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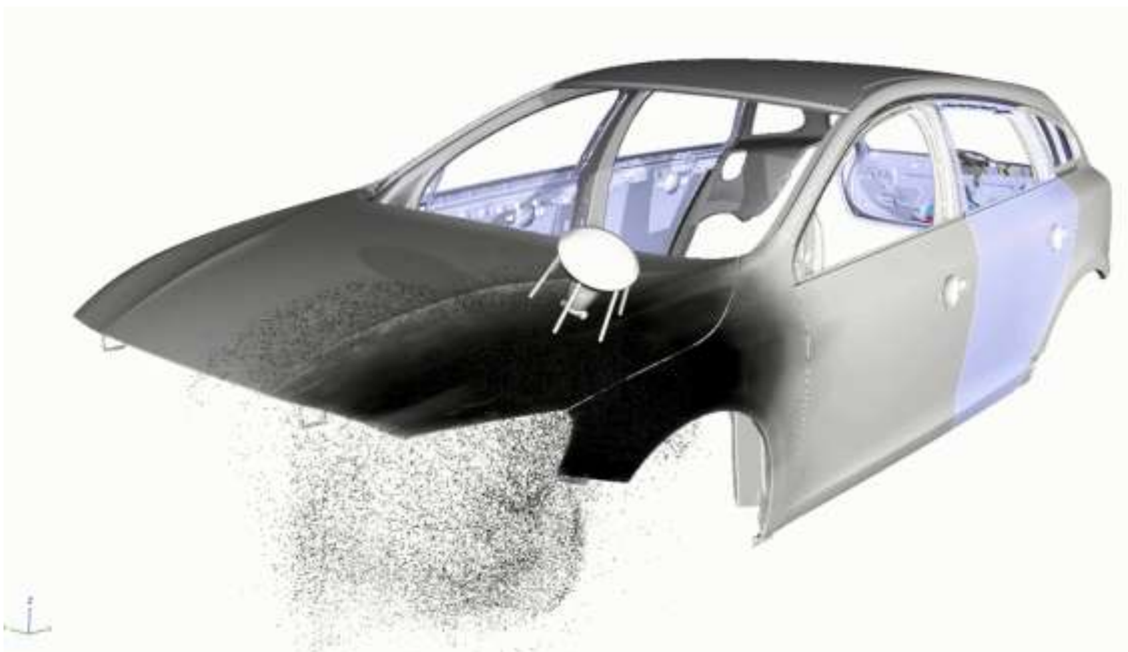
The Virtual Paint Shop – Powder and Externally Charged Wet Paint



Project within FFI-Sustainable Production Technology

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Date: 2015-06-22

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Content

1. Executive summary

The surface treatment is the process in an automotive factory that consumes most energy, water and chemicals, and produces most waste and pollution. Roughly 40% of the energy in major OEM operations is used in the paint shop with an average consumption of 700-900 kWh per car body. Within the paint shop the dominating energy cost is the ventilation and heating of the air in the booth (50%) followed by the ovens (25%). Virtual tools are frequently used to support an effective product and production realization in other parts of the automotive factory, but that is not the case in the paint shop. In the paint shop the product preparation, when robot paths and process parameters are fine-tuned, is a slow and costly trial-and-error procedure, where a large number of prototypes are painted, washed and painted again etc. There is therefore a great need to improve the product preparation process and this is absolutely necessary to meet the future demands on fast adaption and tailored solutions for new material combinations and products. The possibility to perform systematic simulations is then essential and contributes to sustainable production by reducing the number of prototypes that needs to be painted, and by making it possible to optimize the processes with respect to quality, cost and environmental impact.

The unique methods and tools for simulation of spray painting, which were developed in earlier FFI and MERA project, have in this projects been extended to simulation of powder and externally charged wet paint, and support companies to develop and optimize their surface treatment

- to be more environmentally friendly,
- to be more energy efficient,
- to be more cost efficient,
- to give a higher product quality result.

The main goals of the project were

- Methods and algorithms for simulation of corona discharge at paint applicators
- Methods and algorithms for simulation of paint particle charging dynamics
- Methods and algorithms for velocity tuning along a given robot path to optimize the paint coverage
- Techniques for electrostatic measurements of externally charged paint applicators
- Further development of Paint Center, a unique facility where the industry can evaluate their painting processes off-line
- Simulation software for fast and accurate simulation of externally charged powder and wet paint

The project results show that it is possible to accurately simulate spray painting of a truck cab or a car in only a few hours on a standard computer. This is an extreme improvement compared to earlier approaches that require weeks of simulation time. Unique algorithms for coupled simulations of air flows, electrostatic fields and charged paint particles have made this possible. Several successful measurements campaigns have been performed on relevant industrial cases with very good results. The fast simulation time make it possible to use such detailed simulations in the product preparation and off-line programming of the paint robots. The extensions in this project facilitate a wider use of the software within the automotive industry and also to other branches and SMEs.

A big challenge in the project has been the modeling of the corona discharge at the electrode tip and the charging of the paint particles as they pass through the Corona region. The complex physics puts high demands on the numerical methods. The novel methods developed in this project are much more robust than the ad-hoc methods found in the literature and also relevant to other applications such as e.g. electrostatic precipitators.

Furthermore, new methods and techniques to adapt the robot speed along the paint to optimize the resulting paint coverage have been developed. The results show a reduction of the thickness variation with a factor of at least 2-3, which means a significant potential to reduce the material consumption and increase quality. An analysis of the fork lift case showed a potential to reduce paint material consumption by 20% still keeping the desired minimum thickness level. In future projects the results will be generalized such that also other process parameters can be changed along the robot path, and even the path itself.

The project results are ready for industrial implementation and have been commercialized in the software IPS Virtual Paint, which is used by Volvo Cars, AB Volvo, Scania, Daimler and GM. The spin-off company IPS IBOFlow AB, founded in 2014, will handle the marketing, sales and support. Volvo Cars is using the software in production and it was for example used successfully to program the paint robots for the new XC90 car model.

The long term funding from Vinnova has made it possible to build-up a world-leading research team for paint and surface treatment processes with expertise in modeling and simulation, advanced measurement and validation, and industrial process knowledge.

2. Background

The surface treatment is the process in an automotive factory that consumes most energy, water and chemicals, and produces most waste and pollution. Roughly 40% of the energy in major OEM operations is used in the paint shop with an average consumption of 700-900 kWh per car body. Within the paint shop the dominating energy cost is the ventilation and heating of the air in the booth (50%) followed by the ovens (25%). Furthermore, today’s product preparation when robot paths and process parameters are fine-tuned is a slow and costly trial-and-error procedure, where a large number of prototypes are painted, washed and painted again etc. The result depends heavily on how well the plant people have succeeded with the task of setting the different process parameters. The setting is complicated by the fact that every combination of product specification, material specification, product design and equipment design is unique and a small deviation can give large effects on the final result. Discovering defects at the end of the production line, or even worse by the costumer, can be extremely costly.

There is therefore a great need to improve the product preparation process and this is absolutely necessary to meet the future demands on fast adaption and tailored solutions for new material combinations and products. The possibility to perform systematic simulations is then essential and would contribute to sustainable production by reducing the number of prototypes that needs to be painted, and by making it possible to optimize the processes with respect to quality, cost and environmental impact.

However, the spray painting and surface treatment processes pose great challenges for mathematical modelling and simulation, and are characterized by multi-phase and free surface flows, multi-physics, multi-scale phenomena, and large moving geometries. In earlier projects world-leading software solutions have been developed for simulation of spray painting with internally charged electrostatic rotary bells.

3. Objective

The objective of the project is to further develop the unique methods and tools for simulation of spray painting, which were developed in earlier FFI and MERA projects, to simulation of powder and externally charged wet paint. This supports a wider use of the tools within the automotive industry and also in other branches. The project results support companies to develop and optimize their surface treatment

- to be more environmentally friendly,
- to be more energy efficient,
- to be more cost efficient,
- to give a higher product quality result.

The main goals of the project were

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- Methods and algorithms for simulation of paint particle charging dynamics
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- Simulation software for fast and accurate simulation of externally charged powder and wet paint

4. Project realization

The project was divided into seven work packages. The first three focused on the modeling, simulation and optimization, and the remaining four concerned the measurements and validation, software demonstrator and exploitation, long term strategy of the area and project management. The general approach in the first work packages was to develop and implement models in a general form and continuously compare simulations to experiments, initially on simplified test cases that still retain the relevant physics, and later on full scale problems. Only when the full model compared well to experiments, model simplifications to speed-up the simulations were initiated. The results were continuously implemented in the IPS software demonstrator that is available to the project partners.

4.1 WP1: Modeling and simulation of corona discharge at paint applicators

In this work package the focus was on calculating the electrostatic field and the ion charge density for externally charged paint applicators. A large negative potential is put on an electrode, which is either attached to the bell or located in its vicinity. This causes a Corona discharge that releases negative ions that move towards the paint target and bombard the paint particles and charge them. The boundary condition on the sharp needle electrodes are numerically very complex to handle and a very fine computational grid is needed. To improve the accuracy and robustness a three species (electrons, negative ions and positive ions) model has been developed and implemented. The boundary conditions are then straightforward but also in this case a very fine grid is needed. Therefore, a combination of the three species solver used in the ionization region close to the electrodes with a faster one species solver used outside this region was developed. This hybrid concept was successfully validated with measurements. The novel research in this work package has been published in Journal of Electrostatics.

4.2 WP2: Modeling and simulation of paint particle charging dynamics

The Corona solver gives an accurate description of the electrostatic properties of externally charged paint applicators: powder guns and externally charged wet-paint applicators. This has been used to model the charging of the paint particles. The speed of the charged ions, the primary charge carrier is $O2^-$, is at least 100 times faster than the paint particles. The ions transfer charge to the paint at impact, and the charging, i.e., how much charge that is transferred from an ion to a paint particle, depends on the effective surface area of the particles. For an uncharged particle the effective surface area is the entire surface area. As the particle accumulates charge, ions can only hit a shrinking region around the equator of the particle, decreasing the effective surface area. This is modeled by the Pauthenier and Moreu-Hanot formula, which we have implemented into the particle tracking algorithms, adding both the charging of the paint particles and the electrostatic forces acting on them. The coupling of the fluid dynamics and the electrostatics solvers has also been implemented.

4.3 WP3: Generation of paint paths for automated spray painting

The scope of this work package was changed during the project to focus on velocity optimization to improve the paint coverage for a give robot path and process parameters. The development of robot code for linear machines was pushed to the future since the project partner interested in that postponed the investment.

An optimization algorithm based on the interior point method was developed. Given a single paint simulation the velocity along the path is optimized such that the paint thickness fluctuations on the surface are minimized. The results show a reduction in fluctuations of roughly a factor two to three for the test cases (a car fender, a truck cab door and a part of a fork lift). For the fork lift an analysis showed a potential 20% reduction of paint material consumption while still satisfying the desired minimum thickness level. This implies a significant potential to reduce the paint material consumption and increase quality. In the future the algorithm will be extended to not only allow velocity changes along the path but also brush changes (changing of process parameters), and finally also the path will be allowed to change.

4.4 WP4: Measurements and validation

In this work package the required methodology for measurements of the electrostatic properties of the applicators has been developed and measurements have been carried out to ensure a successful implementation of the methods and algorithms in WP1 to WP3. This included electrostatic, PIV and particle size measurements to characterize the three different bells and guns used in the project, painting and measuring the resulting paint thickness on plates and the test objects (a car fender and a cab door). Measurements and validations have been carried out at Paint Center, a test- and demo center at Swerea IVF, making it possible to evaluate painting parameters and processes externally without affecting the production at the industrial partners.

4.5 WP5: Surface treatment demonstrator and exploitation

The deliveries from this work package have been demonstrators on the IPS platform that integrate the methods and algorithms developed in WP1 to WP3. Several education sessions on the developed software tool have been arranged during the project with participants from the project partners. In addition the project results have been presented at several international conferences, the Scandinavian coating fair, and published in journals, conference proceedings and in the specialist magazine, Ytforum. Furthermore, the software tool and the project results have been presented at several meetings with international automotive companies that have shown a big interest in the results.

4.6 WP6: Long term strategy for virtual paint

In this work package the long term strategy of the virtual paint project was discussed at several meetings by a project group with participants from the institutes and companies. The vision for 2020 is “A simulation software which allows the paint process engineer to automatically generate a complete painting/sealing program including robot paths and process parameters that guarantees a certain coverage and cycle time”. The detailed software requirements, input and output was discussed and summarized in a report. Available funding resources that can complement FFI was also discussed. FCC is for example submitting a proposal to an internal Fraunhofer program that aims to fulfill part of this vision.

4.7 WP7: Project management

A project group consisting of members from all participating partners was appointed and was responsible for project management, finance and report to Vinnova.

5. Results and deliverables

The project results show that it is possible to accurately simulate spray painting of e.g. a truck cab in only a few hours on a standard computer. This is an extreme improvement compared to earlier approaches that require weeks of simulation time. Unique algorithms for coupled simulations of air flows, electrostatic fields and charged paint particles have made this possible. Several successful measurements campaigns have been performed on geometries from the industrial partners with very good results. The fast simulation time make it possible to use such detailed simulations in the product preparation and off-line programming of the paint robots. The extensions in this project facilitate a wider use of the software within the automotive industry and also to other branches and SMEs.

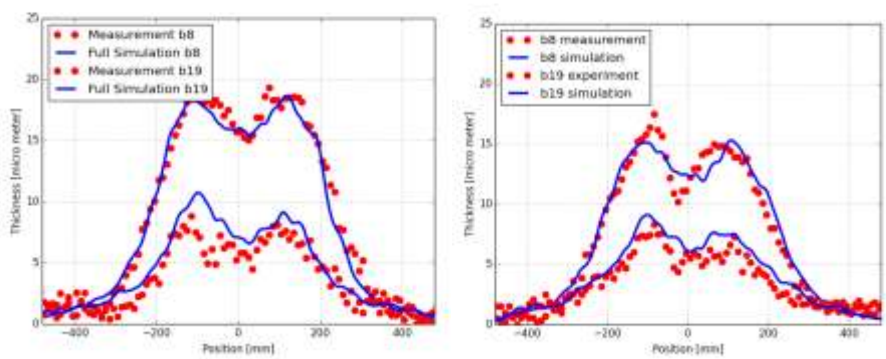

Figure 1. Comparison between measurements and simulation results on a plate painted with an externally charge ABB G1 applicator. The results on the edge of the plate are shown to the left and the results in the middle of the plate are shown to the right.

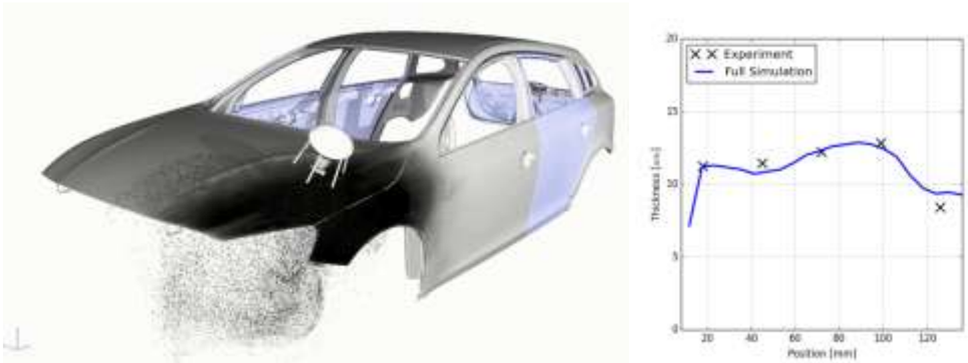

Figure 2. Simulation of the painting of a Volvo V60 fender (left). Comparison between measurements and simulation results in a few positions on the fender.

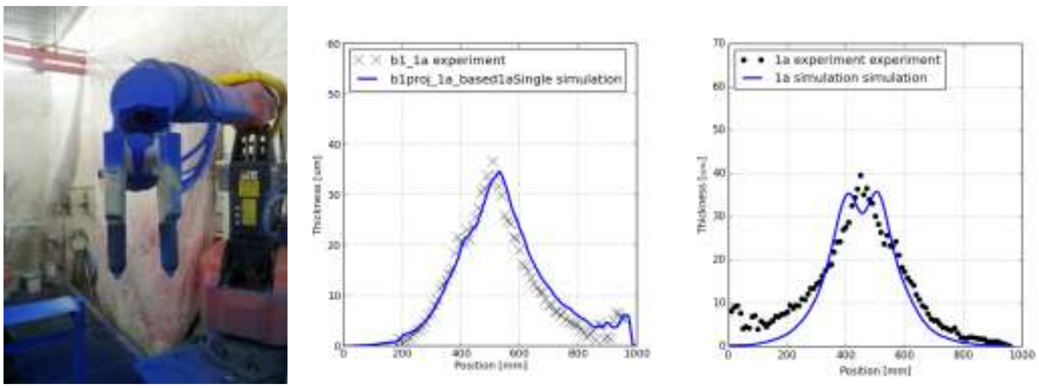

Figure 3. The GEMA twin gun applicator (left). Comparison of simulation results by the projection method and measurements on a plate (middle), and comparison of simulations results using full simulation and measurements on a plate (right).

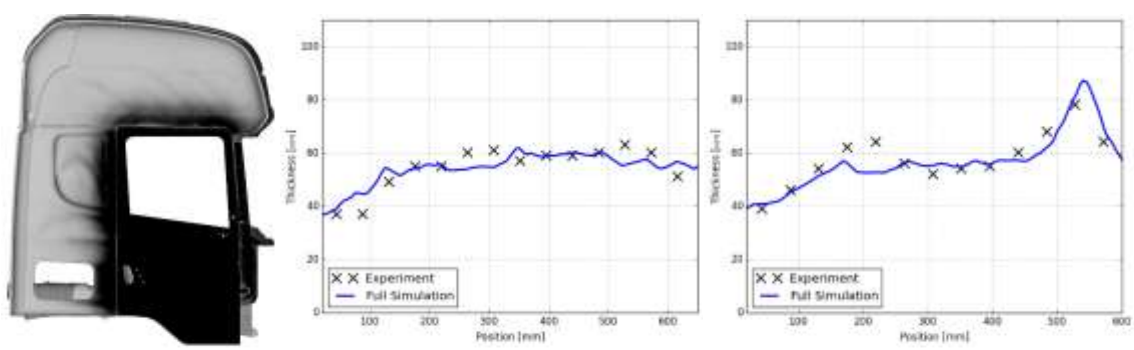

Figure 4. Validation of the paint thickness for a cab door painted with a Dürr Ecobell 2 powder bell.

A big challenge in the project has been the modeling of the corona discharge at the electrode tip and the charging of the paint particles as they pass through the Corona region. The complex physics puts high demands on the numerical methods. The novel methods developed in this project are much more robust than the ad-hoc methods found in the literature and also relevant to other applications such as e.g. electrostatic precipitators.

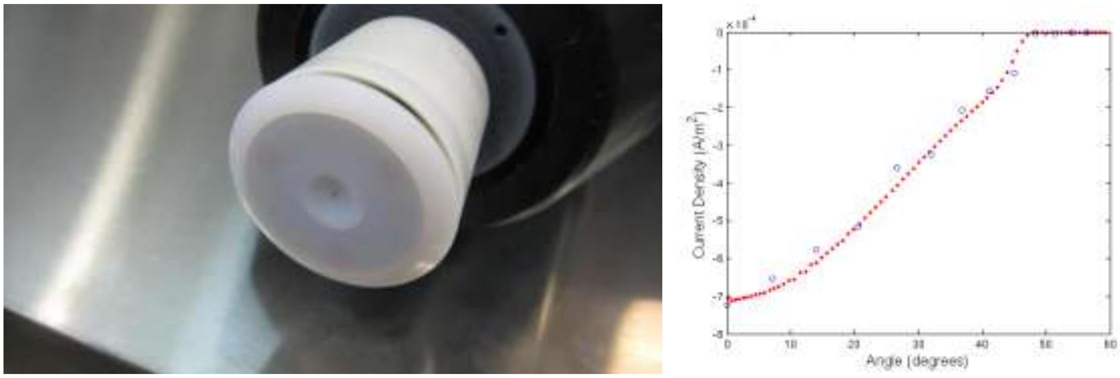

Figure 5. The Ecobell 2 applicator with the small electrode needle visible in the middle (left). A comparison between the simulated and measured current density on a plate located under the applicator (right).

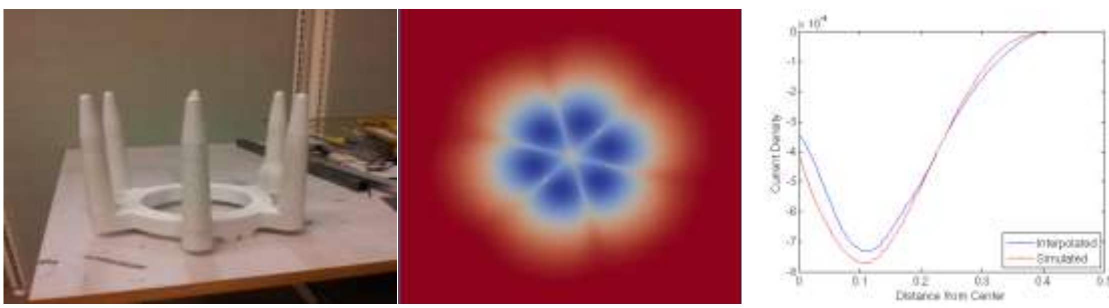

Figure 6. The ABB G1 applicator with six electrodes (left). The ion charge density between bell and target (middle). A comparison between the simulated and measured current density on a plate under the applicator (right).

Furthermore, new methods and techniques to adapt the robot speed along the paint to optimize the resulting paint coverage have been developed. The results show a reduction of the thickness variation with a factor of at least two to three, which in turn means a significant reduction of the paint material consumption. In future projects the results will be generalized such that also other process parameters can be changed along the robot path, and even the path itself.

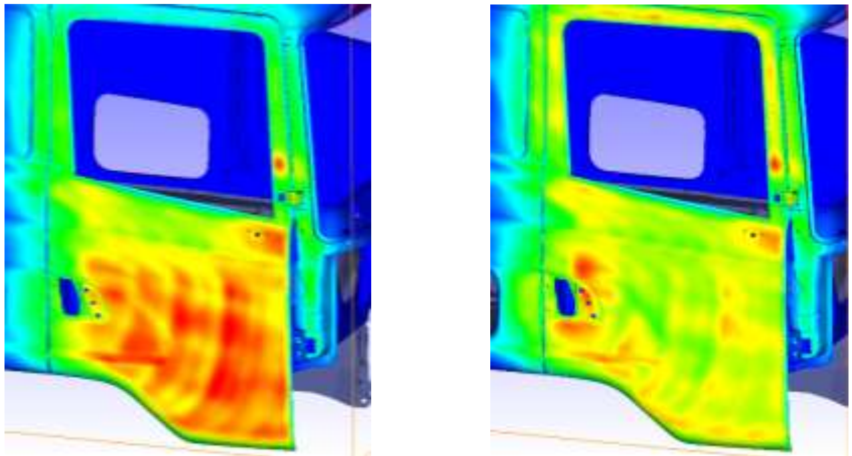

Figure 7. Thickness results for of a Scania truck cab using the original settings (left) and the velocity optimized settings (right). The average thickness was 70 µm in both cases but the standard deviation of the thickness variation reduced from 20 µm to 8 µm by a velocity optimization.

The project results are ready for industrial implementation and have been commercialized in the software IPS Virtual Paint, which is used by Volvo Cars, AB Volvo, Scania, CEVT, Daimler and GM. The spin-off company IPS IBOFlow AB will handle the marketing, sales and support. Volvo Cars is using the software in production and it was for example used successfully to program the paint robots for the new XC90 car model. The work has resulted in four journal publications, two conference papers, two articles in surface treatment specialist journals, two master theses, and one PhD thesis.

5.1 Delivery to FFI-goals

- The project has developed methods, algorithms and software tool that contribute to sustainable production by substantially increasing the productivity in the preparation process since significantly less prototypes needs to be painted. Furthermore, the cycle time can be reduced by optimizing the robot paths and load balance the paint robots work. The environmental impact can be reduced by choosing paint paths and process conditions that maximize the transfer efficiency.
- By enabling more of the product preparation to be done offline new products can be introduced with shorter lead time.
- By offering an efficient software for simulation of the surface treatment more companies will be able to take the step from manual to robotized spray painting with large benefits in efficiency, product quality and reduced human exposure to un-healthy paint substances.
- The project has further strengthened the world-leading research team in simulation of paint and surface treatment processes that contributes to a vehicle industry in Sweden that continues to be globally competitive.

- The math based approach in this project is a key to meet the challenge of increased complexity in the paint shops due to an increased number of product and material variants.
- Increases the use and the understanding of advanced mathematics in production development.
- The project has contributed to a development of the Paint Centre, in terms of expertise and equipment. The centre makes it possible for the industry, to evaluate the painting processes without losing availability in their own production line.
- Increases the collaboration between industry and research institutes.
- The project resulted in a PhD thesis at Chalmers in fluid dynamics.
- The project has further strengthened Sweden's competitiveness as advanced user and developer of digital tools in the border line of product and production.
- The research group in Geometry and Motions Planning at FCC which is part of the environment for innovation and collaboration; Wingquist excellence centre at Chalmers for efficient product realization, has been further strengthened and grown to 20 researchers.
- The research group in Computational Engineering and Design at FCC has been further strengthened and grown from 11 (2012) to 15 researchers. The generality of the project results has made it possible to apply them in projects with companies in the paper and pulp and electronics industries.
- The software platform IPS for math based virtual product realization has been further developed and will continue to secure comprehensive and fast implementation of research results, as well as to facilitate technology exchange between the industrial partners.
- A spin-off company was founded during 2014, IPS IBOFlow AB, that focuses on commercial product development, support, marketing and sales of the software IPS Virtual Paint. First international customers were General Motors and Daimler.

6. Dissemination and publications

6.1 Knowledge and results dissemination

This project has resulted in an increased interest to simulate the paint and surface treatment processes to be able to reduce the time required for introduction of new products, reduce the cycle-time, reduce the environmental impact and increase quality. Volvo Cars has used the software tool for several years in production to program their paint robots. The new XC90 model is one example where the product preparation benefitted from the results of this and previous virtual paint projects. Scania has chosen IPS as a key platform for simulation of paint and surface treatment processes, based on the successful project results. AB Volvo has an ongoing project with FCC where a prototype system for manual spray painting is being developed partly based on the project results. A validation project on spray painting of a cab was successfully performed during

2014. General Motors that was involved in earlier project has recently bought a commercial license of the spray painting software. The results have also attracted considerable international interest and have been presented several times at international automotive congresses. There is e.g. an ongoing collaboration with Daimler on spray painting and validation projects are planned with Volkswagen and Audi.

The project results and demonstrator have continuously been disseminated during company visits, seminars and educations, including e.g.:

- Den virtuella målerifabriken", Ytforum, 2:21-22, March 2013.
- Invited presentation at the European Automotive Coating Jubiläumstagung in Pottsdam, May 2013.
- Booth and presentation at the Scandinavian coating fair, May 2013 and May 2015.
- Meeting at Mercedes Benz, Stuttgart, December 2013.
- Presentation at Commercial Vehicle Cluster, Kaiserslautern, March 2014.
- Invited seminar at Fraunhofer IPA, Stuttgart, March 2014.
- Presentation at SurCar 2014 conference, Shanghai, April 2014.
- Education for AB Volvo, June 2014.
- Invited seminar at Uppsala University, October 2014.
- IPS Paint education for project partners, November 2014.
- IPS Paint education for Scania, November 2014.
- Presentation at Audi, Ingolstadt, November 2014.
- Invited presentation at the European Automotive Coating workshop in Stuttgart, June 2015.

6.2 Publications

1. A. Mark, B. Andersson, S. Tafuri, K. Engström, H. Söröd, F. Edelvik, J. S. Carlson, "Simulation of Electrostatic Rotary Bell Spray Painting in Automotive Paint Shops", Atomization and Sprays, 23(1):25-45, 2013.
2. "Den virtuella målerifabriken", Ytforum, 2:21-22, March 2013.
3. Niklas Karlsson „An Incompressible Navier-Stokes Equations Solver on the GPU Using CUDA", MSc thesis, Chalmers University of Technology, advisor A. Mark, August 2013.
4. B. Andersson, V. Golovitchev, S. Jakobsson, A. Mark, F. Edelvik, L. Davidson, J. S. Carlson, "A Modified TAB Model for Simulation of Atomization in Rotary Bell Spray Painting", Journal of Mechanical Engineering and Automation, 3(2):54-61, 2013.
5. B. Andersson, "Modeling and Simulation of Rotary Bell Spray Automizers in Automotive Paint Shops", PhD thesis, Chalmers, December 2013.

6. A. Mark, R. Bohlin, D. Segerdahl, F. Edelvik, J. S. Carlson, “Optimization of Robotized Sealing Stations in Paint Shops by Process Simulation and Automatic Path Planning”, International Journal of Manufacturing Research, 9(1), 2014.
7. F. Edelvik, A. Mark, C. Zémerli, O. Hermanns, “Efficient numerical simulation of spray painting processes”, In proceeding from Third Commercial Vehicle Technology Symposium, Kaiserslautern, Germany, pp. 499-508, March 2014.
8. C. Zémerli, K. Dressler, O. Hermanns, F. Edelvik, A. Mark, “Efficient numerical simulation of spray painting processes in automotive manufacturing”, AE Technical Paper Series, 2014-36-0418, Sao Paolo, Brazil, October 2014.
9. T. Johnson, S. Jakobsson, B. Wettervik, B. Andersson, A. Mark, F. Edelvik, “A Finite Volume Method for Electrostatic Three Species Negative Corona Discharge Simulations with Application to Externally Charged Powder Bells”, Journal of Electrostatics, 74:27-36, April 2015.
10. B. Svedung Wettervik, ”Three-species negative corona discharge simulations using domain decomposition”, MSc thesis, Chalmers University of Technology, advisor T. Johnson, May 2015.
11. ”Tillämpad matematik ger effektivare lackeringsprocesser”, Ytforum, 3:19-20, May 2015.
12. F. Edelvik, A. Mark, N. Karlsson, J. S. Carlson, Math-Based Algorithms and Software for Virtual Product Realization Implemented in Automotive Paint Shops, Book chapter, Mathematics for digital factories, Springer, submitted.

7. Conclusions and future research

The project results show that it is possible to accurately simulate spray painting of a truck cab or a car in only a few hours on a standard computer. This is an extreme improvement compared to earlier approaches that require weeks of simulation time. Unique algorithms for coupled simulations of air flows, electrostatic fields and charged paint particles have made this possible. Several successful measurements campaigns have been performed on industrial geometries with very good results. The Paint center contributed to input and validation data without affecting any own production for the industrial partners. The fast simulation time makes it possible to use such detailed simulations in the product preparation and off-line programming of the paint robots. The extensions in this project facilitate a wider use of the software within the automotive industry and also in other branches and SMEs.

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The longer term vision with the research on the virtual paint shop is to radically rationalize the surface treatment in Swedish industry by developing simulation tools that make it possible to completely automate the product preparation process in the paint factory. With a geometry description and available brushes as input, optimal robot paths and process conditions that guarantee a certain coverage and visual results such as gloss and color match, should be automatically calculated. This is obviously an extremely complex problem but the research group has a unique platform to take on this challenge. If successful it would dramatically improve the productivity and reduce the environmental impact during product preparation as well as in production. This vision will be realized in several steps and the project group will at the end of 2015 apply for a new FFI project targeting near bell simulation and building up a database with the most common applicators used in industry. The project has a high TRL level but is necessary to realize a wider use of the software within the automotive OEMs and their suppliers. In addition, it facilitates a wider use outside of the automotive industry including SMEs.

8. Participating parties and contact persons

This has been a collaboration project with the industrial partners Scania CV, Volvo Car Corporation, AB Volvo, BT Products AB, Allt I Plåt AB, and Falk Lack AB, and the research partners Fraunhofer-Chalmers Research Center (FCC) and Swerea IVF. A steering group with one representative from each partner has been appointed for the management of the project. It has been responsible for the project control, economy and reporting to VINNOVA. The daily operations have been handled by Christer Bodén, Scania (Industrial project leader) and Fredrik Edelvik, FCC (Academic project leader).

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