ultra-low power sensor, with an integrated battery with a lifetime of several years, for early detection of leaks in process valves

High-performance sensor platform capable of real-time synchronised measurements and high-performance signal processing using an integrated FPGA circuit

Global Interconnectivity Architecture for networked asset management

Pilot implementations of wireless condition monitoring systems:

- **Industrial valves:** Valve leakage and torque measurements using ultra-low-power wireless sensor nodes. Fault Detection and Diagnosis for tools for Intelligent Process Control Valves
- **Minerals production process:** Vibrating screen condition monitoring system with integrated energy-harvesting
- **Propulsion engines:** Wireless condition monitoring solutions for propulsion motor shaftline.
- **Steel ropes & belts:** Trend analysis and fault diagnosis for condition-based maintenance.
- **Bearings:** Lifetime estimation of counterweight pulley bearings. Bearing fault analysis algorithms studied and implemented on high performance sensor nodes in co-operation with the Tolkku project.

The Intersync project was given the 2013 FIMECC prize award as the best project of the year, with particular regard to the high potential of the Zero Power Sensor concept.

Key publications

1. Nyländen, T., Janhunen, J., Hannuksela, J., Silvén, O. (2011), FPGA-based application-specific processing for sensor nodes. In International Conference on Embedded Computer Systems (SAMOS), IEEE, pp. 118–123.
2. Peippola, T. (2010), Langattoman sensorisolmun energiatehokkaan signaalinkäsittelyn arkkitehtuuri. Master's Thesis. University of Oulu.
3. Manninen, T. (2011), Process control valve fault simulator. In The Twelfth Scandinavian International Conference on Fluid Power, Tampere, Metso Automation.
4. Song, J. (2012), On Optimization and Read-out Resolution of the Zero Power Sensor, Master's Thesis. Aalto University.

5. Song, J., Viikari, V., Pesonen, N., Martila, I. & Seppä, H. (2013) Optimization of Wireless Sensors Based on Intermodulation Communication. IEEE Transactions on Microwave Theory and Techniques, Vol. 61, No. 9, pp. 3446–3452.

Number of publications: 13
Number of Master's Theses: 4
Number of Doctoral Theses: 1

Networks and international co-operation

Co-operation has taken place with other FIMECC EFFIMA projects, in particular, Tolkku, Fovi, DiHy and SEEE. The research topics have substantial commonalities, and many of the industrial partners are the same as for Intersync.

Applications & impact

- The commercialisation phase for the high performance sensor node is ongoing
- There is great interest shown towards the commercial applications of the Zero Power Sensor Network technology
- Participating companies have actively used the project outcome in their R&D

"The work in the Intersync project resulted in the development of a robust and field-applicable wireless sensor network pilot that is easy to install and use in real environments. Konecranes has utilised the set in testing the use of wireless sensing technologies in crane condition monitoring. The work initiated co-operation between the Intersync and Tolkku projects, resulting in inclusion in the Tolkku Toolbox of the basic analysis methods for bearing and gear condition monitoring. The on-going testing at Konecranes will support the future development of methods and tools for remote services and field maintenance work."

Heikki Mesiä, Senior Research Engineer
Konecranes Oyj

"Various new technologies were researched, developed and tested as part of ambitious research projects conducted during the programme. Two focus questions for Kone during the project were the feasibility of energy harvesting and wireless sensor networks for condition monitoring. A key output of such collaboration, besides the technological know-how, was the network of professionals that was formed."

Hannu Rytilä, Senior Chief Design Engineer
KONE Oyj

"During the first project years, InterSync developed very much so-to-say established WSN issues like low-power consumption, sensoring methods, energy harvesting, and VTT's own WSN module platform called VTT Node. But gradually the invention of the so-called zero-power sensor draw most of the attention of both the companies and research. Calculations and laboratory measurements indicated that passive measurement elements could be monitored wirelessly over distances beyond 10 m. The zero-power sensor proved quickly a successful and widely recognized outcome of EFFIMA, although certain obstacles remain to be overcome to make it an ultimate industrial flagship."

Olli Ventä, Research Manager
VTT Technical Research Centre of Finland

PROJECT NAME

WP 2 Technologies for Life-cycle Cost Management

Tolkku

From Measurement Data to Information

Tolkku – Building blocks for operations and maintenance

Measurement data provides a key basis for condition-based maintenance (CBM), among others. Tolkku is a software toolbox designed for condition monitoring, diagnosis and prognostics of machines. The toolbox implements both new methods and prior art and is aimed at practical, down-to-earth data analysis work. The target is to improve knowledge of the operation and behaviour of machines and processes through the entire life cycle. Tools and methods developed in the Tolkku project facilitate turning data masses to information that brings value company-wide from product development, machine operation and maintenance to management decision-making.

Toolbox and process for developing condition based maintenance systems

The FIMECC EFFIMA project "From measurement data to information" (Tolkku) brings a comprehensive view to managing the operation of moving machines at different stages of product life. The tools developed in the Tolkku project facilitate the turning of data masses into information that brings value company-wide: from product development, machine operation and maintenance through to management decision-making.

The idea behind the Tolkku approach is simple. Instead of offering a software tool with fixed features, companies are provided with blocks that facilitate the building of O&M tools for varying situations and requirements. By combining the modules developed in the project, a company can build customised software to match its needs: early detection of faults, optimising maintenance plans, monitoring the use profiles of a machine fleet, to name but a few.

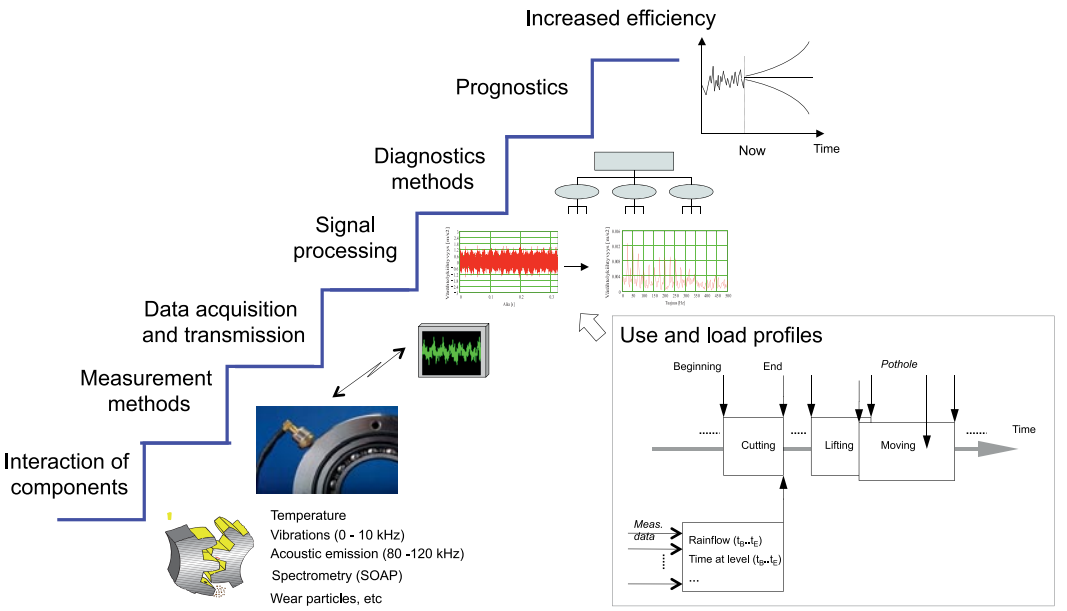


Figure 1. **A stepwise procedure elevated efficiency and reliability**

Scenarios for utilising the Tolkku toolbox include:

- For research and development: Acquiring increased understanding of the system's load and behaviour through its entire life cycle (e.g. information on usage, operating situations, loadings, etc.). Gaining quantitative evidence on the feasibility and reliability of different solutions.
- For operation of the machines: Providing feedback on the systems' behaviour (e.g. a "traffic light" that informs operators about their style of operation). Optimising operation (e.g. anticipating service needs and avoiding emergency actions).
- For service and maintenance: Anticipating the wear and failure of machine/process parts (e.g. information on the extensive load and possible breakdown of individual parts). Supporting condition-based maintenance, remote condition-monitoring, maintenance service, etc.

The Tolkku toolbox includes modules for:

- Data import
- Data preparation
- Feature extraction
- State recognition
- Load profiles
- Anomaly detection
- Analysis of causality
- Time-frequency analysis
- Analysis of bearings and gearboxes
- Decision support
- Implementing CBM.

Key steps towards CBM

- Reliability, criticality and cost analysis
- Select appropriate maintenance tasks
- Select monitoring methods
- Define methods for diagnostics, prognostics etc.
- Determine maintenance actions.

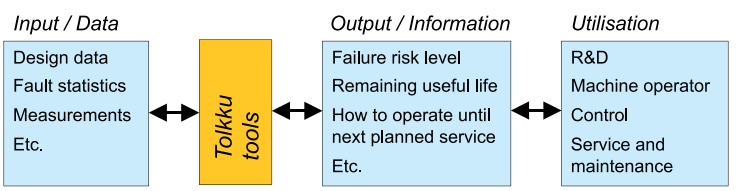


Figure 2. **Procedures for the decision support**

Industrial relevance

"The Tolkku project has created a practical and applicable data analysis toolkit that has already shown some promising results in use. We are very pleased with the way a project that is essentially research-oriented has been so well focused on the industrial needs. The full potential of the Tolkku Toolbox is now in the hands of its users, but the advantages can be reached through well planned and effective use."

***Heikki Mesiä**, Konecranes Oy*

PROJECT NAME

WP 2 Technologies for Life-cycle Cost Management

Tolkku

CONTACT PERSON

MIKKO LEHTONEN
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PARTICIPANTS (ORGANISATIONS)

VTT TECHNICAL RESEARCH CENTRE OF FINLAND
AALTO UNIVERSITY
TAMPERE UNIVERSITY OF TECHNOLOGY
BRONTO SKYLIFT OY AB
JOHN DEERE FORESTRY OY
KONECRANES OYJ
METSO OYJ

PROJECT DURATION

2009 – 2012

PROJECT VALUE (EUR)

1.438 MILLION

From Measurement Data to Information

Main targets & motivation

Continuous measurements are taken from various machines and processes of different variables relating to their state, operational environment, production process, etc. The very large amounts of measurement data that are thus generated should be processed into information that is efficient in serving product development, operation, maintenance and other functions.

Improved knowledge on the operation and behaviour of the product in the various circumstances throughout its life cycle enables advanced optimisation and risk management, and supports, among others, the implementation of the maintenance service.

Results

The main result of the project is the Tolkku toolbox. Tolkku is a software toolbox designed for condition monitoring, diagnosis and prognostics of machines. The toolbox implements both new methods and prior art, and is aimed at practical, down-to-earth data analysis work. The target is to improve knowledge of the operation and behaviour of machines and processes through the entire life cycle. The toolbox supports different phases of condition-based maintenance with tools that extract essential information and automate data processing.

The Konecranes target was to detect different types of developing machine faults by recognising their descriptive patterns and 'fingerprints' through analysis of test and condition monitoring data. The results are expected to enhance the effectiveness of the condition monitoring and service through better understanding of machine behaviour. The targets were reached through effective co-operation with the research partners during the development of the Tolkku Toolbox.

Bronto Skylift has developed powerful tools under the Tolkku project for transferring and analysing data generated by a mobile embedded system. Here there were three focus areas: 1) Data transfer over the Internet between a mobile embedded system of Bronto platforms and the server, 2) Registers in the embedded system, and tools for analysing the data in the registers and 3) Black box and tools for analysing the collected data.

Key publications

1. Saarela, O., Lehtonen, M., Halme, J., Aikala, A. & Raivio, K. (2012), Tolkku – a toolbox for decision support from condition monitoring data. COMADEM 2012, Huddersfield.
2. Halme, J. & Aikala, A. (2012), Fault tree analysis for maintenance needs. COMADEM 2012, Huddersfield.
3. Raivio, K. (2012), From time series measurements to rules of causality. COMADEM 2012, Huddersfield.
4. Mutanen, T. (2012), Using heuristic search for optimising maintenance plans. COMADEM 2012, Huddersfield.
5. Ulvila, V. (2010), Online Data Acquisition System for Mobile Machines, Master's Thesis, Tampere University of Technology, Tampere.

Number of publications: 7
Number of Master's Theses: 2

Networks and international co-operation

International research co-operation: Visit to Berkeley 07/2010 and 12/2010–5/2011, Teemu Mutanen/VTT.

Applications & impact

The importance of measurement data in machine O&M is increasing continuously. Measurement data provides a key basis for CBM, which facilitates service business. Systematic collection and processing of data allows information from single machines to be effectively utilised in monitoring, diagnosis, and maintenance of fleets of machines.

Scenarios for utilising the Tolkku toolbox include:

- For research and development: Acquiring increased understanding of the system's load and behaviour through its entire life cycle (e.g. information on usage, operating situations, loadings, etc.). Gaining quantitative evidence on the feasibility and reliability of different solutions.
- For operation of the machines: Providing feedback on the systems' behaviour (e.g., a "traffic light" that informs operators about their style of operation). Optimising operation (e.g. anticipating service needs and avoiding emergency actions).
- For service and maintenance: Anticipating the wear and failure of machine/process parts (e.g. information on the extensive load and possible breakdown of individual parts). Supporting condition-based maintenance, remote condition-monitoring, maintenance service, etc.

"The Tolkku project was a big step in data mining in modern work machines. It gave common knowledge and new tools for creating information for maintenance prediction from a vast number of control and sensor signals in machines. These tools have been used widely in machine-building companies and in further research."

Antti Siren, Secretary General
FIMA ry

"The Tolkku project gave us tools for collecting, organising and analysing huge amounts of data in a very short time. Tolkku tools are a powerful package for finding out the real cause of failure (root cause). The analyses result in the repair being carried out exactly on the right part of the machine. Machine down time and service visits are minimised."

Jouni Törnqvist, R&D Manage
Bronto Skylift Oy Abj

PROJECT NAME

WP2 Technologies for Life-cycle Cost Management

Fovi

Forces and Vibrations as Fault Indicators for Electrical Machines

Multi-physics analysis – from electro-magnetic fields to vibrations and fault/ ride comfort indicators

Fault diagnostics of electrical machines can be based on different quantities such as currents, magnetic fields or forces and vibrations. Currents are easy to measure, and therefore commonly employed in fault diagnostics. Magnetic field, on the other hand, offers an 'insight' into the machine operation condition but is more difficult to measure, and requires the use of quite specific technology, i.e. sensors. As the magnetic forces are due to the magnetic flux density distribution in the machine, they contain the same information as the field itself yet are easier to monitor, particularly the vibrations induced by the forces. For this reason we concentrate on studying the forces and vibrations as fault indicators, and on the development of the related techniques.

A main priority in the lifting business is safety. Developing advanced fault diagnostics and condition monitoring can enhance the reliability of lifting equipment.

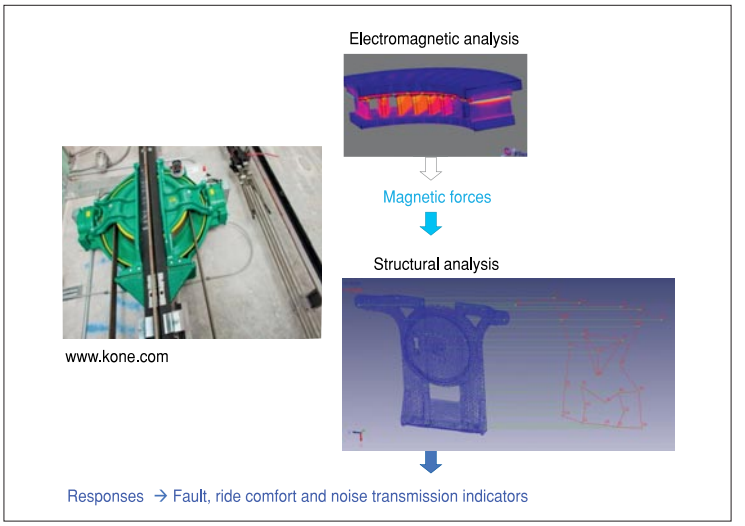
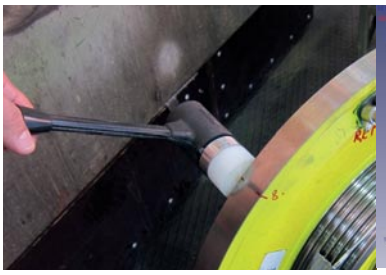


Figure 1. **Analysis of vibrations in electrical machines**

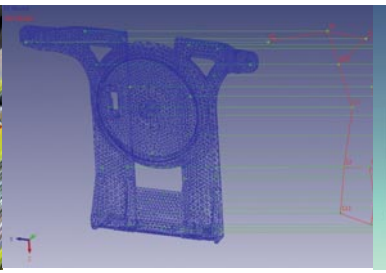
Improving ride comfort by accurate structural analysis and testing on an elevator hoisting motor

The magnetic forces of the motor were solved based on a three-dimensional (3D), time-dependent solution of the electromagnetic field and circuit equations. Analysis of the motor studied cannot be reduced to two dimensions (2D) as straightforwardly as with typical radial flux machines. The search was made for a balance between computational time and modelling accuracy. The magnetic forces couple to the rotordynamics and structural characteristics of the motor.

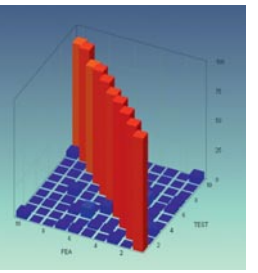
The structural analysis was realised in a systematic manner, building the model of the motor sequentially, part by part. The modal parameters of each of the motor structures (cast frames, stator and rotor) were extracted experimentally and used for the verification of the respective model part. The detailed modal tests and systematic finite element model building and updating approach resulted in models that capture the vibration behaviour of the motor with a high accuracy within the frequency band of 0–1000 Hz.



Experimental modal testing.



Finite element mesh of one of the frames.



MAC chart. Comparison between experimental tests and finite element computations for one frame.

KONE EcoDisc® motor

Figure 2. **Overview of the approach taken to mechanical model building and analysis of a Kone hoisting motor. The machine parts were measured one by one using the results for updating the respective model parts. Outcome: accurate and verified computational models of the machine. Concentration of the red bars on the diagonal of the MAC chart indicates good correspondence between measurement and computation.**

Industrial relevance

"Ride comfort has risen to become a focus area for the elevator business. Fovi presented the KONE Machine R&D department with a prime opportunity to deepen our understanding of machine performance from the point of view of noise and vibration. During Fovi, the tools used to analyse noise and vibration performance in KONE hoisting machines took a clear step ahead, and gave KONE the opportunity to improve this aspect when developing new hoisting machines or improving existing products."

***Asmo Tenhunen**, KTO Category Manager, Machines; KONE Corporation*

Slice model for fault diagnostics of crane hoisting induction motors

Proper modelling of the harmonics in the current and vibration spectra is essential when using field computation methods to assist fault diagnostics. Radial flux electrical machines often have skewed rotors, and accurate modelling requires time-discretised three-dimensional analysis. The computation burden for solving these 3D models is extremely high.

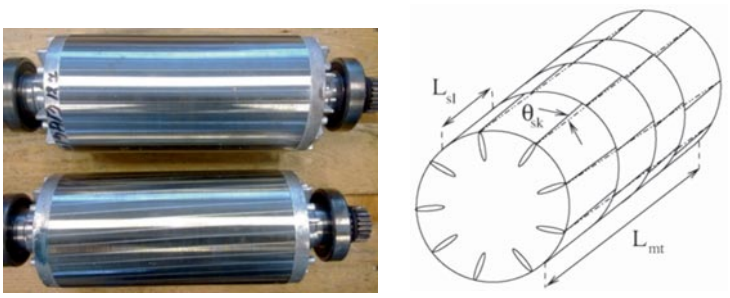


Figure 3. **A non-skewed and skewed rotor on the left. Principle of the slice model on the right.**

A slice model was developed to reduce the computation burden. The machine is cut into slices which are modelled in 2D. Each rotor slice is rotated with respect to the others according to the skewing angle. The electromagnetic model has been validated and shows good agreement with the measured results.

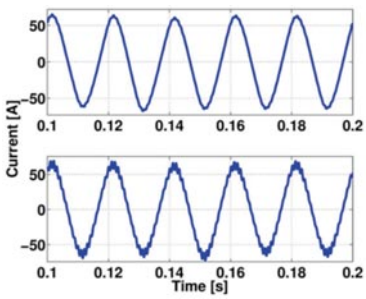


Figure 4.
Stator currents computed for loaded machines equipped with the skewed and non-skewed rotors. Skewing dampens the effect of rotor slotting in the current waveform (upper figure).

The electromagnetic model has been combined with a 3D mechanical model to analyse the vibrations caused by typical faults. Study was made of the effects of a shorted turn in the stator winding, a broken rotor bar, and static and dynamic eccentricity. The combined electromechanical model has been validated in many aspects. Nonlinearity and time-periodic phenomena challenge the exact validation at several operating points. The model updates and validated experimental results have been adopted, and further research focus is on models working in a wider operating range.

Industrial relevance

"Electric motors specifically designed for crane applications are part of our core competency. We need advanced numerical models if we are really to get to the bottom of vibration behaviour in motors. The Fovi project has provided extensive knowledge that can be used in condition monitoring to ensure the safety of lifting equipment."

*Dr **Anna-Kaisa Repo**, Senior Research Engineer, Konecranes Oyj*

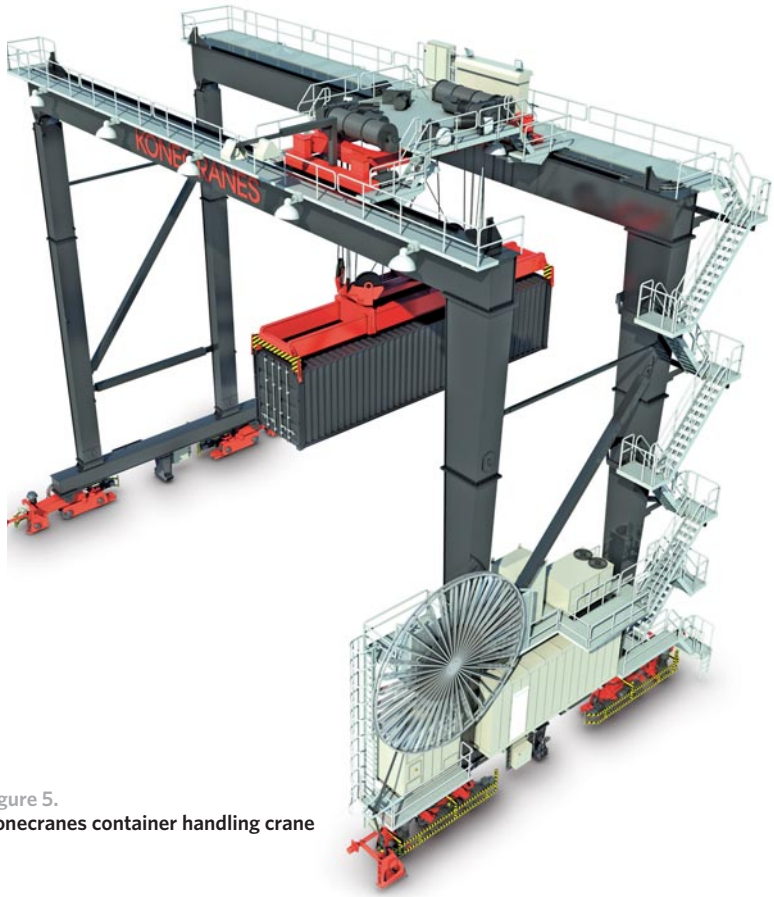


Figure 5.
Konecranes container handling crane

PROJECT NAME

WP2 Technologies for Life-cycle Cost Management

Fovi

CONTACT PERSON

ANTERO ARKKIO
AALTO UNIVERSITY

KARI TAMMI
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PARTICIPANTS (ORGANISATIONS)

ABB OY
KONE OYJ
KONECRANES OYJ
AALTO UNIVERSITY
VTT TECHNICAL RESEARCH CENTRE OF FINLAND

PROJECT DURATION

2009 – 2013

PROJECT VALUE (EUR)

1.864 MILLION

Forces and Vibrations as Fault Indicators for Electrical Machines

Main targets & motivation

- To find out whether an electrical motor is healthy as a whole, and to recognise possible faults in the motor or its subsystem.
- To increase our understanding of dynamic phenomena as an aid for decision-making in electrical machine design and operation. The goal was to develop tools for estimating electrical machine health by means of vibration and force measurements. To achieve this, the project focused on accurate dynamic models of electrical machines, their validation, and automatic model-update methods. The work included the development of electromagnetic, mechanical and vibro-acoustic models.
- Due to the complexity of the material properties, geometry, and operation of electrical machines, some simplifications are often needed. The significant part of the project focused on validating full 3D electro-magneto-mechanical models for an axial flux permanent magnet motor and a radial flux induction motor. The validation of the models opened an opportunity to estimate the machine health and noise and vibration performance (comfort) by external measurements.

Results

Analytical models were developed for detecting different types of faults in induction motors. The study continued previous work, but was extended in Fovi and focused on methods for detecting any fault in the machine.

A combined 2D electromagnetic and 3D mechanical model was constructed for an axial flux cage induction motor. The model was validated by electromagnetic and vibration measurements.

A full 3D electro-magnetic model of an axial flux permanent magnet hoisting motor was also created in addition to the mechanical model. Both models were validated by measurements on a prototype, and an automatic model update method applied on the mechanical model. The modelling accuracy was improved significantly.

New signal processing tools for fault diagnostics of electrical machines in transient operation.

A brake health indicator was developed for a safety brake in an induction motor.

Various model test methods were applied on electrical motors, including modal testing on a running machine, operational deflection shape testing, classical modal testing, etc. The detailed modal tests and systematic finite element model building and updating approach resulted in models capturing the vibration behaviour of the studied motor with a high accuracy within the frequency band 0–1000 Hz. The most significant vibration and noise excitations occur within this frequency band.

After model updating, experimental and computed natural modes up to about 800 Hz correlated well. Differences between natural frequencies were less than 5% and Modal Assurance Criterion (MAC) between experimental and computed mode shapes was higher than 80% in this case. Models of this accuracy can be used for developing next-generation elevator hoisting motors.

Key publications

1. Simbierowicz, G. & Nieminen, V. (2012), Challenges of modal testing and modelling of an axial flux permanent magnet machine. 19th International Congress on Sound and Vibration, ICSV 2012, 8–12 July 2012, Vilnius, Lithuania. Vol. 1, pp. 57–64.
2. Pippuri, J., Manninen, A., Keränen, J. & Tammi, K. (2013), Torque density of radial, axial and transverse flux permanent magnet machine topologies. IEEE Transactions on Magnetics. Vol. 49 No. 5.
3. Martinez, J., Belahcen, A. & Arkkio, A. (2013), Broken bar indicators for cage induction motors and their relationship with the number of consecutive broken bars. IET Electric Power Applications, Vol. 7 No. 8, pp. 633–642.

4. Martinez, J., Belahcen, A., Detoni, J. & Arkkio, A. (2014), A 2D FEM analysis of electromechanical signatures in induction motors under dynamic eccentricity. International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, Vol. 27, pp. 555–571.
5. Climente-Alarcon, V., Antonino-Daviu, J.A., Haavisto, A. & Arkkio, A. (2014), Particle filter-based estimation of instantaneous frequency for the diagnosis of electrical asymmetries in induction machines. IEEE Transactions on Instrumentation and Measurement. In press. 10 p. Available on: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6778035

Number of publications: 30
Number of Doctoral Theses: 1 (under preparation)
Number of Master's Theses: 3

Networks and international co-operation

Fault detection from electrical machines in transient operation was studied together with researchers from Universitat Politècnica de València, Spain. Dr. Vicente Climente-Alarcon visited Aalto University for six months in 2013. This collaboration led to three common journal papers and four conference papers.

Applications and impact

- The virtual design tools provided faster and more accurate design capability, and provided information on the electrical machine dynamics and health during operation. The modelling accuracy was improved significantly from the state-of-the-art before Fovi.
- Model updating procedures improved automatic model fitting.
- Computational accuracy on electro-magnetic modelling was improved with the right approximations applied.
- A multiphysics approach was developed for the acoustic optimisation of an axial flux permanent magnet motor, used for elevator applications.
- New signal processing tools were developed for detecting faults in electrical machines in transient operation.

"The Fovi project brought together the manufacturers and researchers of electrical machines and enhanced the collaboration between them. Multidisciplinary modelling of electrical machines took long steps forward."

Antero Arkkio, Professor
Electrical Engineering, Aalto University

"We have been taking steps in the Fovi project towards full virtual validation of electrical machines. The project gave us a unique opportunity to focus on challenges related to electro-mechanical phenomena. We were delighted to solve these challenges and improve the speed and accuracy of R&D. At best, these phenomena were 100% relevant, and we were able to work in close collaboration with industrial partners."

Kari Tammi, Research Professor
Electrical Machines and Energy Efficiency,
VTT Technical Research Centre of Finland

WORK PACKAGE 3:
Efficiency by Means of Human-compatible Multi-machine Systems

PROJECTS:

- Control of Information in Multiple Work-machine Systems – Motti
- New Generation Human-centered Design Simulators for Life-cycle-efficient Mobile Machines – Lefa
- Reliable and Safe Processes – Respo
- Assisting and Adaptive Agricultural Machine – Agromassi
- Future Semi-autonomous Machines for Safe and Efficient Work Sites – Famous

Control of Information in a Multiple Work-machine System

Tools for facilitating multi-machine communication and for speeding up system integration and setup

MOTTI worked on methods for multi-machine communication and for controlling a multi-machine fleet. Machines were abstracted so that they could be controlled in the same way despite their kinematic model. It was also made possible to connect and control a fleet of machines without knowing in advance the number or types of machines. Other work included development of tools for speeding up system integration and setup, and the creation of multiple tools for working and testing multi-machine systems in office without the need for real machines or environment.

Open Machine Concept and Multi-machine Simulator

The open machine concept is one of abstracting the machine so that it can be controlled even though there is no prior knowledge of the machine type. This means that every machine is drivable through the same interface, while just one interface is necessary for the provision of sensor data. The analogy with the computer world is that computers can have keyboards of different manufacture but every keyboard works in the same way. This enables the development of machine-independent software for the control of machine fleets.

The project began with development and publication of a communication framework called GIMnet and a hardware abstraction layer called MaCI (Machine Control Interface). From that point, multiple machines were controlled through these systems. The communication framework abstracts the physical address of the machine so that the machine's services are available on the network, and all machines can be controlled or monitored directly. In MaCI the machine is abstracted as a bunch of actuators and sensors. In this way, generic components can be developed for different machines if they are providing the necessary interfaces. Combining these enables connection to a fleet of machines in the absence of prior knowledge of the actual configuration of the fleet.

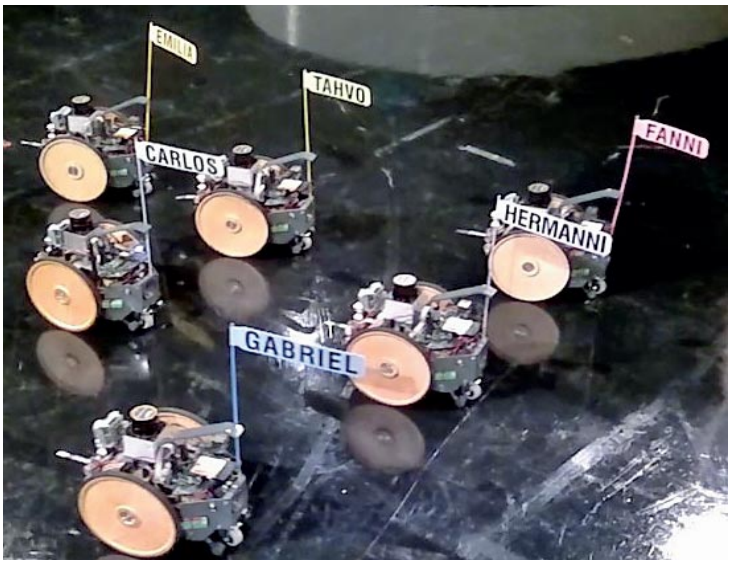


Figure 1. **GIMnet and MaCI provides a way to easily connect and control a fleet of machines**

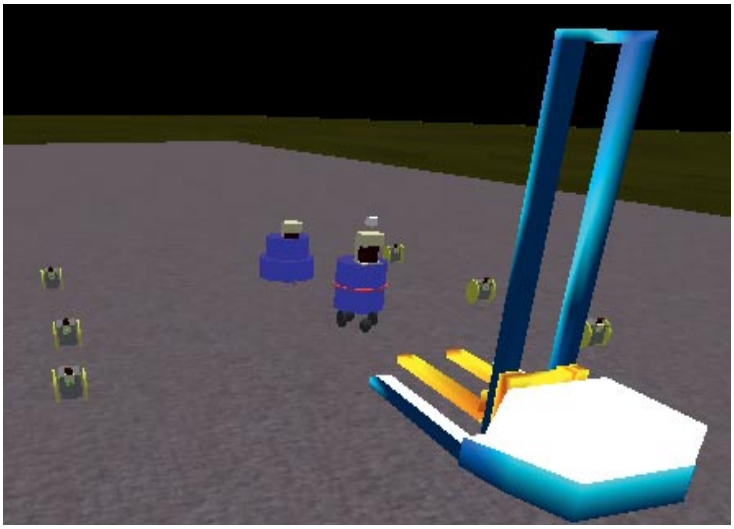


Figure 2. **Simulator provides a way to easily test to control a heterogenous fleet of machines**

Furthermore, a multi-machine simulator was developed using these communication and control methods. The simulator enables development and easy testing of different methods of controlling machine fleets.

Because the simulator uses GIMnet and MaCI, the algorithms can be tested first in the simulator and then with real hardware without modifications. The simulator is capable of simulating dozens of machines in very large environments, thus fulfilling the needs of most work sites.

The machine fleet simulator made it possible to test and verify that the task execution and traffic control systems worked as intended. The simulator allows the driving of any number of machines in the area. Navitec Systems is using the simulator for further development of fleet control software for automated machines.

Improving the Efficiency of Order-Picking In Distribution Centres

In order-picking, the pickers drive around inside the warehouse and pick items according to customer orders. Although the machines are driven by humans, the humans are essentially computer-controlled through a voice commanding system. This highly labour-intensive operation can account for as much as 50% of total warehousing operating costs, added to which most of the order-processing time is spent on driving around inside the warehouse.

Each picker has three roll cages to which the items are picked. The content of a single roll cage cannot be altered because it belongs to one customer order. However, one can select which roll cages are given to which picker, a process called order batching. Pickers have different strengths and weaknesses: some are more skilled in driving the truck, while others excel in stacking items or are able to lift heavy items with ease. Statistical data analysis can be used to extract the skills of the pickers from process data, and to form mathematical models that can in turn be used to assign the right picker to the right job. In the Motti project, researchers studied new ways of optimising order batching and modelling workers to take advantage of their specific skills.

Researchers received a three-month dataset from an order picking warehouse and used the method to recompute all routes for pickers, resulting in a 15% saving on average. *"Another way of putting it is that the annual saving equates to about 18,000 km, the distance covered in one year by two hired tow-truck drivers,"* says Motti researcher Marek Matusiak. *"If you add in the skills of the pickers, our method saves 9% in total order picking time compared to state-of-the-art solutions for optimising order-picking processes."*

The co-operation partner is also satisfied with the results. *"This is an ideal method for our Visual Assistant product we partly developed during the project,"* says Team Manager **Jani Mähönen** from Rocla.

Industrial relevance

With Rocla's Visual Assistant, the picker receives information on several picking locations in line, so he can drive in the middle of them and collect sufficiently closely-spaced items with only one stop. Using this visual display in picking work reduces unnecessary stops up to 80 %."

"The method developed in Motti groups the collected items even closer together, which will increase the performance of the Visual Assistant even further," says Mähönen.

Tools for Automated System Integration and Setup

Building new automation systems consisting of a fleet of machines is a demanding and time-consuming task. In Motti we generated tools for making this task faster and easier, saving time and money. Tools include ways of modelling the environment, machines, making route network for different machine types, and testing environments.

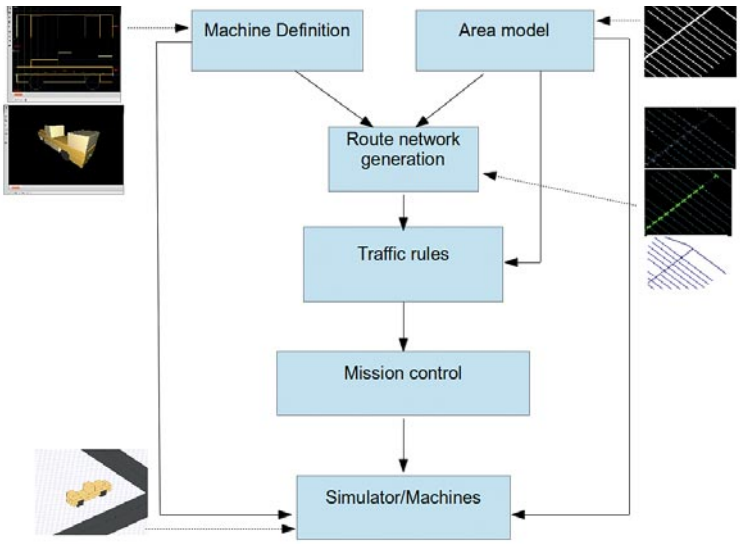


Figure 3. **Steps for automated system integration and setup**

A localisation algorithm was developed which matches a point cloud (coming e.g. from a laser scanner) to an existing map. This not only helps a machine to locate itself, but also constructs an environment map from measurement. This can then be fitted into the same coordinate system as a CAD-model where any previous integration work may have been done.

A tool was also developed for defining a machine model. The application was designed to permit easy construction of the model, while the program generates a kinematic model and simulator model of the machine. The kinematic model can be used to generate route networks for a specific machine. The model is also directly ready for use in the multi-machine simulator that was developed in the project.

The tools also included generation of the route network and automatic area segmentation, taking any machine kinematics or environment layout into account. The area can be divided into lanes (one/two-way) depending on the size of the machines.

Navitec Systems developed tools that generate drivable routes and traffic rules automatically for the whole automation area. The measured environment model formed the input data for automatic route generation, but a CAD model of the area can also be used. We also developed tools that allow manual editing of the routes and traffic rules for more precise control.

We demonstrated how a task that took hours to do manually could be done automatically in minutes.

Task Execution and Traffic Control Methods

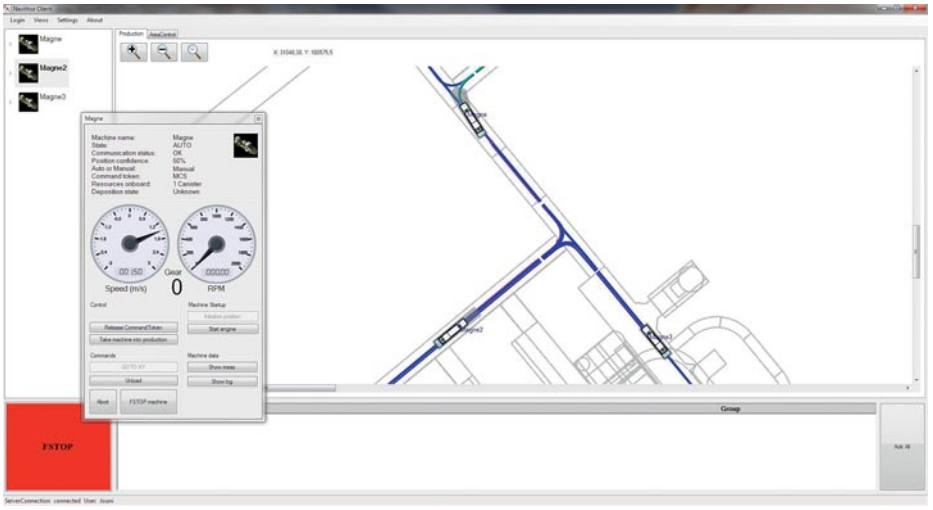


Figure 5. **Traffic control and task execution system called Navithor**

Navitec Systems developed fully operational task execution and a traffic control system for controlling a fleet of machines. The system has been tested against a simulator, where it successfully controlled the production of a simulated fleet. Traffic control developed in Motti has several features, including finding an optimal route to the destination that takes account of the current traffic situation. Traffic control can also adjust the speed of machines to eliminate unnecessary stops, and can reroute machines if necessary in order to avoid deadlocks. The task execution system can accommodate several different kinds of machines in the same production area.

Industrial relevance

"Task execution and traffic control methods developed in Motti will be used in Sweden for controlling fully automatic machines in final nuclear waste depository. These have also been developed for use in fleet control in other environments, such as warehouses, harbours and factories,"says

***Hannu Mäkelä**, General Manager of Navitec Systems Oy*

PROJECT NAME

WP 3
Efficiency by Means of Human-compatible Multi-machine Systems

Motti

CONTACT PERSON

PEKKA FORSMAN
VILLE KYRKI
AALTO UNIVERSITY

PARTICIPANTS (ORGANISATIONS)

AALTO UNIVERSITY
TAMPERE UNIVERSITY OF TECHNOLOGY
VTT TECHNICAL RESEARCH CENTRE OF FINLAND
ROCLA OY
NAVITEC SYSTEMS OY
KONECRANES OYJ
FIMA FORUM FOR INTELLIGENT MACHINES RY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

2.380 MILLION

Control of Information in a Multiple Work-machine System

Main targets & motivation

The level of automation is rising in multiple industries, with the focus changing from machine-level automation to the control of machine fleets. For example, work in harbours, AGV systems and nuclear fuel and waste management systems is carried out by a fleet of machines. These fleets often contain machines from different manufacturers. The possibility of operating a fleet of heterogeneous machines is increased through the adoption of an open communication and control system.

In addition, designing, integrating and setting up an automated machine fleet is time-consuming and a business bottleneck. For this reason, tools that enable prior testing and verification of system functionality are essential for efficient multi-machine system design and implementation.

The main targets of the project have been:

- Communication models for a multi-machine system
- New traffic control methods for a multi-machine system
- Development of a generic multi-machine simulator
- Methods for automated generation of routes and traffic rules

- Open machine interface, to enable development of machine independent software for machine fleet control
- Tools for automated system integration and setup.

Results

Service-oriented communication framework and open machine concept enabling different communication models between machines and higher-level systems

Optimising task distribution to machines in distribution centres

Multiple tools for automated system integration and setup

Multi-machine simulator for testing fleet-level control in large areas

Matching maps made from sensor data to a CAD-based map

Tool for generating machine models and kinematics

Route network generation for multiple machine types

Task execution and traffic control system for controlling a fleet of machines.

Key publications

1. Matusiak, M. (2014), Optimizing Warehouse Order Batching when Routing Is Precedence Constrained and Pickers Have Varying Skills. Ph. D. dissertation, Aalto University.
2. Saarinen, J., Paanajärvi, J. & Forsman, P. (2011), Best-first branch and bound search method for map based localization. Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference.
3. Maula, A., Myrsky, M. & Saarinen, J. (2012), Gimnet 2.0-enhanced communication framework for distributed control of generic intelligent machines. Proc. 1st IFAC Conf. Embedded Syst., Comput. Intell. Telemat. Control.
4. Matthieu, M., Saarinen, J. & Maula, A. (2012), Interface for controlling a fleet of generic machines. Multivehicle Systems. Vol. 2. No. 1.
5. Matusiak, M. & Saarinen, J. (2010), Solving the parallel pickup problem for multiple machines in warehouse applications with best-first searches in Proc. The 15th IASTED International Conference on Robotics and Applications, Cambridge MA, November 2010, pp. 260–267.

Number of publications: 20

Number of Doctoral Theses: 1

Number of Master's Theses: 5

Networking and international co-operation

Professor Erwin Prassler, from Bonn-Rhine-Sieg University of Applied Sciences' Department of Computer Science, visited Aalto University during 2009–2010. He has long experience in robotics and an extremely large network in German universities and companies dealing with autonomous machines. Prof. Prassler is also a co-ordinator of the EC project "Best Practices in Robotics", which formalises the robot development process. Two BRICS Ph.D. students also studied at Aalto and took part in Motti meetings there.

Motti researcher Marek Matusiak collaborated with Professor René de Koster from Operations Management at the Rotterdam School of Management. Collaboration was related to Motti research topics and also to writing articles. René de Koster was one of the advisors for Matusiak's Doctoral Thesis which was defended during the project.

Dr Jari Saarinen visited Örebro University's group of Applied Autonomous Sensor Systems (AASS) for 10 months. The main subject during the exchange was long-term mapping. Afterwards Saarinen stayed at Örebro as a part-time Post Doc.

Applications & impact

Task execution and traffic control methods developed in Motti will be used for controlling fully automatic machines at a final nuclear waste depository in Sweden.

Developed toolchain tools will be used for further research at Aalto University.

GIMnet and MACI are published as open source and can be downloaded from http://gim.aalto.fi/MaCI/Downloads.

"The Motti project has enabled Navitec Systems to expand from single-machine automation to the automation of a fleet of machines. The project has been a success, and co-operation with Aalto, Konecranes and FIMA open and rewarding."

Jouni Sievilä
Partner / Software Engineer, Navitec Systems Oy

"The Motti project has made it possible to transfer novel research results in modelling fleets of mobile machines into designs and implementations with high practical relevance."

Ville Kyrki, Associate Professor
Intelligent mobile machines, Aalto University

fimecc

FINAL REPORT 2/2014

PROJECT NAME

WP 3
Efficiency by Means of Human-compatible Multi-machine Systems

Lefa

New Generation Human-centred Design Simulators for Life-cycle-efficient Mobile Machines

Creating radical product concepts with VR-technology-enabled agile and participative design methods

The project develops novel user-centred R&D methods for mobile working machines based on real-time virtual prototypes and environments. The novel methods enable studies of the usability, safety and life-cycle efficiency of the participating companies' new and existing products.

Main Results

Two Finnish mobile machinery manufacturers (Cargotec Finland Oy and Sandvik Mining and Construction Oy) have integrated virtual reality (VR) technology into the R&D processes. To enable this significant achievement, all the partners have developed novel tools and methods. MeVEA Oy has developed versatile and efficient real-time simulation tools. Savant Simulators Oy on the other hand has been developing highly immersive product development simulators. VTT Technical Research Centre of Finland has studied integration of virtual environments (VE) into the R&D processes of companies. VTT has also developed a dynamic field of view analysis for studying the safety and ergonomics of cabins. Tampere University of Technology has been developing an eye tracking system for VE applications. A prototype haptic human-machine interface for remote operation of mobile working machines has been developed at Lappeenranta University of Technology (LUT).

Integration of VR technology into R&D processes

Product development processes at Cargotec have evolved greatly during the Lefa project. Formal design reviews at the virtual stage have been added to the processes. All product development projects with mechanical design content need to pass the virtual design review before they can obtain approval to start the manufacturing drawing preparation stage. In particular, the visualisation environment built right next to the simulator has shown its usefulness in design reviews, and proved its value as a tool for demonstrating the potential of virtual environments. The active stereo viewing system has made it possible for design reviews to include the full involvement of people from outside mechanical engineering. Feedback from participants has been extremely positive and encouraging.

Haptic Human-Machine Interface

At LUT, the project developed a novel haptic device and software for the purpose of controlling working machines. The functionality of the device was demonstrated by controlling a rubber-tyred-gantry (RTG) crane and load-haul-dumb (LHD) loader in a real-time simulator. The key features of the haptic controller are:

- Machine control and force feedback in 6 degrees of freedom
- Any symbolic tool can be used to control a machine
- Multiple placement and user configurations
- Replacement for traditional joysticks
- No similar products available for mobile machine control
- Suitable for all kinds of mobile machines (forest and mining machines, excavators, wheel loaders etc.).

Industrial relevance

"The functionality of the novel haptic device and software were demonstrated by controlling a rubber-tyred-gantry (RTG) crane in LUT's virtual reality environment. Although the device was an early prototype, the first impression was positive. Damping of sway, especially, was quite easy with this haptic device. The research scientists have been successful in tuning the parameters. The system's response helped in rapid assimilation by the user of proper sway damping practice. It's hard to say anything about the ergonomics of the system because the test period was so short. These need to be investigated carefully, because for the machine driver this is a totally new way of working."

***Pekka Yli-Paunu**, Cargotec Finland Oy*

Validation of the VR-based design process in designing new a cabin concept for the mobile working machine

As part of the Lefa project, Sandvik made their own virtual reality (VR) environment using four projectors to conduct design reviews under the new drilling rig cabin project. New cabin concepts featuring different design alternatives were compared to current examples in the search for best possible visibility. All design changes were approved by the project team as virtual validation decisions. This allowed quick decision-making at the beginning of the project process, resulting in rapid changes in the design and quality solutions.

Although use of VR methods in ergonomic studies was also attempted, traditional physical mock-ups were found to be better. VR methods are nonetheless well suited to ergonomic reviews of the preliminary concept. A survey of the two approaches revealed that the ideal choice may be a combination of physical mock-ups and virtual models, but that this should be based on system versatility and cost.

Air conditioning and noise simulation was implemented successfully for the first time in the design of the Sandvik cabin. Vibro-acoustic simulations based on Statistical Energy Analyses (SAE) were used for correct material choice and leakage studies to reduce drilling noise inside the cabin. Significant benefits were obtained from air transfer simulation that helped to prevent hazardous silica dust from infiltrating the breathing air.

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FINAL REPORT 2/2014

PROJECT NAME

WP 3 Efficiency by Means of Human-compatible Multi-machine Systems

Lefa

CONTACT PERSON

LAURI LUOSTARINEN
HEIKKI HANDROOS
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LAPPEENRANTA UNIVERSITY OF TECHNOLOGY LABORATORY OF INTELLIGENT MACHINES
VTT TECHNICAL RESEARCH CENTRE OF FINLAND
SANDVIK MINING AND CONSTRUCTION OYJ
CARGOTEC FINLAND OYJ
MEVEA OY
SAVANT SIMULATORS OY
TAMPERE UNIVERSITY OF ECHNOLOGY/EDE

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

2.745 MILLION

New Generation Human-centred Design Simulators for Life-cycle-efficient Mobile Machines

Main targets & motivation

- The project develops novel user-centred R&D methods for mobile machines based on real-time virtual prototypes and environments. The usability, safety and life-cycle efficiency of the participating companies' new and existing products are studied using the new methods and technologies. Research institutes develop and test simulators in research cases, with the results and experiences disseminated among the participating companies. Novel user interface ideas, particularly for remote operation, are also developed and tested by the simulators.
- Novel simulator and virtual reality technologies enable more rapid and cost-efficient development of mobile machines. The novel technologies provide a more extensive analysis of the machines and human-machine interactions than has previously been achieved. This enables the development of significant improvements in mobile working machines.

Results

Haptic Human-Machine Interface for remote operating mobile working machines

- Provides motion, machine control and force feedback in 6 degrees of freedom
- Any symbolic tool can be used to control a machine
- Multiple placement and user configurations
- Replacement for traditional joysticks
- No similar products available for mobile machine control

- Suitable for all kinds of mobile machines (forest and mining machines, excavators, wheel loaders, etc.).

Integration of virtual reality technologies into machine manufacturers' R&D processes

- Development of a virtual prototyping implementation maturity model (VIRMA) to support companies in improving their adaptations of virtual prototyping (VP) and allow them to benefit sooner from the use of VP in design. Use of VIRMA enables easy measurement of the current maturity level in companies and the definition of further development steps for VP implementation.
- Development of practices for the use of virtual reality technologies during the design review and participatory design. A design review template was created to aid preparation for the design review, enable more efficient reviews, and gather the conclusions drawn from them. The template consists of three categories: initial information, model description and model implementation.

Field Of View analysis method based on dynamic virtual reality.

- Development of a task-related dynamic field of view (FOV) analysis method to support decision-making during the virtual-environment-based design reviews. The method considers the behaviour and activities of operators when analysing the FOV.

Validation of the virtual-reality-based design process in designing a new cabin concept for a mobile working machine

- A VR environment was developed for design reviews
- The VR environment enabled rapid decision-making and virtual validation of new concepts during cabin development
- A combination of physical mock-ups and virtual models was found to be the best solution for ergonomic reviews of the preliminary concept
- Air conditioning and noise simulation was implemented successfully for the first time in the design of the Sandvik cabin. The results helped to prevent hazardous silica dust from infiltrating the breathing air.

Method for analysing the effects of human operators on the life-cycle efficiency of working machines.

- VR-based real-time simulator advantageous in finding the effects of human operators on life-cycle efficiency
- Logging of relevant factors easier in VR compared to physical prototypes

- Possibility of providing equal conditions for all test runs of great benefit
- Suitable for comparative studies.

Key publications

1. Heikkinen, J. & Handroos, H. (2013), Design of a Human Machine Interface for a Mobile Machine using Simulation in Virtual Reality Environment. International Review on Modelling and Simulations (I.RE.MO.S.), February 2013, Vol. 6, No. 1.
2. Luostarinen, L. & Handroos, H. (2013), Using Simulation in Virtual Reality Environment to Find Effects of Human Operators on the Life-cycle Efficiency of Off-highway Working Vehicles. International Review on Modelling and Simulations (I.RE. MO.S.), November 2013, Vol. 6, No. 5.
3. Aromaa, S., Viitaniemi, J., Helin, K. & Vento, A. (2014), Ergonomic evaluation of cab design employing digital and physical mock-ups. In: Proceedings of the 5th International Conference of Applied Human Factors and Ergonomics (AHFE2014), Kraków, Poland 19–23 Jul.
4. Aromaa, S., Leino, S-P. & Viitaniemi, J. (2013), Are companies ready for the revolution in design? - Modelling maturity for virtual prototyping. International Conference on Engineering Design (ICED13), 19–22 Aug., Sungkyunkwan University, Seoul, Korea.
5. Aromaa, S., Viitaniemi, J. & Philippon, N. (2012), New task-related dynamic field-of-view analysis in virtual environment. The 44th Annual International Nordic Ergonomics and Human Factors Society Conference (NES2012). 19–22 Aug. Stockholm, Sweden.
6. Heikkinen, J., Luostarinen, L. & Handroos, H. (2013), Virtual environment for investigating Human Machine Interface in machines with hydraulic transmissions. Proceedings of the 7th FPNI PhD Symposium on Fluid Power, pp. 225–234, Reggio Emilia, Italy, June 2012.

Number of publications: 10
Number of Doctoral Theses: 2

Networks and international co-operation

Most of the tasks required the collaboration of several project participants, all of whom have collaborated throughout the project. Jani Heikkinen (LUT) has taken part in a research exchange at the University of Eindhoven.

Applications & impact

Cargotec Finland and Sandvik Mining and Construction have integrated virtual environments for part of their R&D processes, which are highly advanced compared to the international competitors.

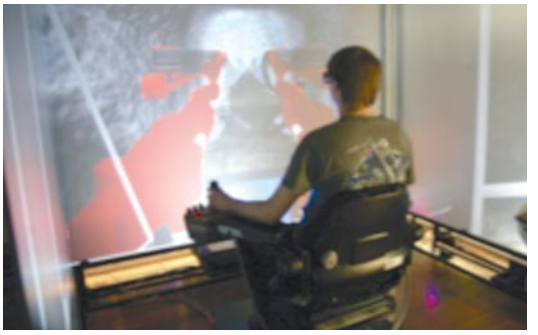

Figure 1. **VR environment at Sandvik**

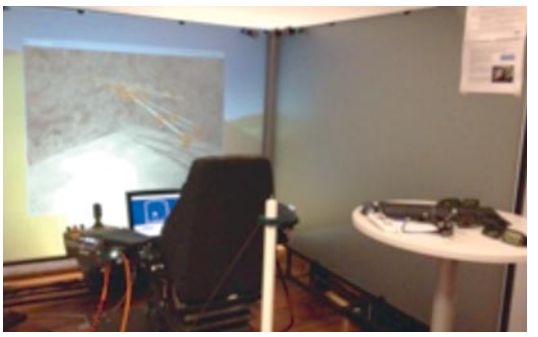

Figure 2. **VR environment at Sandvik**

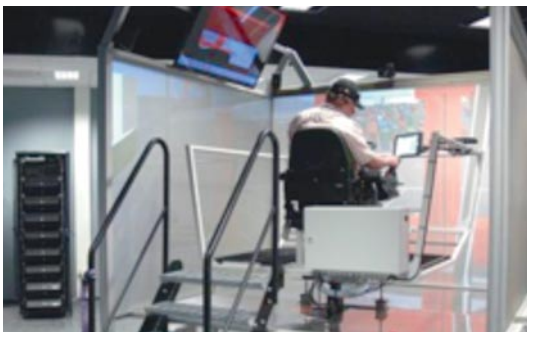

Figure 3. **VR environment at Cargotec**

"In the Lefa project we developed a schematic-based hydraulics modelling tool. This was to complete the simulation software that helps engineers design better machines in less time than before. Working machines can now be designed and re-designed with one single simulation software and no interface problems. The process model was also approved in practice during the project."

Olli Aho, Sales Manager
Mevea Oy

"The Lefa project has enabled us to find new business problems that can be solved by our system, as well as giving us the opportunity to test new hardware and software solutions with co-companies. Presentation of the result (SHOKSUMMIT) was a good platform for feedback and visibility."

Antti Itäsalo, Sales/Technical Specialist
Savant Simulators Oy

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FINAL REPORT 2/2014

PROJECT NAME

WP 3
Efficiency by Means of Human-compatible Multi-machine Systems

Respo

Reliable and Safe Processes

Our control systems are industry benchmarks & success stories!

The project aimed at maximising the life-cycle value of machines and processes by improving their availability, reliability, safety and maintainability through development of enhanced system engineering methods and control system design solutions:

- New modular designs replacing custom-engineered systems enable faster process re-configuration to address demand variations and improve reliability and safety thanks to fewer design and component errors
- New human-machine interfaces improve reliability and safety thanks to fewer human errors
- New fault and safety analysis methods supplement and support the improved reliability and safety from modularisation and enhanced human-machine interfaces.

Main results In common integration test environments we have proved that the machine control system can be built on the basis of platforms.

There are now new automation offerings for crushing plants, whose foundations lie clearly in the Respo project.

A fully functional container handling machine control system was created with the new platform. The functionality was verified in a virtual laboratory environment.

Software Platform; Powerful Engine of Change

The work machine manufacturer produces significantly lower volumes of machines and equipment when compared to other industry sectors, such as on-highway vehicle manufacturing. Although work machine manufacturers are market leaders in many fields, volumes per company are low. The costs of product changes must therefore be amortised over longer periods, while there is a need for common control platforms (HW and SW).

Software platforms have already improved productivity and innovation in many projects. Machine and equipment manufacturers in the field of machine automation often contribute only parts of the whole automation process, wishing to avoid spending time and effort on building a complete system. It thus seems beneficial to provide a general purpose software platform that offers significant advantages:

- Developers can concentrate on their core tasks
- Time to market can be reduced significantly
- Enables easy integration
- Makes co-operation easy over organisational boundaries.

CASE 1: Control system for horizontal transport

A new machine control system platform was tested with the horizontal transport equipment. Rather than improvement or further development of control features of the existing equipment control PLC program, the target was to prove that new architecture, user interface and diagnostic ideas can be implemented in a real work machine environment. These goals were achieved in the project in demonstrations using different kinds of test machines.

Another important task in the project was to estimate the workload needed to implement the fully functional work machine control system with the new platform, and the kind of methods that could be used during implementation of the work process. Functionality was verified in a virtual laboratory environment.

The shuttle carrier is the Kalmar brand's horizontal transport equipment for container handling, capable of stacking containers 2-high. These provide quick and versatile transport between ship-to-shore and automatic stacking cranes.

The shuttle carrier control system consists of the following major components: Machine control PLC, Remote IOs, Diesel engine and Touch screen GUI.

Fleet management

A new version of the automated shuttle carrier fleet management software (path planning, routing, task management) has been tested in a virtual environment with a fleet of 30 machines. Automated shuttle carrier demo version testing has continued in the new Tampere technology centre. Test field visitors have been very impressed by the demo.

CASE 2: Mobile crane simulator

A mobile crane simulator (RTG simulator) is used for training and testing purposes. Prospective RTG drivers can be taught before being allowed to drive the real thing. New features on the real machine can be tested on a simulator before these are used in real life.

The RTG simulator consists of the following major components:

- Linux computer (Real-time simulation software, Visualising Environment and Interface to PLC)
- Windows computer (Trainer Interface, Interface to Motion Platform, and Sounds)
- Trainer seat with controllers
- Machine control PLC and Graphical User Interface
- Motion platform
- Display and audio system.

Benefits Platforms and test environments have shown their strengths. Apart from reduced time-to-market and easy integration, there has been significant improvement in the co-operation between different organisational parties. In many cases the duplication of development work has been avoided. Co-operation with subcontractors is also more efficient where common platform modules have been used. In common integration test environments we have proved that the machine control system can be built on the basis of this kind of setup.

Figure 1. **Rock crushing plant**

ICx000 product family

The requirements for each control system in a control system family are very similar, even though some variations exist due to development history. The use of ineffective software engineering and different hardware has nevertheless burdened the control system family with unnecessary variations. These unmanaged variations have reduced the family's cost-effectiveness, reusability and maintainability, and increased the time-to-market.

One way of coping with the problems presented lies through combining product lines with proper variation management. This may even extend to other substantial benefits throughout the product life-cycle. Easier maintainability can be achieved through deriving all products from the same product line architecture, and using common core assets.

The environment embodied certain limitations, such as building the product line on the Metso DNA platform and with project-oriented processes. The designed product line is far from complete and requires more detailed planning of different aspects, but can be used as a starting point for product line evolution.

Plant-wide control concept for crushing plants

Adopting advanced automation is rather more than installing black boxes in electrical rooms – it changes the way the plant is run, transforming and becoming part of the work culture. The acceptability of such a big change needs to be addressed through a clear approach: that we are providing a tool which allows the plant to automate repetitive, boring, dirty and dangerous tasks.

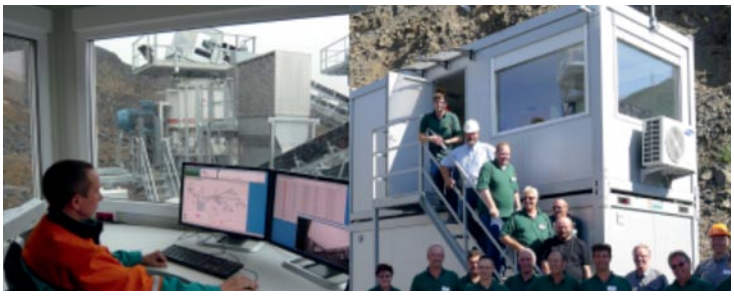

Figure 2. **Portable operator's office for crushing plants**

A very important message is that the result should be a "joint intelligence", where the computers do what they are good at (keeping watch and remembering) and humans do what they are good at (setting targets and solving problems).

In applications where automation is as yet unknown, the automation provider really needs to provide a complete solution. It is not enough to deliver computers and software – the delivery often needs to include physical spaces, such as the electrical room and the control room. The goal is to make the core – the automation system – an acceptable tool for helping with everyday work.

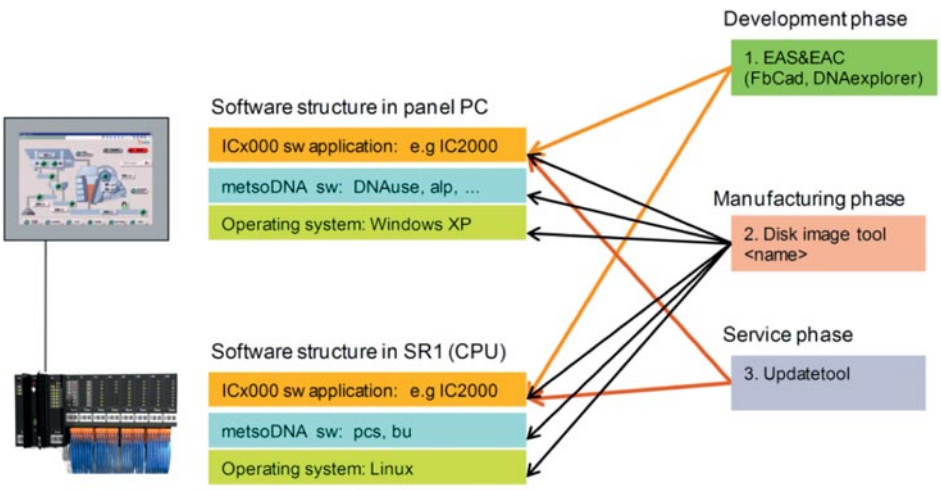

Figure 3. **Software structure of Metso DNA and tools for different life cycle phases**

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FINAL REPORT 2/2014

PROJECT NAME

WP 3
Efficiency by Means of Human-compatible Multi-machine Systems

Respo

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
ANTTI JAATINEN METSO AUTOMATION OY **PEKKA YLI-PAUNU** CARGOTEC FINLAND OY	**METSO AUTOMATION OY** **METSO MINERALS OY** **CARGOTEC FINLAND OY**	**2009 – 2012**	**3.325 MILLION**

Reliable and Safe Processes

Main targets & motivation

Response to control system modifications, especially at the end of their life cycle, is challenging. Components, tools, skills and knowledge of how the system was originally built may no longer be available. In designing the system, have the needs of the whole life cycle been considered?

→ Let's stop passing this burden to following generations!

The project objective was to develop a life-cycle-efficient automation system that gives the operator/driver better means of controlling individual machines, as well as processes/machine fleets comprising several co-operating machines.

Results

Platforms and test environments have shown their strengths. Apart from reduced time-to-market and easy integration, there has been significant improvement in the co-operation between different organisational parties. In many cases the duplication of development work has been avoided. Co-operation with subcontractors is also more efficient where common platform modules have been used.

In common integration test environments we have proved that the machine control system can be built on the basis of this framework.

Applications & impact

There is now a Minerals Processing Solutions product line at Metso Automation, whose foundations lie clearly in the Respo project.

- Metso is able to deliver plant-wide automation for crushing plants
- Metso Automation has started providing automation for mass products
- There are two DNA-based products for automation of single crushers, and more to come (i.e. the product family is growing)
- Wireless technologies can be used for connecting plant devices.

At Cargotec, project efficiency has been improved through co-operation between organisational parties.

The Engineering Toolbox provides a solid and harmonised SW development environment.

- One entity, all the tools, up-to-date environment
- Real-time visibility for project status
- Traceability of development operations
- Increased project efficiency – focus on the essential
- Engineering Toolbox provided as full scale service.

QT-based GUI framework in wayside systems.

- This brings significant cost savings (expensive SCADA system licences are not needed)
- QT-based GUI in crane GUIs.

The TOS interface development enables internal and external system integration, including all machine types.

Key publications

1. Kylliäinen, P. (2010), A Graphical User Interface Framework for Container Handling, Master of Science Thesis (2010) Tampere University of Technology
2. Lehtonen, A. (2010), Data Distribution Protocol for Container Handling Equipment Interface, Master of Science Thesis (2010) Tampere University of Technology
3. Flink, N. (2010) Operator needs for a mobile plant control system, Master of Science Thesis (2010) Tampere University of Technology
4. Kuosmanen, J. (2012), Komponenttipohjainen suunnittelu liikkuvien työkoneiden ohjausjärjestelmissä, Master of Science Thesis (2010) Tampere University of Technology

5. Huhtanen, K. (2012) Applying Product Line Approach for a Control System Family, Master of Science Thesis (2010) Tampere University of Technology
6. Rissanen,T. (2012), Service-oriented Architecture in Dynamic and Distributed Systems, Master of Science Thesis (2010) Tampere University of Technology

Number of publications: 8

Number of Master's Theses: 6

Networks and international co-operation

Within the project, Metso and Cargotec have identified similar needs towards modularisation, human-machine interfaces and combined development resources wherever possible. Project partners involve an extensive network of Finnish small and medium-sized enterprises as component- and development service suppliers.

The project partners also participate in other projects within the FIMECC EFFIMA programme. Cargotec is involved in the Neffi, Famous, DiHy and Lefa projects, and Metso in Intersync and DiHy.

The partners also anticipate opportunities for co-operation with several other FIMECC EFFIMA projects as the programme work progresses.

The Respo and Motti projects had a mutual steering group called MOPO. Because their research topics are closely related, the Respo, Motti and Agromassi projects conducted an intensive exchange of results and progress.

The operations, customers, and development organisations of both Metso and Cargotec are global. The project work requires global co-operation with internal organisations and pilot customers because the processes are mostly located abroad.

"Our SHOK career really did start with a shock, with economic recession causing our great plans to be readjusted just as we were starting. The Respo project enabled Metso to create the beginnings of modern rock crushing plant automation, and was the basis for a product family in a completely new field for process automation. Rock crushing continues to be a challenging environment for modern automation, but the work started in Respo carries on, with development proceeding as technological development allows for better measurement and control in difficult conditions.

To some, the new SHOK reporting model was a big change. We saw few problems, with little experience of how TEKES reporting used to be done. We obtained good advice and training from FIMECC during the project."

Antti Jaatinen, Project Manager
Metso Automation Inc

"The SHOK concept made it possible for Kalmar to work on methods for selecting and developing life-cycle-efficient control system platform concepts for off-road work machines. These give the system operator and machine driver better means of controlling individual machines and machine fleets inside terminal areas. The Respo results give a good basis for future automation development: time to market can be reduced, integration work will be easier, and co-operation between different organisation parties and subcontractors more efficient.

The main framework components for a common integration test environment were also developed for single machines and machine fleets. These tools, together with the open source tools used, can speed up system integration and commissioning phases. HW and SW platform ideas have already been tested in a few on-board and off-board control system prototypes in harsh environment conditions."

Pekka Yli-Paunu, VP
R&D Automation, Automation Division, Cargotec Finland Oy

PROJECT NAME

WP 3
Efficiency by Means of Human-compatible Multi-machine Systems

Agromassi

Assisting and Adaptive Agricultural Machine

The intelligent system should be the operator's best friend – it should be a co-driver or a secretary when necessary

There is a growing demand in agriculture for increased efficiency. Agricultural contracting is also becoming more and more popular, while the average size of farms is growing. This has led to ever larger machines and an increasing usage of automation. One of the motivations of this project was to investigate and develop methods of maintaining and improving the competitiveness of the tractor-implement combination compared to self-propelled systems

The ISO 11783 standard is a widely accepted standard for realising the information exchange between tractors and implements, and therefore one of the key technologies used and developed in this project. The central goal was to develop assisting and adaptive features for the tractor-implement system that will reduce the operator's workload, while improving the efficiency and precision of the work process and ensuring the appropriate application of productive inputs.

Project Tasks

TASK 1: **Integrated Automation and Control for Tractor-Implement Systems**
GOAL: "safety"

TASK 2: **Integrated Navigation for Agricultural Machines**
GOAL: "co-driver"

TASK 3: **Interface Design for Tractor-Implement Systems**
GOAL: "assistant"

TASK 4: **Appropriate Application of the Productive Inputs**
GOAL: "improved productivity"

TASK 5: **Operation Management in Field**
GOAL: "secretary"

TASK 6: **Distributed control system over ISO 11783**
GOAL: software platform

The results highlights selected are *Navigation System, HydroBalance, Smart Secretary* and *Embedded control system development tools*. The first result is achieved in task 2, the second in task 4, the third in task 5 and the last in task 6.

Navigation System for Modular Agricultural Machines using Optimal Control Methods and Industrial Standard Network

Most modern tractors are now fitted with GPS-based guidance and automatic navigation systems. The majority of these commercial products only consider the tractor itself, however. Implements are more commonly towed nowadays because of their size, and need to be taken into account by the navigation system. The challenge with a combined navigation system commanding both tractor and implement is that the control problem is multivariate, rendering traditional solutions ineffective. Another challenge lies in the great variety of tractor-implement combinations, all having to work together.

This project applies optimal control methods to a combined navigation system. This helps to achieve the required level of accuracy even with modern large-scale towed implements. Optimal control methods are also applicable where speed and the steering mechanism of the implement must be controlled in addition to the tractor steering wheels.

Figure 1. **The machinery used in the field tests of the navigation system**

Solutions within the project for other challenges of the navigation system are also developed and presented:

- Semi automatic parameter tuning procedure to ease the farmer's work
- Obstacle detection and collision avoidance methods incorporated in the combined navigation system to reduce the risk of accidents

- Local positioning system based on a laser scanner and a method of merging all measurements to enable navigation during GPS blackouts
- Headland driving line generation and simplified path planning method to complete autonomous navigation in field
- Automatic connection of the towed implement.

The results of the field tests show that the goals were met; accuracy of the navigation system is within the given limits. The system is also able to complete the field work without human intervention, including making headland turnings and avoiding electricity poles. The required information on combined navigation has been illustrated based on the case studies. It is possible to build a combined navigation system based on the ISO 11783 standard and to distribute sensors and actuators.

Industrial relevance

"The project demonstrates that new features such as collision avoidance and implement connection are clearly exploitable, and would bring added value to commercial navigation systems. Valtra looks forward to opportunities to develop these features further into commercial products."

***Jussi Kaarlonen**, Valtra Oy*

HydroBalance: Active suspension of the mower conditioner

The ELHO DUETT 7300 mower conditioner is designed for use with a tractor equipped with reverse driving capability, for example Valtra TwinTrac. In this manner, the properties of self-propelled machines can be achieved using a low-cost tractor-implement combination.

Figure 2. **ELHO DUETT 7300 working on a field**

This solution presents certain challenges, however. The mower conditioner has no supporting wheels: cutter heads are supported by skids and suspended using hydraulic accumulators. In an optimal situation, 95% of the machine's total weight is transferred through the rear tractor hitch. On slopes and uneven field, the lifting height is controlled actively to achieve proper weight balance. Where control is poor, the cutter head scratches the surface of the field, leading to impurity of the silage, an increased requirement for power and even breakdown of the machine.

This project also develops active HydroBalance weight control, a system that can be applied to any similar implement requiring weight balancing. The method developed in the project dispenses with hydraulic valves on the implement by making use of the hydraulic facilities on the tractor. The implement controls the tractor's hydraulic valves directly using standardised messages through the CAN-bus. The method is suitable for a wide range of implements traditionally requiring separate hydraulic valves.

The ELHO Duett 7300 with active HydroBalance suspension has been used successfully in actual field work. Power measurements show that an optimally balanced cutting head can save 20% of the required machine power and corresponding fuel cost. In Finland alone, the potential annual saving can be up to 2 million euros, with start-up costs 10–15% lower than with traditional solutions involving separate proportional hydraulic valves.

Smart Secretary: A data assistant for agricultural contracting

Agricultural contracting involves the co-ordination and movement of slow, heavy machinery. Often the contractor relies on manual record keeping of completed work and customer orders. A typical year may include up to 200 individual orders, and keeping track of them all may prove time-consuming. A contractor must also maintain a clear record of his working hours for invoicing purposes. Navigating to the precise, and correct, location is based mostly on human memory, a potential cause of additional inquiry to the customer.

The project developed a prototype portable data assistant to address these issues. The assistant itself is an application running on smartphones and tablet computers that have the Android operating system.

The main features are:

- Large map view for navigational aid and situational awareness
- Real-time information, such as task states and locations of other machines
- Automated data collection on working hours
- Automated ordering capability via internet.

In addition to the software, an analysis was also made of the contracting process itself. The process was modelled on the basis of contractor interviews and a literature review, and the model used to develop an algorithm for optimisation purposes. The variables considered were time windows for orders and distances between job sites. Benchmarking suggests that for instances of practical size the algorithm produces solutions within a tolerance of 3% from optimal.

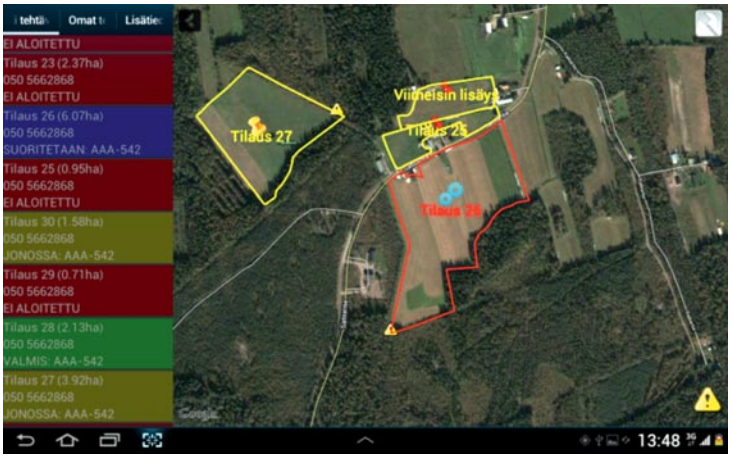

Figure 3. **Smart Secretary user interface**

When presented with preliminary screenshots from the software, the majority of contractors expressed interest in the idea of such a system. The potential is most apparent where the job involves several workers performing simultaneous operations. With this scenario the real-time information was perceived as useful. Newer portable devices with touch-screen capability are well suited to use in a tractor cabin, and are likely to be the best platform for a data assistance system. While agricultural contracting may not be the most feasible practical application for an optimisation algorithm, testing points to solutions of better quality than those achieved by manual planning.

Embedded control system development tools for modular agricultural machines

Developing an embedded control system for intelligent machines can be carried out using state-of-the-art fast prototyping tools. This enables faster development and integration with modelling, analysis, simulation and control design toolset. Finding an integrated tool – with all necessary functions embedded – that fulfils all requirements of the product design process, is hard. The same benefits, however, can be achieved with software integration. The Agromassi project developed

a toolchain for making embedded control system prototypes for agricultural machinery, combining PoolEdit (GUI designer), Matlab/Simulink, Visual Studio 2008 and Windows CE.

The main reason for a dedicated toolchain for making prototypes stems from the communication standard specific to agricultural machinery – the ISO 11783 series. The standard defines its own graphical objects and HMI devices that are used over CAN bus. Predefined design patterns help an engineer to make similar functionality for providing similar user interface logic for various machines. The toolchain starts from PoolEdit (developed at TKK 2006-2009), by designing a user interface, exporting XML definition. The next step is to use the converter software that generates a Simulink function block library from XML, containing function blocks in order to read/write the properties of each GUI object. The engineer continues the process by integrating the GUI components into the Simulink model, where all functionality is programmed graphically. Finally, C-code generation is used to generate the runtime code which is compiled together with libraries and deployed into a WinCE target. It is possible to debug the program running in target by using Simulink to study signals and states.

Industrial relevance

"The experiences and ideas of this project will be used by Wapice in future ISOBUS implement ECU development. The main emphasis will be on code reusability and configurability."

***Sami Pietikäinen**, Wapice Oy*

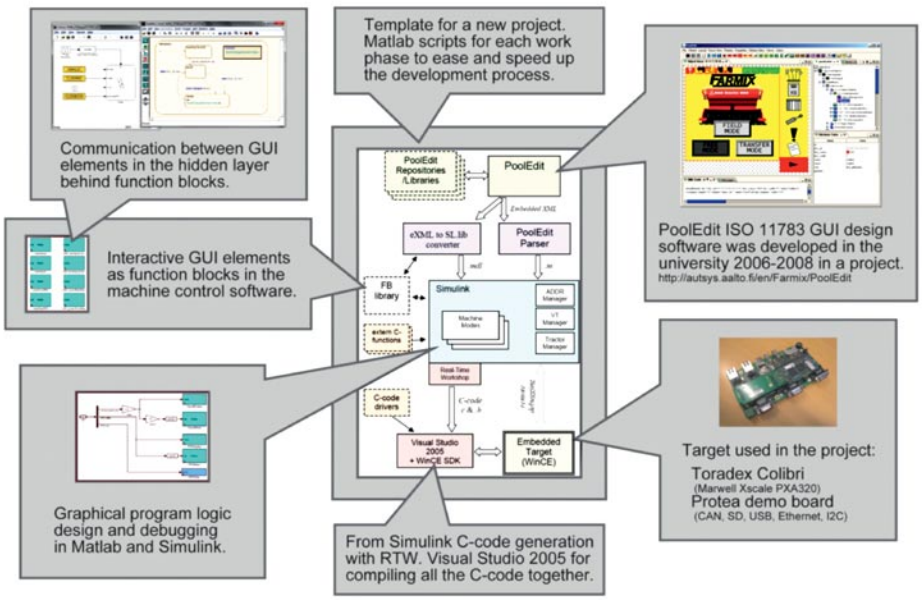

Figure 4. **The embedded control system toolchain**

PROJECT NAME

WP 3
Efficiency by Means of Human-compatible Multi-machine Systems

Agromassi

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UNIVERSITY OF HELSINKI
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SUONENTIETO OY
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VALIO OY
VIESKAN METALLI OY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

2.184 MILLION

Assisting and Adaptive Agricultural Machine

Main targets & motivation

The central goal of this research project was to develop assisting and adaptive features for the tractor-implement system that will reduce the operator's workload, while improving the efficiency and precision of the work process and ensuring the appropriate application of productive inputs.

The specific objectives were:

- To improve the overall efficiency in agricultural working machinery by using advanced navigation and integrated control
- To guarantee safety of operation for the driver and other human beings in the operational area during automatic or semi-automatic operation
- To enable a precise farming culture that is more environmentally friendly (precision farming) using technology that allows dosage on demand
- To develop a support system allowing the contractor to reduce the operator's workload
- To develop economically viable technology and to lower life cycle cost through e.g. easily configurable systems, reusable software components, modular control hardware and open standards.

Results

- Design guidelines for the user interface of ISOBUS Class 3 system and prototype of an ISOBUS Class 3 tractor
- Prototype for an advanced navigation of a tractor-implement system and a simulation environment for the development process
- Prototypes of semi-automatic functions for driver assistance: advanced control of rear hitch; semi-automatic coupling of trailer; ISOBUS sequence control (i.e. headland automation)
- Prototypes of advanced control systems for forage harvesting: forage wagon and mower conditioner
- Prototype of a contractor work support system
- Graphically configurable modular ECU software development platform that supports ISO 11783.

Key publications

1. Ronkainen, A. (2013) Design guidelines for the interface of the ISOBUS class 3 system. MTT.
2. Backman, J. (2013) Navigation System for Modular Agricultural Machines Using Optimal Control Methods and Industrial Standard Network. Aalto University.
3. Matikainen, V. (2012) Traktorin kehittyneen takanostolaitteen karteesinen ohjaus. Aalto University.
4. Kunnas, A. (2011) Embedded Control System for Agricultural Machinery Implemented in Forage Harvesting. Aalto University.
5. Pentikäinen, J. (2011) Isobus-väylattömän traktorin ja työkoneen tiedonkeruujärjestelmä ja kerätyn tiedon analysointimenetelmä urakoitsijan laskutuksen pohjaksi. Suonentieto Oy.

Number of publications: 34

Number of Doctoral Theses: 1

Number of Master's Theses: 7

Number of patent applications/patents: 1

Networks and international co-operation

Agrifood Research Finland MTT has taken part in the development of ISB requirements and specifications at the Agricultural Industry Electronics Foundation (AEF).

Wapice has a contact person in the ISO TC23/SC10/WG5 telematics subgroup which prepares the telematics part of the ISO 11783 standard.

Aalto has participated in the ISO TC23/SC19/WG1 implement guidance subgroup which prepares the implement guidance part of the ISO 11783 standard.

Applications & impact

Commercialised results:

- Elho: HydroBalance
- Suonentieto: Agri Smart TaskMonitor
- Wapice: ISOBUS support on the WRM system
- Junkkari: Maestro telematics
- Valtra: ISO 11783 TECU.

ISOBUS implement ECU development will be continued in a joint product development project.

"The Agromassi project has been very helpful for exploring the possibilities and functionalities of Isobus Class3. In addition, it gave us good guidelines on further development of our Isobus Tractor ECU, something we actually carried out. We also discovered other new ideas during the Agromassi project, and these are now waiting for development."

Jussi Kaarlonen, Research Agronomist
Valtra Oy Ab

"A characteristic feature of agriculture, and basic production of bioeconomy in general, is that the production is very distributed, and taken care of by small holders, e.g. farmers and machine contractors. The production processes are run with a diversity of machines and machinery systems, where small and medium-size technology providers play an important role. The results gained in the Agromassi project enhance the composition of diverse production technology so that it becomes a resource-efficient, safe and user-friendly operation environment for the end-users. This means more business opportunities for all actors in the sector. Generic solutions and open standards create a base for the required technology. Sharing the fresh research findings and generic solutions within the FIMECC EFFIMA programme gave researchers up-to-date awareness of the latest developments and experts in the research field, which is something that will be utilised in the coming research projects."

Liisa Pesonen, Customer Manager
MTT Agrifood Research Finland

fimecc

FINAL REPORT 2/2014

PROJECT NAME

WP 3
Efficiency by Means of Human-compatible Multi-machine Systems

Famous

From environment perception to situational awareness and adaptive safety at semi-autonomous multi-machine work sites

Future Semi-autonomous Machines for Safe and Efficient Work Sites

Figure 1. Straddle carriers driving towards each other at situational awareness system demonstration at Vuosaari harbor.

'What, why, so what?' summary

Customers require higher productivity, efficiency and safety throughout their entire work process e.g. in mines, harbours, road construction sites and forests. Famous developed situational awareness and adaptive safety concepts and technologies to increase the level of automation without compromising safety and efficiency requirements. Technologies were tested in industrial environments with many promising results, although further development work and productisation is needed.

Predictive situation awareness system for multi-machine systems

Supporting the operator with situational awareness (SA) or semi-autonomous functions enables improvement in productivity, quality, and safety at manually operated work sites. The SA system provides both the driver and the system supervisor with up-to-date prediction information of the surrounding environment, and especially of the mobile entities nearby even without direct line of sight. The information is used to find safe moving paths for the machine and to notify the driver of possible collision. Dangerous and vulnerable objects are avoided. The SA system can thus be used to provide active safety by prediction.

SA system architecture includes the following components:

- **Wireless** M2M communication based on the IEEE 802.11p protocol

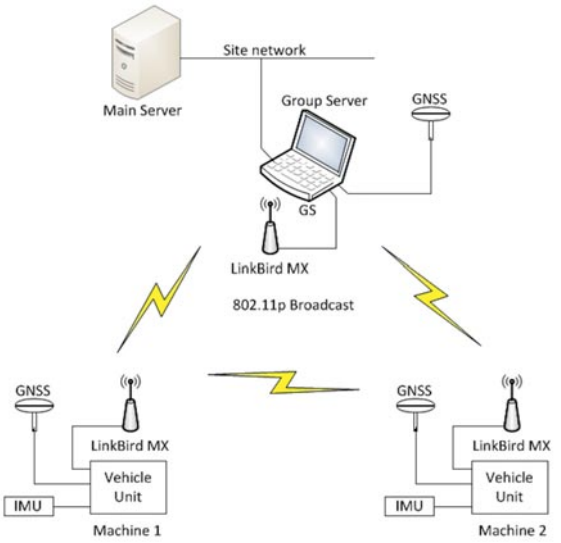

Figure 2. **M2M communication module**

- **Server** for managing the system

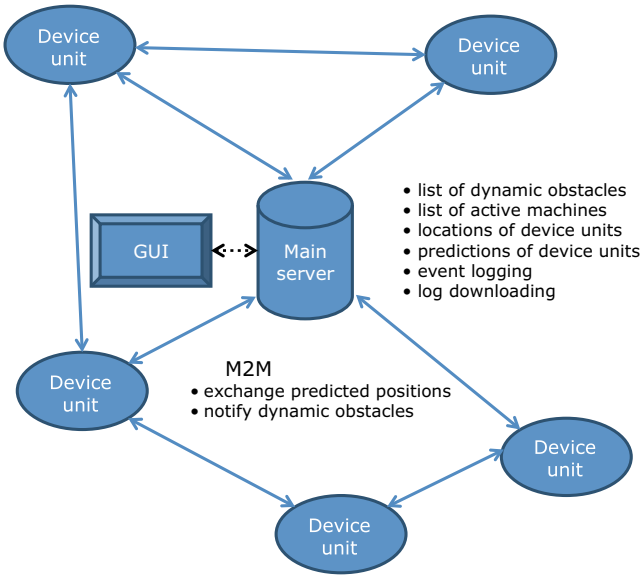

Figure 3. **Server module**

- **Pose estimation** of each machine in the field
- **State prediction algorithm** for estimating the future state of each machine.

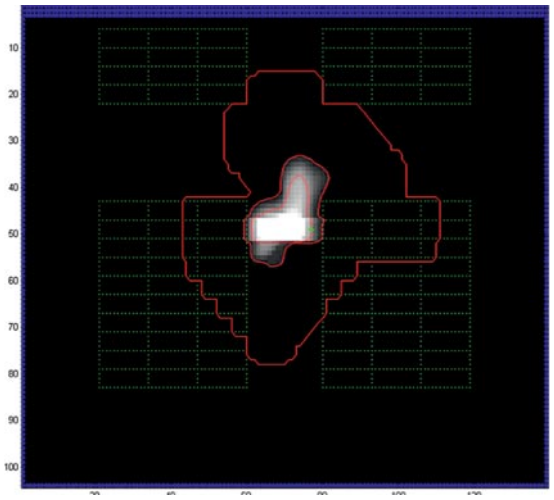

Figure 4. **State prediction module**

- **User interface** for presenting the operator with collision probability information

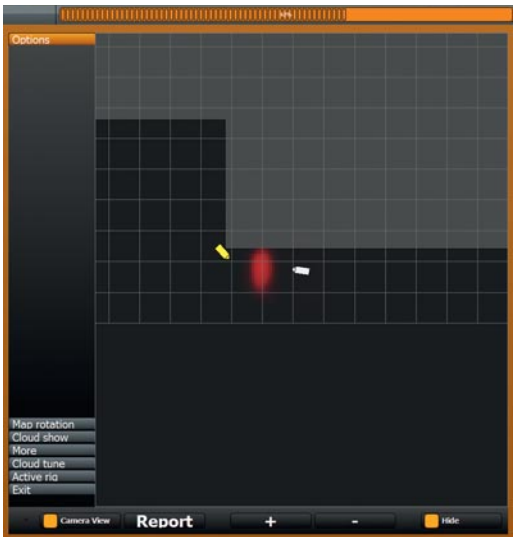

Figure 5. **User interface module**

A complete SA system was tested in the Vuosaari harbour area using two straddle carriers equipped with a retrofitted SA system, and one stationary device. A user interface was installed in one of the straddle carrier cabins.

The Vuosaari tests provided very promising results in terms of applying this kind of technique in working machine environments.

Development work was carried out in cooperation with TUT, VTT, Wapice, maximatecc, Cargotec and Konecranes.

Figure 6. **A straddle carrier receives reflected messages from another machine around the corner. Direct messages are marked as blue dots, hopped messages as yellow dots. Red means that the message did not arrive.**

Figure 7. **A conceptual example of system level safety function evaluation using virtual environments**

The full utilisation of work machine automation requires a change in safety concepts and a systems engineering approach at work site level. Traditional fixed machinery safety solutions based on single risk need to be changed into proactive system-safety solutions. The safety paradigm in adaptive safety solutions that use situational awareness information and dynamic risk assessment changes from "risk-based" to "risk-informed" decision-making.

The overall system thinking makes it clear that the safety of complex mobile machine application cannot be solved by machine-level safety solutions. A system-safety solution integrates risk reduction measures from all system levels considering all available types of safety measures.

Analysis of complex automated machinery applications, different operating scenarios and innovative safety solutions is made possible today by virtual environments and simulator-assisted engineering methods. Famous developed new virtual supporting tools and evaluated a new process model for observing the effect of agile design principles when designing demanding safety features.

The safety function development platform was a HIL (hardware-in-the-loop) simulator using the actual machine control system hardware and sophisticated dynamic modelling of an open pit mine environment. Among the new simulation features were the capacity to execute experimental safety logic code alongside the dynamic simulation, and the graphic visualisation of the safety control system states.

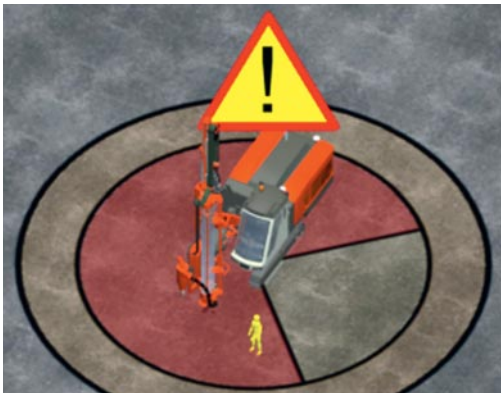

Figure 8. **Development platform expresses machine level safety function states and observation zones with clear graphical markers**

A pilot task using the proposed agile process implemented a work machine safety function that adapts intelligently and efficiently to changing work site conditions. Different approaches to safety mechanisms were tried in quick cycles, their capabilities evaluated and lessons learnt from the intermediate results.

The final result is ready for evaluation by the machine end user audience.

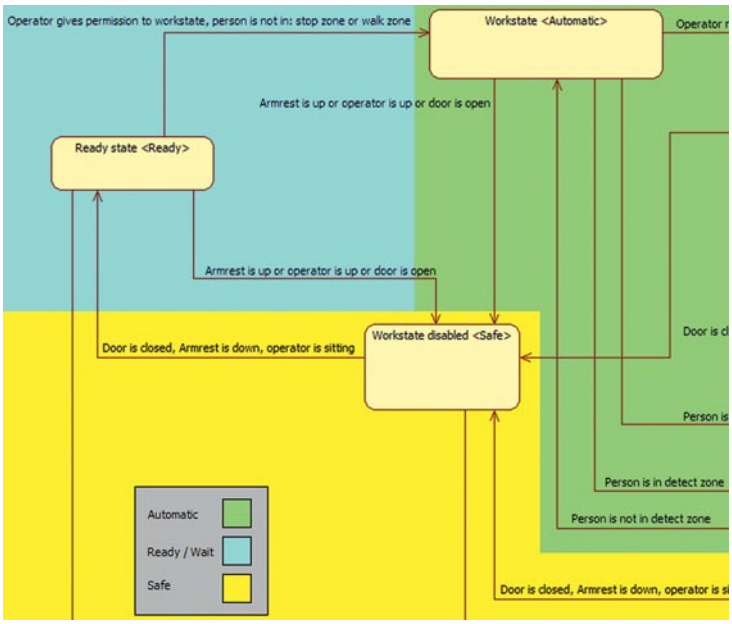

Figure 9. **State diagram of the adaptive safety function**

Main results of safety design process sub-task are:

- A successful development process for a novel safety function, covering the full spectrum of analysis, design, implementation and functional testing phases
- New virtual environment features for supporting the requirements arising from a previously unfamiliar adaptive safety engineering discipline
- A functional prototype of an adaptive safety function running alongside the actual control system hardware of a mobile work machine
- An observed decrease in development time for advanced safety functions helps to compensate the projected cost increases of future intelligent machinery automation
- The proposed process model was applied to prototype development at this point, confirmation of the usefulness for full system development was not achieved in the project time frame.

The development work was carried out in cooperation with VTT, Creanex, Wapice and Sandvik.

UWB-based Real-time Location System

The objective was to develop the hardware, firmware, estimation algorithms and application software to provide a Real Time Location System, referred to as an RTL system. The system calculates the position of the active tag node in relation to multiple stationary anchor nodes using the wireless UWB (ultra-wideband) distance measurement data.

RTLS was developed because there are market needs for enhanced safety in remote control applications. When the control system or machine knows the location of the operator, it can prevent both unintentional and intentional hazardous control by the operator. A good example is to restrict the machine's movements towards the remote operator, or limit the speeds and/or functionality if machine or operator moves to a restricted area.

Another reason for developing the RTL system was based on the fact that knowledge of the position of the user, obstacles and "targets" in remote control applications will often enhance productivity.

The UWB technology developed is considered to be the most accurate radio technology for 3D positioning today. Inaccuracy is eventually expected to be reduced to below 10 cm in point-to-point measurement and to about 40cm in the RTL system with almost 100% reliability thanks to the very broad band the radio is using. The technology is energy-efficient, and both immune to disturbances caused

by traditional radio communications and free of disturbing them in return because of the extremely low energy level used.

As an RTLS, the UWB technology can be used to measure the relative displacement and position of machinery and operators in multiple applications where GPS does not work, for example indoors. Furthermore, UWB-based ranging and positioning provides better accuracy compared to GPS.

As a point–to-point distance measurement, UWB is the ideal solution for applications with long measurement ranges, and where ease of installation is an important benefit. A good example is positioning of a boom end with long linear booms.

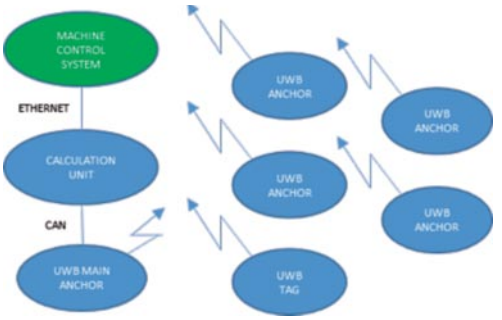

Figure 1. **The figure illustrates the RTL system: Tag node, main anchor node, anchor nodes (1–7 pcs), calculation unit and connection to a higher level system.**

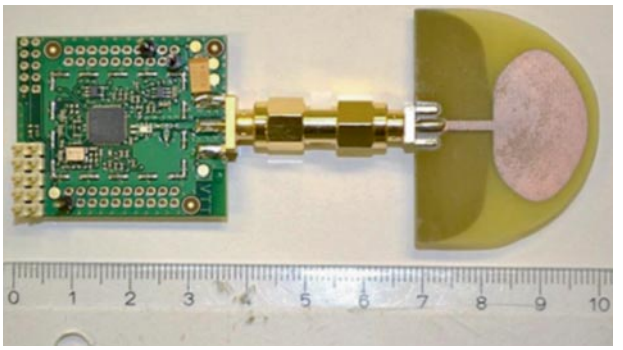

Figure 2. **The prototype used, UWB PCB**

The technology could be commercially applicable after a productisation phase.

Development work was carried out in co-operation with Technion Ltd and VTT.

PROJECT NAME

WP 3
Efficiency by Means of Human-compatible Multi-machine Systems

Famous

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HERMIA GROUP

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PROJECT DURATION
2011 – 2014

PROJECT VALUE (EUR)
6.590 MILLION

Future Semi-autonomous Machines for Safe and Efficient Work Sites

Main targets & motivation

Customers require higher productivity, efficiency and safety at their work sites e.g. mines, harbours, road construction sites and forests. This can be achieved by increasing automation, not only in the mobile work machine itself but throughout the whole work site and process, thus decreasing the possibility of human error. Famous developed new technologies for increasing the level of automation.

Raising the level of automation requires the machine or operator to be aware of the operational environment even amid rapid changes. Mobile work machines need to be equipped with suitable sensors and other devices that enable collection of appropriate data on the environment. Where multiple machines are operating, suitable algorithms are also necessary for processing the data in real-time into information on the current and potential near-future situation in the working environment. This situational information needs to be presented to machine operators and shared among the machines to enable features such as collision avoidance.

Safety is an important factor at work sites, and becoming ever more so. Where mobile machines and humans interact, safety of the work site must be guaranteed. The present situation is one where in order the carry out maintenance on a single machine – in, say, a mine – the entire autonomous work site either continues operating or, in the case of a human entering the work area, grinds to a halt. There is no flexibility. This is one clear obstacle to greater efficiency at (semi-)autonomous work sites. Increased flexibility requires machines to have exact knowledge of what is happening around them, including the location of humans, as well as the ability to adapt safely to different conditions based on the information received.

Objectives

The objective of the Famous project was to achieve essential steps towards increasing work site automation without compromising safety and efficiency requirements. Two main objectives were to

- provide real-time and even predictive situational awareness information for mobile work machines and for (tele)operators to support decision-making; and to
- develop new adaptive safety concepts and simulation-based tools – and as early as in the design phase – for the purpose of studying the impacts of adaptive distributed safety functions in a complex multi-machine environment.

In order to achieve these main objectives, many other objectives were set for developing methods, algorithms and technologies (e.g. sensor fusion and data analysis, state estimation, UWB, M2M communication using 802.11p protocol).

Results

Famous researched and developed many technologies. These were combined into larger demonstrations in industrial environments:

- Situational awareness system for collision avoidance in a multi-machine environment
- Excavator positioning and state-estimation methods
- Autonomous drive in a forest environment
- Adaptive safety concepts and dynamic risk assessment
- Indoor positioning based on UWB for machine operator safety
- Sensor fusion system and algorithms for data analysis to enable automation features in machine operation
- 3D teleoperation and obstacle detection in target approach

Key publications

1. Tiusanen, R. (2014), An approach for the assessment of safety risks in automated mobile work machine systems. Espoo. VTT Science. To be published in 2014.

   Hietikko, M., Malm, T., Alanen, J. & Saha, H. (2013), Evaluating performance levels of machine control functions. CAN Newsletter. CAN in Automation. Vol. 2, No. June, pp. 32–37.
2. Tiusanen, et al. (2014), SECO summary report. Safety engineering approach, methods and simulator based tools for the development of adaptive safety functions. Espoo. VTT Technology. To be published in 2014.
3. Virtanen, A. & Jankkari, J. (2013), V2X in Industrial Site Safety Applications ITS World Congress. Tokyo, Japan, 14–18 October 2013.

Number of publications: 15

Number of Doctoral Theses: 1

Number of Master's Theses: 8

Networks and international co-operation

Famous was the first project that extensively utilised FIMECC Factory and developed co-creation concepts e.g. regular joint workshops, agile development and demonstrations within the consortium. Two researcher exchanges from Aalto University were realised during project. One was to the Applied Autonomous Sensor Systems (AASS) group at Örebro University and another to the Australian Centre for Field Robotics. The exchange research topics were well aligned with research in Famous.

In addition the research results have also been presented at several international conferences.

Applications & impact

Famous research work was groundbreaking and thus resulted in proof-of-concept type simulations, demonstrations and tests. Most of the developed technologies were not only simulated but demonstrated and tested in real industrial environments, for example in a harbour or forest.

The project's results demonstrate that technologies of semi-autonomous, efficient and safe work sites exist and work in demonstration environments. A few years of development work will be necessary, however, before these technologies are implemented and commercially available for use in mobile work machines, and thus at future semi-autonomous work sites.

After development and productisation work, companies that participated in Famous will use some of the developed technologies in their products:

- Novatron and TUT studied a new IMU (Inertial Measurement Unit) sensor used to determine inclination of boom parts and machine frame, as well as machine frame yaw angle. The new sensor is able to deliver an inclination signal with significantly decreased latency in comparison to current solutions. This leads to better usability in guidance solutions, and also allows entry into research on more advanced cases of use involving boom load or boom control. The new sensor will replace the Novatron product line's current solution in 2015.
- OptoFidelity developed a 3D teleoperation system that was tested in an industrial environment. Compared to current teleoperation applications, 3D teleoperation gives the operator more confidence in operating the machine and also improves efficiency of operation in certain applications. Combined with augmented reality, 3D teleoperation offers even greater assistance to the user, increasing the safety and speed of remote operations.
- Technion and VTT developed a real-time positioning system based on UWB technology. This was tested in an industrial factory scenario for enhancing machine operator safety. UWB enables positioning indoors, where GPS does not work. The technology could be commercially applicable after a productisation phase.
- maximatecc performed a survey on how safety standards impact control system design process and tools, and evaluated safety-certified automotive multicore processors in a safety controller. This type of processor enables realisation of a future controller SW and HW platform with safety requirements, and results will be applied in their products in 1–2 years.
- Creanex, together with VTT, MTT, Wapice and Sandvik, developed scenario-based adaptive safety design concepts and tools. They used Creanex's simulator to analyse and visualise different use cases.
- Wapice's role in adaptive safety was to design and implement an adaptive safety module. Their role in the situation awareness system was to design and implement a communication server that uses Car2X communication for M2M communication. This can be used in the future in their WRM remote management products for fleet communication solutions, in applications requiring situation and location awareness.

"The Famous project has been an excellent operative environment for designing new ideas and future technologies for machine safety together with researchers and other companies sharing a similar interest. Future ideas and research targets have been mutually understood through the project demonstrations, and all participants have been able to take a stance on results from the viewpoint of their own expertise. The project gave a good base for planning safe operating models from a sufficiently wide perspective. Machine safety was observed as part of whole operative model and system productivity – not only as a restriction."

Antti Peltola, Managing Director
Creanex Oy

"From the marketing perspective, Technion has gained abundant visibility and been able to present its know-how and expertise to leading Finnish industrial manufacturers of mobile machinery, vehicles and equipment.

Technion has received a lot of valuable information about new technologies, especially UWB, which would have been impossible without this project.

Despite the fact that there were many research parties and industrial companies working together, some even in competition with each other, the atmosphere was open, and co-operation fluent.

Technion will most probably continue working towards commercial solutions using UWB technology."

Markku Laaksonen, Managing Director
Technion Oy

"The Famous project has been a very good opportunity for wide-scale collaboration with big companies, universities, research centres and suppliers. The combined effort has enabled us to share common research challenges and join together to find technological solutions, especially in the closer co-operation with universities and research centres. It has enabled us to make new contacts, discover new needs and challenges, and expand our network towards possible new business partners."

Jyrki Keskinen, Project manager
Wapice Oy

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