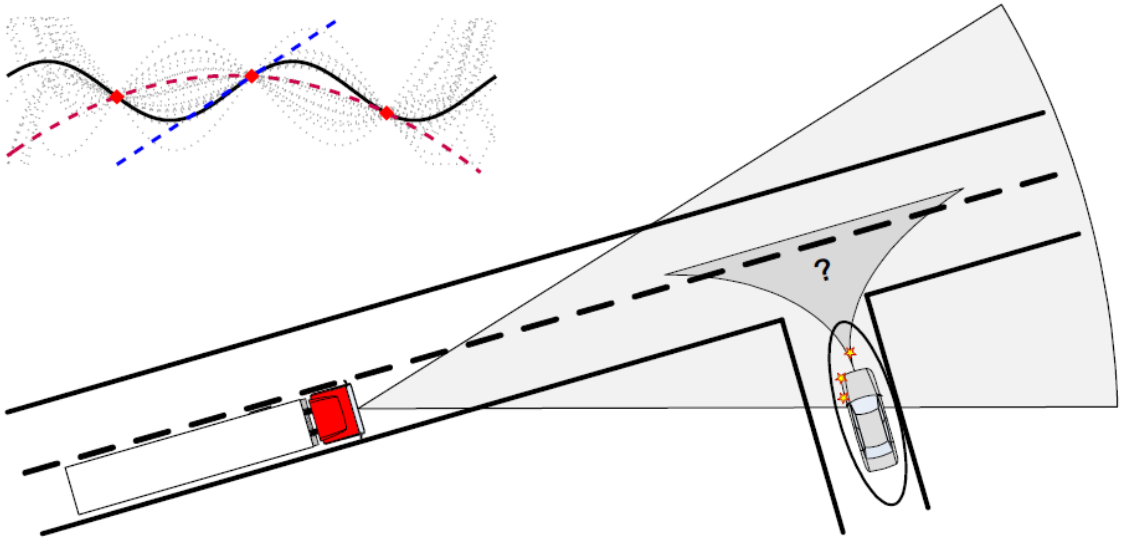
Filtering Techniques for Sensor Fusion



Project within FFI - Vehicle and Traffic Safety.

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Content

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 project has funded research with practical as well as theoretical significance regarding methods for fusing data from from a variety of sensors that vehicles are expected to be equipped with in the near future. The purpose of the project's research activities has been to develop fusion strategies for use in intelligent safety systems in order to save lives and reduce injuries resulting from traffic accidents, either by reducing the accident frequency or by making the accidents less severe.

The goals have been achieved through several contributions within the area, published in prestigious journals and on selected conferences. Examples of the practical significance of the work can be seen in the project NHCT, where some of the results were implemented and tested in demonstration vehicles. Another example is the article *Sensor data fusion for multiple sensor configurations* [4] which describes a fusion architecture that will have practical impact at AB Volvo.

The significance and direction of research is reflected in the contributions, wholly or partially funded by the project , see chapter 6.2 in the report. In addition, the form of collaboration where co-location at the University was essential and significantly contributed to the close cooperation between industry and academia, illustrated by the many ad-hoc networks that contributed to the publication list.

2. Background

West Sweden and especially Gothenburg is a hub for vehicle safety research in Sweden, which has several reasons: AB Volvo and Volvo Cars have both safety as a core value and has long recruited expertise from, and collaborated with, Chalmers University of Technology, which in turn provides a research environment with several relevant areas of focus for road safety. The proximity of VTI, with its new vehicle simulator, and the national competence center SAFER with 25 partners from academia, institutes, industry and government consolidates the environment.

The project partners and team members have previously worked together, *e.g.*, in the IVSS project SEFS - sensor data fusion for safety, with satisfactory results. For the year 2010 we could see that there were resources, needs and potential for a special investment in fusion methodology, which was the basis for the project application.

3. Objective

In summary, the project aims to meet the general FFI objectives, the automotive research program objectives[1], and the project partners' goals. The latter is to become the world leader in vehicle safety for commercial vehicles, which requires competence within the own organizations as well as in the region. The project is more fully described in the appendix "måluppfyllad" (only available in Swedish).

The project's goal has been to (a) publish research articles, and (b) award doctorates, to investigate and develop fusion methods appropriate for the fusion of sensors relevant to road safety systems.

4. Project realization

The research project was conducted by Malin Lundgren, Fredrik Sandblom and Lennart Svensson. Malin and Fredrik was initially full-time graduate students and Lennart was their supervisor. Fredrik was awarded his PhD at the end of 2011 and since then continued as a part-time researcher in the project. The research has mainly been carried out at the Department of Signals and Systems at Chalmers University of Technology. Co-location has proved especially fruitful due to the large network of researchers and industrial partners who visit the school, for long and short assignments. This allows for more discussion and more perspectives on ideas and opportunities for collaboration. Moreover, co-location facilitates for researchers from industry to focus on a research question undisturbed. Even if it concerns only one or two days a week, it is especially important when the industrial environment and way-of-working involves timely communication and a high degree of availability.

The parties have regularly met to discuss and plan research. Both work and planning has been handled informally and been flexible in terms of following up promising results and exploiting opportunities for collaboration. In particular, collaboration have involved researchers at the Department of Signals and Systems (employees and visitors) and ongoing research projects in the field of road safety. Especially the FFI project Non Hit Car and truck (NHCT) should be mentioned, as Volvo's research resource in the project since 2012 has been shared with NHCT which, however, is a more practical oriented project.

Periods of sickness and parental leave within the workgroup led to an extension of the project for another year. It has not affected the results (except that they were postponed one year). It proved to be a simple change from a labor perspective, as the working group was small and could prolong the research rather than look for temporary replacements.

[1] In Swedish: ”fordonsforskningsprogrammets särskilda mål”.

5. Results and deliverables

The project has published far more results than the participants expected from the beginning. This is a result of the favorable conditions regarding existing research environment and good cooperation between the parties. Furthermore, a doctoral examination has been achieved and a second one is expected in the middle of 2014 /2015.

The results consist of the publications in Sec. 6.2., and a short summary of each contribution can be found in the appendix "Teknisk projektredovsining" (only available in Swedish). The results include a new filtering algorithm – 'the marginalized Kalman Filter' (MKF) [2, 13] – which wholly is a result of the project. The algorithm makes use of efficient numerical approximations to calculate the statistical moments needed to linearly update a state using a measurement, when the models that relate older states to new measurements are nonlinear. A model of the nonlinear function is estimated and uncertainties can be marginalized analytically. The model clarifies the underlying assumptions that implicitly are made in sigma point approximations, which are used by many filters.

To accurately represent the estimation uncertainties is important for the interpretation of the estimates and their use in driver support systems. A method for decision making for intervention procedures that take account of just that [1, 14] has been developed together with a researcher from Volvo Cars. The contribution compares the system uncertainty to the perceived driver uncertainty, using a model of driver's perceptual ability and desire to avoid accidents, to allow for earlier interventions when the driver is not likely to perceive them as unnecessary. The work corresponds well to the purpose of this project and the model for decision making is a natural extension: filtered data should be used as efficiently as possible in the subsequent decision-making.

5.1 Delivery to FFI-goals

The following summary is also found, slightly ore detailed, in the Appendix "projektuppfyllnad" (only available in Swedish).

At the time of the application the following objectives, in which activities should be conducted according to the vehicle and road safety program description, were identified to be addressed by the project:

- Intelligent safety systems
- Human cognition and tolerance
- Active crashworthiness

Of the program's specific objectives it was estimated that the present project would particularly contribute to the following two objectives:

- Development of technology that allows the vehicle to detect safety-critical situations and act accordingly.
- Vehicle technology that can detect and mitigate the consequences of improper driver behavior.

The description also lists prioritized research areas. We estimate that this project involves *supportive and interactive safety, human cognition and tolerance* and *enhanced impact protection*. In the long term, the project also contributes to the following FFI objectives:

- The capacity for industry to conduct knowledge-based production in Sweden.
- Contribute to a competitive automotive industry in Sweden.
- Lead to development of industrial technology and skills.
- Contribute to employment, growth and strengthen R & D activities.
- Strengthen research on selected and prioritized research areas within production technology, namely road safety.
- Support innovation and collaboration environments; see Chapter Collaboration in the application.
- Strive to ensure that new knowledge is generated and implemented, and that the existing knowledge is implemented in industrial applications.
- Strengthen the collaboration between the automotive industry and the Swedish road authorities, universities and research institutes.
- Ensuring a national supply of skilled resources and the establishment of international competitiveness for research and development.

Achievement of project goals:

Mål	**Kommentarer**
Development of technology that allows the vehicle to detect safety-critical situations and act accordingly.	Such systems are developed by Volvo. All the publications contribute to this goal.
Vehicle technology that can detect and mitigate the consequences of improper driver behavior.	Such systems are developed by Volvo. All the publications contribute to this goal.
The capacity for industry to conduct knowledge-based production in Sweden.	Development of driver assistance systems is knowledge intensive and Volvo focus the development of such systems to Sweden. That expertise can be recruited here is a prerequisite, and projects like this contribute to that, both in the short term and in the long term.

Contribute to a competitive automotive industry in Sweden.	See the comment above. Road safety will be even more important when going forward, we believe. Therefore, it is necessary to be strong in the area to be competitive in the future.
Lead to development of industrial technology and skills.	See earlier comment about education and local expertise.
Contribute to employment, growth and strengthen R & D activities.	See earlier comment about Volvo's investment in Gothenburg for the development of the group's road safety systems.
Strengthen research on selected and prioritized research areas within production technology, namely road safety.	The research project has been carried out at Chalmers and Volvo, and partly together with researchers who have a connection to any of the parties. In this way, the existing research environments have been strengthened.
Support innovation and collaboration environments.	SAFER is a unique collaborative environment in Gothenburg, where researchers in the project had the opportunity to present results or lecturing at seminars. The informal collaboration environment that arose around our co-location at Chalmers has led to several contacts that would otherwise not have happened.
Support innovation and collaboration environments; see Chapter Collaboration in the application.	See section 6.2. Using such knowledge is what Volvo does for a living.
Strengthen the collaboration between the automotive industry and the Swedish road authorities, universities and research institutes.	See earlier comment regarding research environments.
Ensuring a national supply of skilled resources and the establishment of international competitiveness for research and development.	The project has produced a PhD and another is on the way. The list of publications reflects that the research is of high quality, and Volvos participation in the project indicates that the results are judged to be relevant from an international competitiveness perspective.

6. Dissemination and publications

6.1 Knowledge and results dissemination

We, the project partners, believe that the project has been successful. One reason is that results from on-going or recently completed research projects have been used, for example experts (research network for discussions and advice), logged sensor data, and relevant research questions.

From this we draw two conclusions. Firstly, the project would not have been as successful in this form without an existing research-environment that the researchers were already a part of. Secondly, the same environment is aware of the project results that have been generated. Therefore, it is our opinion that the results will reach a wide audience over time.

To make the most of the results, new research initiatives are advised to be initiated such that the overall discussion between all parties in the research network is, in some sense, continuous.

6.2 Publications

The project has contributed to the publication of 10st conference papers, 7st journal papers and one dissertation. Parts of the thesis and two early journal articles [11, 12] is essentially based on results from the Vinnova financed project SEFS – sensor fusion for safety (in the IVSS program) but final editing was made during this project.

Active researchers funded by the project are Lennart Svensson, Malin Lundgren and Fredrik Sandblom. Other authors time has been funded from other sources. See Annex 'teknisk projektreovisning" (only available in Swedish) for a summary of the contents of the publication list below.

6.2.1. Conference publications

[1] Sandblom, F.; Brännström, M., "Probabilistic threat assessment and driver modeling in collision avoidance systems," *Intelligent Vehicles Symposium (IV), 2011 IEEE* , vol., no., pp.914,919, 5-9 June 2011
doi: 10.1109/IVS.2011.5940554
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5940554&isnumber=5940387

[2] Sandblom, F.; Svensson, L., "Marginalized sigma-point filtering," *Information Fusion (FUSION), 2011 Proceedings of the 14th International Conference on* , vol., no., pp.1,8,

5-8 July 2011
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5977671&isnumber=5977431

[3] Andersson, M.; Sandblom, F., "Transforming local sensor tracks prior to track-to-track fusion in an automotive safety system," *Information Fusion (FUSION), 2013 16th International Conference on* , vol., no., pp.655,660, 9-12 July 2013
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6641343&isnumber=6641065

[4] Sandblom, F.; Sörstedt, J. "Sensor data fusion for multiple configurations"
Godkänd för publicering på *Intelligent Vehicles Symposium (IV)*, 8-11 June 2014, Dearborne, Michigan, United States.

[5] Lundgren, M.; Stenborg, E.; Svensson, L.; Hammarstrand, L. "Vehicle self-localization using off-the-shelf sensors and a detailed map "
Godkänd för publicering på *Intelligent Vehicles Symposium (IV)*, 8-11 June 2014, Dearborne, Michigan, United States.

[6] Särkkä, S.; Hartikainen, J.; Svensson, L.; Sandblom, F., "Gaussian Process Quadratures in Nonlinear Sigma-Point Filtering and Smoothing"
Godkänd för publicering på *17th International Conference on Information Fusion*, 7-10 July 2014, Salamanca Spain.

[7] García-Fernández, Á.F., Svensson, L.; Morelande, M.R., "Iterated statistical linear regression for Bayesian updates"
Godkänd för publicering på *17th International Conference on Information Fusion*, 7-10 July 2014, Salamanca Spain.

[8] Crouse, D.F.; Willett, P.; Pattipati, K.; Svensson, L., "A look at Gaussian mixture reduction algorithms," *Information Fusion (FUSION), 2011 Proceedings of the 14th International Conference on* , vol., no., pp.1,8, 5-8 July 2011
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5977695&isnumber=5977431

[9] Hagmar, J.; Jirstrand, M.; Svensson, L.; Morelande, M., "Optimal parameterization of posterior densities using homotopy," *Information Fusion (FUSION), 2011 Proceedings of the 14th International Conference on* , vol., no., pp.1,8, 5-8 July 2011
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5977458&isnumber=5977431

[10] Taghavi, E.; Lindsten, F.; Svensson, L.; Schon, T.B., "Adaptive stopping for fast particle smoothing," *Acoustics, Speech and Signal Processing (ICASSP), 2013 IEEE International Conference on* , vol., no., pp.6293,6297, 26-31 May 2013
doi: 10.1109/ICASSP.2013.6638876

URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6638876&isnumber=6637585

6.2.2. Journal papers

[11] Sörstedt, J.; Svensson, L.; Sandblom, F.; Hammarstrand, L., "A New Vehicle Motion Model for Improved Predictions and Situation Assessment," *Intelligent Transportation Systems, IEEE Transactions on* , vol.12, no.4, pp.1209,1219, Dec. 2011
doi: 10.1109/TITS.2011.2160342
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5958607&isnumber=6082048

[12] Hammarstrand, L.; Sandblom, F.; Svensson, L.; Sorstedt, J., "Extended Object Tracking using a Radar Resolution Model," *Aerospace and Electronic Systems, IEEE Transactions on* , vol.48, no.3, pp.2371,2386, JULY 2012
doi: 10.1109/TAES.2012.6237597
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6237597&isnumber=6237562

[13] Sandblom, F.; Svensson, L., "Moment Estimation Using a Marginalized Transform," *Signal Processing, IEEE Transactions on* , vol.60, no.12, pp.6138,6150, Dec. 2012
doi: 10.1109/TSP.2012.2215605
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6307890&isnumber=6357313

[14] Brannstrom, M.; Sandblom, F.; Hammarstrand, L., "A Probabilistic Framework for Decision-Making in Collision Avoidance Systems," *Intelligent Transportation Systems, IEEE Transactions on* , vol.14, no.2, pp.637,648, June 2013
doi: 10.1109/TITS.2012.2227474
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6374680&isnumber=6521414

[15] Lundgren, M.; Svensson, L.; Hammarstrand, L., "A CPHD Filter for Tracking With Spawning Models," *Selected Topics in Signal Processing, IEEE Journal of* , vol.7, no.3, pp.496,507, June 2013
doi: 10.1109/JSTSP.2013.2252599
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6479228&isnumber=6515637

[16] Kianfar, R. et.al. "Design and Experimental Validation of a Cooperative Driving System in the Grand Cooperative Driving Challenge," *Intelligent Transportation Systems, IEEE Transactions on* , vol.13, no.3, pp.994,1007, Sept. 2012
doi: 10.1109/TITS.2012.2186513
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6159089&isnumber=6289408

[17] Ángel F. García-Fernández, Lennart Svensson, ”*Gaussian MAP filtering using Kalman optimisation*” Submitted to the IEEE Trans. on Automatic Control.

6.2.3. Books

[18] Sandblom, F., Filtering and modelling in automotive safety systems, Chalmers University of Technology, Gothenburg, 2011.
ISBN: 978-91-7385-608-9
URL1: http://publications.lib.chalmers.se/cpl/record/index.xsql?pubid=148311
URL2: http://publications.lib.chalmers.se/records/fulltext/148311/148311.pdf

7. Conclusions and future research

The project is considered by the contributing parties to have satisfied the project partners' goals as well the FFI program objectives. The publication list is surprisingly long compared to the time spent, and the ratio of time invested is high. It is mainly due to (1) that we have collaborated with researchers not involved in the project and thus expanded the existing research structures, and (2) we have focused on research in which we could be fairly confident of achieving useful results, namely where previous project results shown promising preliminary results or a need for further work.

We conclude that a directed activity such as this project, with the express purpose of publishing research, work very well in a context where there is an already existing research environment where parties with practical experiences meet and exchange ideas. A following, more uncertain hypothesis, is that such projects are especially suitable to be operated in conjunction with a larger project in which several parties are included. That way there are a lot of on-going activities and plenty of contacts with hands-on experience where ad-hoc environments can be created for individual contributions. This also increases the efficiency of previous projects since knowledge is spread between projects over time and ideas are evaluated by several researchers.

The Department of Signals and Systems at Chalmers constitutes perhaps the most important component to achieve an environment where researchers can meet so that spontaneous collaboration can take place: a location for co-location. In the publication list in chapter 6, we see that collaboration occurred between industrial partners (AB Volvo - Volvo Cars - ÅF), industry - academia (AB Volvo - Chalmers - Aalto University) and between several academic partners across national borders. This strengthens research and automotive industry in the west of Sweden.

8. Participating parties and contact person

Active participants have been AB Volvo and Chalmers University of Technology. Contact persons are Fredrik Sandblom and Malin Lundgren:

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