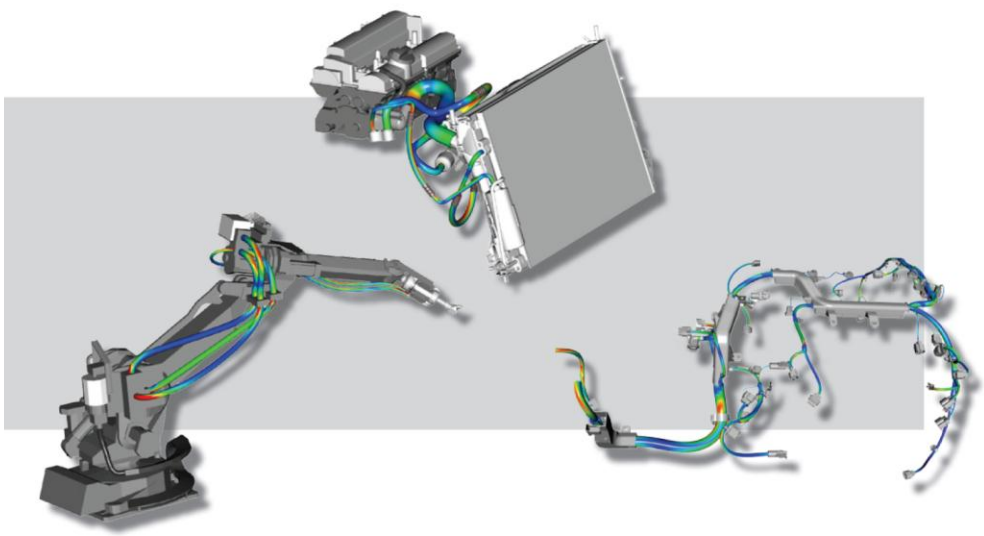
Packing and Assembly Analysis of Flexible Parts in Hybrids and Light Weight Vehicles



Project within FFI-Sustainable Production Technology

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Date: 2013-05-31

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FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

The manufacturing industry is facing considerable changes in the field of engineering as a result of intensified activities to find more environmental friendly solutions. New environmental requirements, regulations and new customer demands aiming at a sustainable society have a huge impact on future products and product realization. The highly competitive automotive industry is in many aspects at the frontline when it comes to utilizing digital tools in the whole chain from design through production to maintenance and services. Vehicles of today and tomorrow are based on more environmental friendly propulsion systems, e.g. uses electricity and battery technology in a higher degree than before. This will result in a dramatically increased usage of complex cables and hoses. But also the challenges on low fuel consumption and CO2-levels will remain and drive development towards lighter vehicles with light weight components.

All together, these trends create challenges during design, verification and production. For virtual product realization this means new and fundamental demands on the simulation capability of flexible structures and new materials.

The objective of the project is therefore faster product realizations of hybrids and fully electrified light weight vehicles. In particular, the goal has been to develop methods and digital tools for efficient geometrical packing, assembly path planning and analysis of flexible parts related to the propulsion systems and to light weight solutions.

The project has been carried out in 4 work packages

- WP1: Geometric packing and design
- WP2: Assembly path planning and analysis
- WP3: Material property knowledge and modelling
- WP4: Demonstrator and dissemination of results

The project has resulted in new algorithms, software tools and methods for (i) automatic routing of cables and hoses, (ii) robust design and tolerancing of hoses and wiring harnesses, (iii) automatic assembly planning of hoses and wiring harnesses, and (iv) harness modelling description enabling efficient interaction with CAD environments.

Some high lights of industrial applications and impact already today are

- Electrical engine packing and design of the Volvo V60 D6 AWD Plugin-Hybrid High Voltage Cable Hybrid.
- Design and analysis of complex wiring harnesses at Delphi.
- Cab tilting at Volvo Trucks.
- Interaction between IPS and NX as well as IPS and Jack, Complex dynamic investigations, Generation of HMD-file for tailgate assembly at Opel/GM.

The simulation technology for real time deformations of cables, hoses and wiring harnesses has created worldwide attention and is today used by companies in Sweden, Germany, Asia and US. A spin off software company, Industrial Path Solutions Sweden AB, has been established for boosting the commercialization of the technology.

2. Background

The automotive industry is facing considerable changes in the field of engineering as a result of intensified activities to find more environmental friendly solutions. New environmental requirements, regulations and new customer demands aiming at a sustainable society have a huge impact on future products and product realization. Vehicles of today and tomorrow are based on more environmental friendly propulsion systems and will, e.g. use electricity and battery technology in a higher degree than before and this will result in a dramatically increased usage of complex cables and hoses. But also the challenges on low fuel consumption and CO_2-levels will remain and drive development towards lighter vehicles with light weight components. For example, metal parts will when possible be replaced with polymer parts. Polymers in general are used in a wide variety of industrial applications and products due to low density, relative strength and form flexibility. All together these trends create challenges during design, verification and production. For virtual product realization this means new and fundamental demands on the simulation capability of flexible structures and new materials.

The automotive industry of today is focusing on hybrid solutions with both conventional combustion engines and battery supplied electrical engines. To fit all new components related to the electrical solution in the already densely packed vehicle is hard. One challenge is to find an acceptable placement of the relatively bulky battery. Each placement must be evaluated with respect to geometrical interference with other disciplines and their components and material usage of electric cables and harnesses (weight and cost). Also the assembly aspects must be considered early during conceptual design with respect to feasibility and ergonomics. For example, the assembly of cables and harnesses are tricky due to its concealed routing, connections, weight and awkward ergonomic postures. Many work-related injuries are caused by this type of assembly tasks. Furthermore the product quality output is to a large extent dependent on the design for assembly. Also, studies in the automotive industry show that approximately 25% of all quality problems are related to flexible parts and connecting tasks. Another challenge with hybrid solutions is the need for multiple cooling systems, one for the conventional engine and one for the electrical engines and batteries. This need leads to a considerable increase of air and liquid hoses and of electrical circulation pumps. For hybrids and electrical vehicles it is important to use light weight solutions. This means new materials and higher percentage of components with increased deformation flexibility. In many cases this flexibility could be utilized during assembly analysis to avoid exaggerated needed space for assembly. However, this requires accurate knowledge of relationship between assembly forces and component deformation behaviours. There is also a need to verify how the flexible components will behave during vehicle motion with respect to e.g. clearance, wear and rattle noise due to vibration.

The above challenges must be solved, due to cost, time, and decreased number of physical prototypes, with virtual methods. In particular, the benefits from increased simulation capability is greatest for low series and mixed production lines, which is the most likely scenario for Swedish automotive industry.

3. Objective

The objective of the project is faster product realizations of hybrids and fully electrified light weight vehicles. In particular, the goal is methods and digital tools for efficient geometrical packing and assembly path planning and analysis of flexible parts related to the propulsion systems and to light weight solutions.

The goal is also that the project partner group is recognized as being the world leading constellation within geometrical packing and assembly analysis of flexible parts of hybrids and fully electrified light weight vehicles. The recognition should apply both to short term industrial implementation and long term strategic research.

4. Project realization

The project has been carried out in 4 work packages

- WP1: Geometric packing and design
- WP2: Assembly path planning and analysis
- WP3: Material property knowledge and modelling
- WP4: Demonstrator and dissemination of results

In more detail,

4.1 WP1: Geometric packing and design

In this work package the focus has been on new algorithms, tools and methods supporting geometrical packing and design of flexible parts such as cooling hoses and pipes, electrical cables and wiring harnesses. This is one of the most challenging (i.e. time consuming) and critical processes during the product realization of new propulsion systems. The positions, routings and cross sections of the flexible parts need to be determined with respect to space, weight, efficiency, life length, quality, and assembly solutions.

Manufacturing and assembly related variation in design parameters such as material stiffness, density, clip positions can drastically affect the shape of the flexible components and hence the packing analysis. Also, the ideas of robust design, to minimize the effect variation, should be applied. Therefore, methods for representing and evaluating the effect of variation in flexible parts have been developed.

Another task has been the extension of mathematical clips locking any combination of degrees of freedom to more realistic type of clips. This extension results in a higher degree of accuracy in many simulation situations.

A lot of effort has been put into finding methods and formats for exchange of flexible parts information between different IT systems. The resulting modelling language for harnesses makes it possible to import an already designed flexible part from another CAD system and redesign it and then make an update.

In summary, to support the packing and design of flexible parts this work package has been focusing on (i) methods and algorithms for automatic packing and design, (ii) simulation of dynamic effects, (iii) robust design and variation simulation, (iv) modeling of new clip types, and (v) interface with CAD systems.

4.2 WP2: Assembly path planning and analysis

One of the top reasons for problems in the final assembly plant is related to flexible parts since their behavior have been hard to predict with digital tools. Therefore, this work package has been focusing on developing new algorithms, tools and methods supporting assembly path planning and analysis of flexible parts. The target is to make it possible to consider assembly aspects as early as possibly to secure feasibility, ergonomics and quality.

One important aspect in the assembly process design is to assure that there exist collision-free assembly paths for all parts. In order to reduce the need of physical verification, the vehicle industry uses digital mock-up tools with collision checking for this kind of geometrical assembly analysis. However, to manually verify assembly feasibility in a digital mock-up tool can be hard and time consuming. Therefore, the recent development of efficient and effective automatic path planning algorithms and tools for rigid bodies are highly motivated. We have in this project extended these algorithms to assembly planning of flexibles including even complex wiring harnesses. Cables and hoses are then deliberately deformed during assembly.

Fast path planning algorithms relies on efficient collision testing. New methods for fast collision, distance and contact calculation between moving flexible parts and surrounding geometries have been developed for this purpose.

In summary, to support the assembly path planning and analysis of flexible parts this work package has been focusing on (i) algorithms for assembly analysis and path planning of flexible parts, (ii) methods for simulation of surfaces, and (iii) fast methods for collision and contacts between flexible parts.

4.3 WP3: Material property knowledge and modeling

Predicting deformations and assembly forces related to flexible parts require detailed knowledge about material behaviors. In this work package we have performed empirical studies to obtain detailed material properties knowledge of flexible parts. By establishing standard properties and standard testing routines, a new flexible part can now easily be classified for simulation. These properties are typically effective density, stretching, bending and twisting stiffness.

Some parts are very complex and need to be modelled on a macro level. For example, a high voltage cable or a wiring harness consists of strands wired together into cables which in turn are put together into a bundle. Bending and releasing such a part often results in a permanent deformation. The reason for this is that the bending makes the individual wires to slide and twist. Then, friction prevents the wires to twist back which creates a permanent deformation. Since the number of strands can be several thousands, it is not possible to do real time simulation on all of them. Instead, they should be replaced by one cable having the aggregated properties of the wiring harness including the plastic effects.

Furthermore, since the batteries and electrical engines need substantial cooling we have also worked with how to model and simulate flexible parts that are pressurized with air in different temperature conditions.

In summary, to support the material property knowledge and modeling of flexible parts this work package has been focused on (i) establish standard material properties definitions and testing routines, (ii) create data base of material properties, (iii) methods for real time simulation of non-linear material behavior, (iv) simulating pressurized hoses in different temperature conditions, (v) calculation model for aggregating material properties of complex wiring harnesses, and (vi) validation results of simulation.

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4.4 WP4: Demonstrator and dissemination of results

The project results have continuously been implemented in the IPS software demonstrator available for the project partners. This way of working has proven to guarantee the usefulness of project results both during and after a project. Results have also been further distributed in journals, conferences, seminars, and master courses at Chalmers, see Section 6.

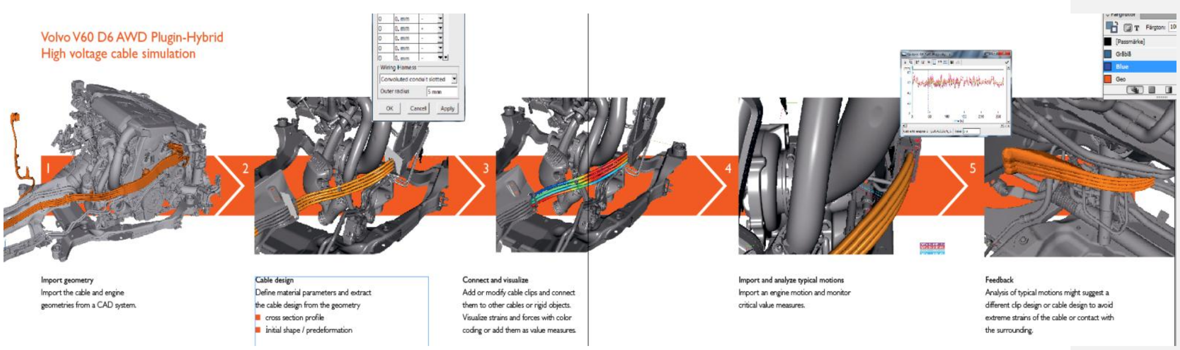
5. Results and deliverables

The main technical results and deliverables of the project are (i) a toolset for robust design and variation simulation of flexibles, (ii) new method for automatic routing of cables and hoses considering manufacturing constraints, (iii) a Harness Modelling Description (HMD) for simulation enabling efficient communication with different IT systems. (iv) a method for automatic assembly planning of wiring harnesses, (v) a toolkit for advanced mechanism clip generation and storage, (vi) a model for real time simulation of plasticity, (vii) testing routines for material data, (viii) a material data base of cables, (viiii) a calculator for aggregating material properties of complex wiring harnesses, (x) improved distance and contact handling for flexibles, and (xi) six scientific publications.

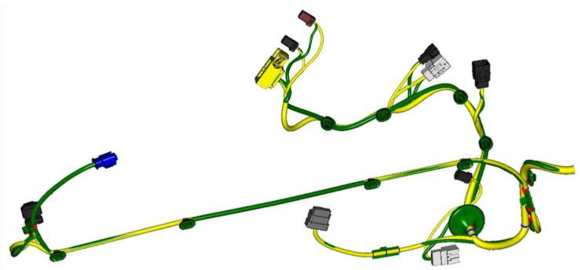
The results will be fully implemented at the industrial partners during 2013 and 2014 and will take simulation of flexibles in (i) engine packing and design, (ii) assembly planning, (iii) wiring harnesses design and manufacturing, and (iv) robot dress packs to the next level.

Some high lights of industrial applications and impact already today are:

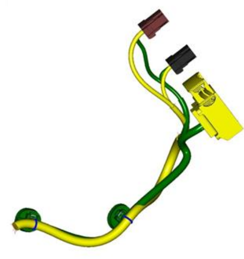
- **Electrical engine packing and design of the Volvo V60 D6 AWD Plugin-Hybrid High Voltage Cable Hybrid.**



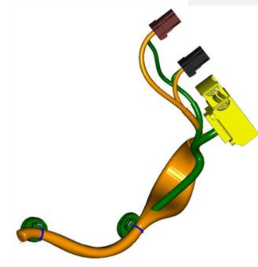
- **Design and analysis of complex wiring harnesses at Delphi (see also appendix)**



Harness shape simulation and comparison with 3D-routing.

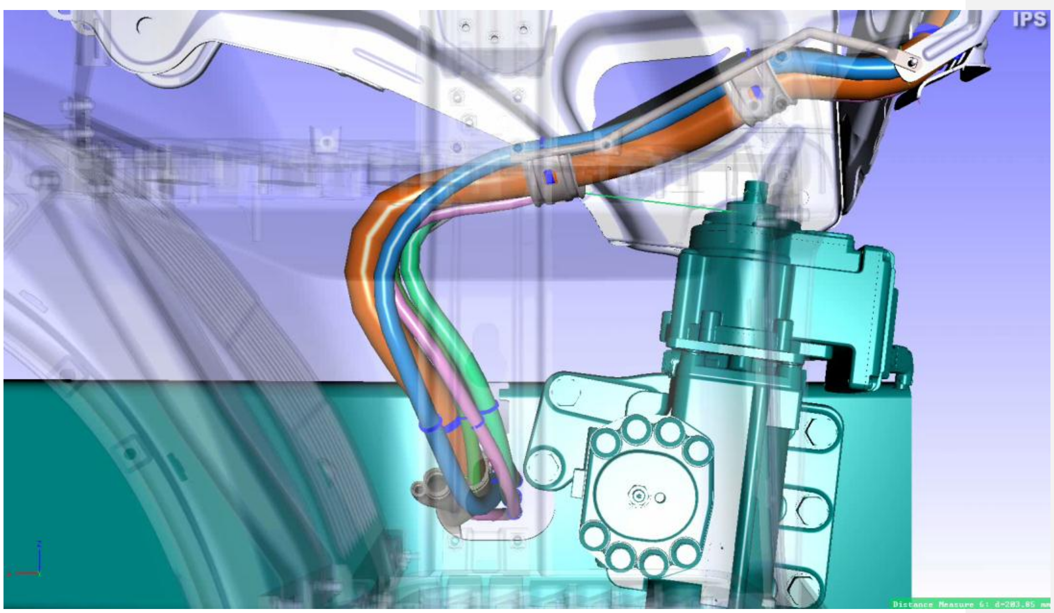


Deviation between 3D-routing and physical 3D-routing.



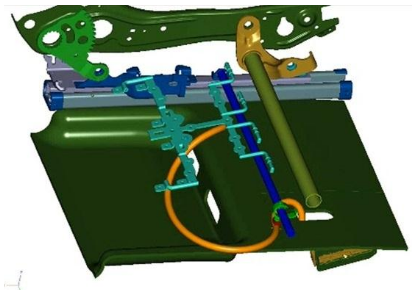
Calculated installation space with tolerances.

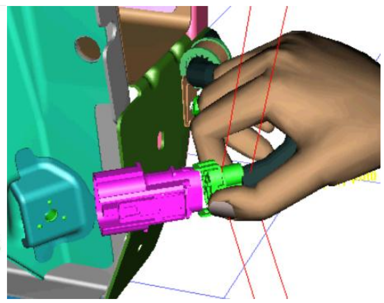
- **Cab tilting at Volvo Trucks**



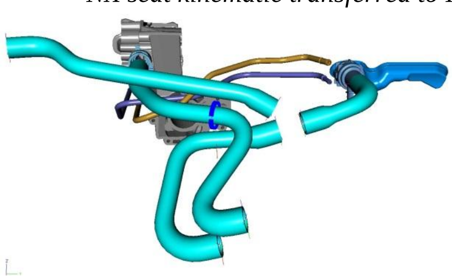
Simulation contains a movable component (driver’s cab) and a fixed part (vehicle body) of the scene

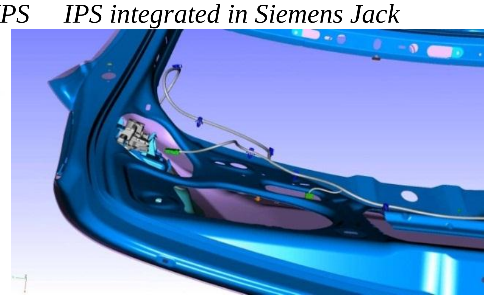
➡ **Interaction between IPS and NX as well as IPS and Jack, Complex dynamic investigations, Generation of HMD-file for tailgate assembly at Opel/GM**





NX seat kinematic transferred to IPS   *IPS integrated in Siemens Jack*





Heater hoses under motion   *Tailgate assembly described with HMD*

Other industrial activities:

Examples of activities at the OEM project partners:

- Regular work in optimization/reduction of the length of pipes and hoses. This has given a reduction of weight and cost in the vehicles.
- Regular work in optimization/reduction f harness fixation points to avoid or minimize the wear effects.
- Usage of IPS in analyses regarding chafing risk connected to cable and harness design and hydraulic hoses design (in wheel loaders).
- Usage of IPS in analyses of clash risk during engine drop, clash or chafing risks in engine bay with flexible parts etc.
- 50-70 IPS daily basis users (flexible analyses combined with path planning) are as a result of the project now active in all project partner companies.

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Examples of activities at Delphi:

- **Harness Shape Simulations (**Transformation **from 2D to 3D mounting position):** A simulation type to check, optimize and verify a w/h design and layout of a defined harness variant.
- **Simulation of the mounting sequence of a High Speed Data connector:** A simulation type in order to identify the best solution based on the deformations, structure and position of twisted wires of a data cable inside a shielding.
- **Investigation of the harness routing in a critical area:**
  The routing of a harness partition in an area with very limited space has been simulated by a mechanical w/h simulation with IPS in order to investigate, if the current routing and fixation of the segment by a cable channel could be replaced by a new routing with one or two clips. Multiple different simulations of the harness segment routed by one or two clips have been setup in order to find the best and most rigid solution for a routing with clips, to indicate possible collision of the harness with the surrounding geometry and to optimize the topology of the harness routing.

5.1 Delivery to FFI-goals

- The project has developed methods, algorithms and a software tool that enables productivity increase of 20% in packing design and 10% in manufacturing engineering of flexible parts. Also a productivity increase of 2-3% in final assembly of flexible parts, by fast and accurate consequence and optimization studies is expected when fully implemented.
- Furthermore, the methods and tools of the project aim at reducing material usage and increases equipment life length. In this way the results directly supports Sustainable Vehicle and Power train Production by minimizing physical efforts and reducing the resources needed to produce each item.
- It significantly speeds up the product realization development process. In this way, the project contributes towards a vehicle industry in Sweden that continues to be competitive.
- The math based simulation approach in this project is a key to meet the challenge of increased complexity in product realization of product variants. In particular when conventional and new environmental power trains are mixed.
- Increases the use and the understanding of advanced mathematics in production development.
- Increases the cooperation between industry, university and research institutes.
- The project will result in a PhD at FCC/Wingquist Laboratory at Chalmers.
- The project has further strengthened Sweden’s competitiveness as advanced user and developer of digital tools methods in the border line of product and production.
- The research group of Geometry and Motion Planning at FCC, which is part of the Wingquist excellence centre at Chalmers for efficient product realization (an

environment for innovation and collaboration), has been further strengthened growing from 9 (2009) to 18 researchers.
- 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 facilitating technology exchange between the industrial partners.

6. Dissemination and publications

6.1 Knowledge and results dissemination

There is a big interest worldwide in the developed technology and software, both from an industrial and academic perspective. The project results and demonstrator has continuously been disseminated during company visits and seminars, e.g.

- Ad on research collaboration and industrial impact on page 3 in Göteborgs-Posten November 12, 2009.
- Invited lecture in master course Robotics and Robot systems, Chalmers, april 2010.
- Presentation at Manufuture Conference, Wingquist Laboratory, Göteborg, December 2010.
- Presentation at Wingquist Laboratory annual seminar, Göteborg, December 2010,
- Presentation at Volvo Cars, Manufacturing Research & Advanced Engineering Seminar, February 3, 2011.
- Invited lecture in master course Robotics and Robot systems, Chalmers, april 2011.
- Presentation at Scania, Södertälje, 2011.
- CIRP International Conference on Computer Aided tolerancing, Huddersfield, UK, 2012.
- Invited lecture in master course Virtual Process Planning, Chalmers, February 2012.
- Invited lecture in master course Robotics and Robot systems, Chalmers, april 2012.
- Mötesplats för framtidens framgångsrika verkstäder, Katrineholm, May 2012 .
- Presentation 4th CIRP Conference on Assembly Technology and Systems - CATS 2012, University of Michigan, Ann Arbor, USA on May 21 - 23, 2012.
- Presentation at Ford Motor Company, May 2012.
- Presentation at Daimler, Ulm, November 2012.
- Presentation at Wingquist Laboratory annual seminar, Göteborg, December 2012.
- Invited lecture in master course Virtual Process Planning, Chalmers, February 2013.
- Invited lecture in master course Robotics and Robot systems, Chalmers, april 2013.

The collaboration on virtual product realization with Wingquist Laboratory at Chalmers and its VINNEX Centre will continue. This is an excellent platform for further disseminations, both in industry and academia.

6.2 Publications

1. Andersson, F., "Surface interpolation for detail restoration", Master thesis, supervisors Andersson R., Hermansson T. and Johansson B., Chalmers, June 2009.
2. Bitar, F., "Adaptive Bounding Volume Hierarchies for Deformable Surface Models", Master thesis, supervisors Shellshear, E. and Assarsson, U., Chalmers 2011.
3. Hermansson, T., Carlson, J. S., Björkenstam, S., Söderberg, R., "Geometric Variation Simulation and Robust Design for Flexible Cables and Hoses", CIRP International Conference on Computer Aided tolerancing, Huddersfield, UK, 2012.
4. Weischedel, C., Tuganov, A., Hermansson, T., Linn, J., Wardetzky, M., "Construction of discrete shell models by geometric finite differences", The 2nd Joint International Conference on Multibody System Dynamics, Stuttgart, Germany, on May 29 – June 1, 2012.
5. Hermansson, T., Bohlin, R., Carlson, J. S., Söderberg, R., "Automatic path planning for wiring harness installations (wt)", 4th CIRP Conference on Assembly Technology and Systems - CATS 2012, University of Michigan, Ann Arbor, USA on May 21-23, 2012.
6. Shellshear, E., Bitar, F., Assarsson, U., PDQ: Parallel Distance Queries for Deformable Meshes, Graphical Models (2013), doi: 10.1016/j.gmod.2012.12.002.
7. Hermansson, T., Carlson, J.S., Björkenstam, S., Söderberg, R., "Geometric variation simulation and robust design for flexible cables and hoses", Journal of Engineering Manufacture Volume 227 Issue 5, May 2013.
8. Hermansson, T., Bohlin, R., Carlson, J.S., Söderberg, R., "Automatic assembly path planning for wiring harness installations", Journal of Manufacturing Systems, Available online May 2013.
9. Schaub, M., Uthoff, J., "Virtual Analysis of Compliant Parts", SAE Int. J. Mater. Manuf. 4(1):799-807,2011, doi:10.4271/2011-01-0531.
10. Schaub, M., Ruppert, W. and Laugwitz, U., "Compliant Parts Simulation Procedure", SAE Int. J. Commer. Veh. 5(1):318-326, 2012, doi:10.4271/2012-01-0948.

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7. Conclusions and future research

The algorithms, tools and methods to support assembly planning will continue to be developed. In particular, the successful test done at GM during summer 2012 to combine simulation of flexibles with virtual ergonomics will continue. The simulation technology is also an integral part of the on-going EU project VISTRA aimed at virtual assembly training including flexibles.

Many industrial robots are dressed with cables and hoses feeding the tool with signals, current, pressurized air, screws, paint and sealing material. These hoses and cables have serious impact on the allowed robot configurations and motions in a robot station. Today, the robot manufacturers provide rules of thumbs on how to avoid high stresses, and collisions are removed by experience and on-line adjustments. However, on-going work aims at combining real time simulation of cables with the FCC technology for automatic path planning and line balancing. Strategies for finding feasible robot configurations and motions with respect to equipment utilization/cycle time and life length of cables are part of a master thesis work together with Volvo Cars, to be presented in June 2013.

There are also discussions in the project group about continuing the successful collaboration in an industrial consortium. The idea is to share implementation cost and material measurements. The group will maybe also be expanded by e.g. Ford Motor Company, Scania and others.

8. Participating parties and contact persons

The project has been a collaboration with the industrial partners Volvo Car Corporation, Volvo AB, Delphi and the research partner Fraunhofer-Chalmers Center (FCC). A collaboration agreement with GM providing extra funding has also been part of the project. 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 of project management have been handled by Lennart Malmsköld, Volvo AB (Industrial project leader) and Johan S. Carlson, FCC (Academic project leader).

Name	**Role**	**Organisation**	**E-mail and Phone**
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Comment [MS1]: In table: GM, but SAAB logo???

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