



# ToMM – Collaborative Team of Man and Machine

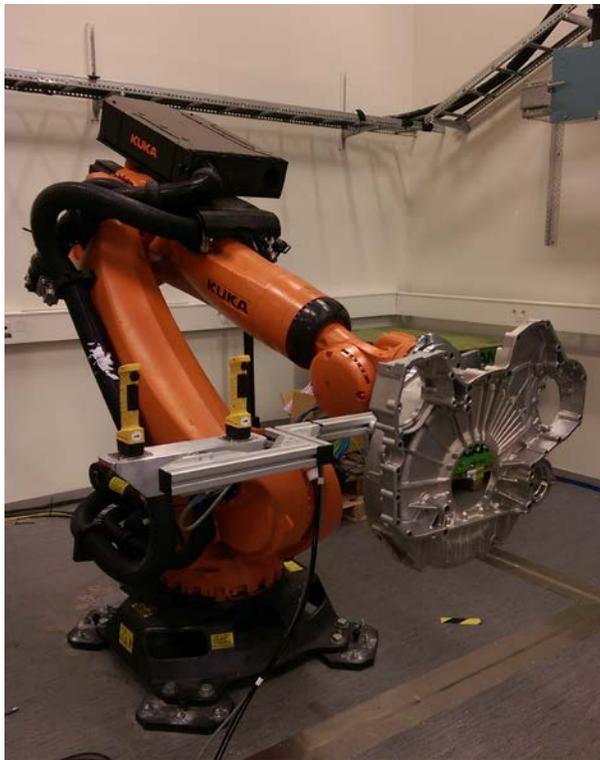


Photo from the robotic laboratory at Linköping university

Project within FFI Sustainable Production Technology

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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](http://www.vinnova.se/ffi)

# 1. Executive summary

The project ToMM is a study to evaluate the possibilities, the flexibility and the requirements for establishing a collaborative team of a robot and an operator in an assembly system. Furthermore, relevant studies regarding legislation that enables man and robot to securely work together sharing assembly tasks without fences will be evaluated.

The objectives of the project are to:

- Increased knowledge of emerging technologies for HRC
- Develop physical and/or virtual demonstrators viewing possibilities and needs for HRC
  - One for placement of light-weighted objects with a huge size
  - One for heavy lifting in few variants
  - One for heavy and large component assembly
- Identify areas to further develop in order to affect future regulations and technology

The technologies in the area of HRC are emerging rapidly and the standardization work globally is intensive. Several robot suppliers are launching new collaborative robots with different solutions for safety management. However, up to now it is only possible to implement a light-weight robot in a collaborative assembly task after performing a careful risk assessment. The project evaluated three cases and the analysis gave i.e. safety is a crucial aspect to solve in a HRC cell, it is challenging to implement a HRC in an assembly task on a moving line and the operator must be involved.

The three cases were selected by the industrial partners as potential task suitable for human-robot collaborative assembly. The placement of panels and the heavy lifting was demonstrated both virtually and physically on a conceptual base. The assembly of a heavy and large component was only demonstrated virtually. The analysis is cross case based and support the theory in the area that indicates the need for industrial case driven research in this field for the moment.

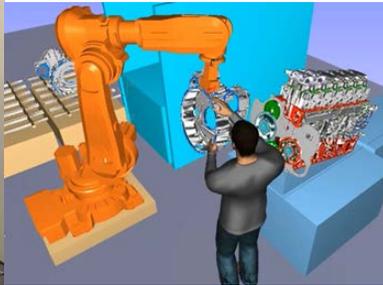
# 2. Svensk sammanfattning

Projektet ToMM har virtuellt och fysiskt demonstrerat olika möjligheter att samverka människa och robot i en monteringslina för fordonstillverkning. Inom projektet har vi arbetat i med tre olika monteringsituationer inom fordonsindustrin. De olika monteringsarna representerar (1) en under-upp-montering av en skyddspanel under en bil, där utmaningen är rörlig lina och många olika typer av lättviktskomponenter som ska

hanteras, (2) en cell som monterar tunga svänghjul på ett motorblock som kräver en stor robot och hög precision i monteringen, samt (3) montering av en instrumentbräda i en lastbilshytt på rörlig lina. Dessa har utvärderats kring hur man skulle kunna montera i samverkan mellan människa och robot, där roboten fungerar som en tredje hand för operatören. Monteringen i fall (1) och (2) har vi utvärderat konceptuellt både virtuellt och i fysiska demonstratorer medan fall (3) har vi endast utvärderat virtuellt. Se figurer nedan.



(1) Fysisk demonstrator för panelmontering



(2) Virtuell utvärdering av montering innan fysisk demonstrator



(3) Virtuell demonstrator för montering av instrumentbräda

Summeringen är att det finns många utmaningar men också möjligheter för att införa en monteringscell som nyttjar människa och robot i samverkan. Säkerhetslösningar kopplade till att robot och människa ska kunna samarbeta utan fysiska hinder är viktigt att utveckla (se fall 1, 2 och 3), speciellt om man ska jobba på en rörlig monteringslina (se fall 1 och 3). En rörlig lina ställer även krav på synkronisering mellan robotens rörelser och monteringslinans rörelse vilket är en utmaning. När det gäller tunga lyft så ser vi stora möjligheter att låta roboten bära tyngden, men då finns utmaningen att en stor robot kräver större säkerhetstänk pga större risker kopplade till bland annat vikt och räckvidd. En viktig del att utveckla är en form av ”risk assessment tool” för att införa människa-robot i samverkan på ett säkert sätt. Trenden när det gäller utveckling av robotar som är utvecklade för samverkan med människor går väldigt fort och vi har under projektet sett nya robotar lanseras, t ex FANUCs robot med mjukt hölje för att fungera säkert tillsammans med en operatör.

Det övergripande målet var att utvärdera möjligheter, flexibiliteten och kraven för att införa människa och robot i samverkan i en monteringsituation. Detta genom att:

- Öka kunskapen om nya teknologier som utvecklas för människa och maskin i samverkan
- Utveckla fysiska och virtuella demonstratorer som visar vilka krav som måste uppfyllas och vilka möjligheterna är till att införa människa och maskin i samverkan i tre olika applikationer:
  - (1) montering av lättviktskomponenter,
  - (2) montering av tunga komponenter i få varianter
  - (3) montering av tunga, stora komponenter
- Identifiera områden att vidareutveckla för att bemöta framtida regler och standarder

Vi har genomfört alla tre fallstudierna och vi ser att utmaningen bland annat ligger i att skapa en bra säkerhet för operatören när den ska samverka med en robot utan fysiska hinder. Vidare behöver man identifiera vilken arbetsuppgift som människan ska göra och vilken som roboten ska genomföra. När det handlar om tunga komponenter så är det lämpligt om roboten lyfter och människan positionerar. När det gäller under-uppmonteringen så utvärderade vi två olika sätt - den ena med roboten som skruvar (gör det monotona arbetet) och den andra där roboten lyfter och placerar panelen. Skruvningen var inte lämplig att genomföra med robot då t ex matningen av skruvar komplicerade hela arbetsprocessen med de krav på matning av skruv som monteringslinan krävde. Att simulera en människa i samarbete med en robot har inte stöd av dagens virtuella verktyg idag, vilket gör att det svårt att fullt ut analysera virtuellt idag.

De tre fallen som vi arbetade med var utvalda av de industriella parterna som lämpliga moment där ny teknik i form av samverkan mellan människa och maskin kan införas. Placeringen av paneler och tunga komponenter demonstrerades virtuellt och fysiskt på konceptuell nivå och den stora tunga instrumentbrädan demonstrerades endast virtuellt. Analysen genomfördes baserat på alla tre fallen och ansatsen att låta industrin välja ut fallen stöds av teori inom detta område. Teorin pekar på att det är bra att involvera industrin i identifiering kring vilka möjliga monteringsituationer som kan vara lämpliga att införa robot och människa i samverkan för, om vi ska snabba upp införandet av detta i industrin.

## 3. Background

Swedish vehicle manufacturers compete in a global arena. To keep the enterprise profitable and to gain market shares, efficiency, cost and quality are key components. Also the manufacturing has shifted more and more towards mass customization which entails that a large variety of vehicles adapted to different markets have to be produced in one or few mixed model assembly lines (MMA) (Lee and Vairaktarakis, 1997; Wenping and Yuming, 2008; Emde et al, 2010). Due to that flexibility and adaptability for mass customized products are increasing, operators guiding or collaborating with robot assisting them in different assembly tasks is identified having advantages compared to full automation (Bley et al, 2004).

Assembly is one of the most labour intense manufacturing processes, and one of the most difficult to automate due to that robots normally is restricted to high programming effort and its ability for handling complex or soft components are limited (Krüger et al, 2009). This is mainly due to the fact that the robot has not been able to react and respond to stimuli as a human can, and therefore has been unable to handle the inherent uncertainty of many assembly processes. Any automation that has been done has often resulted in



limited flexibility of the system or made possible by somehow controlling the environment which often comes with great expense.

The emerging technologies that could be combined with a robot for securing safety in a shared workplace continuously evolves and the standards for supporting Human-Robot Collaboration are reviewed and new regulations are developed, with a planned release during December 2015 according to Björn Matthias, ABB, representing the standardization committee.

In order to achieve more flexible automation in assembly lines for automotive products it is a need to evaluate how and if a robot could act together with an operator as a third hand support. Some examples of benefits could be improved ergonomic solutions, less dedicated fixtures, improved productivity and more stable quality level.

## 4. Objective

The overall objective is to evaluate the possibilities, the flexibility and the requirements for establishing a collaborative team of a robot and an operator.

The objectives of the project are to:

- Increased knowledge of emerging technologies for Man-Machine collaboration
- Develop physical and/or virtual demonstrators viewing possibilities and needs for Man-Machine collaboration
  - One for placement of light-weighted objects with a huge size
  - One for heavy lifting in few variants
  - One for heavy and large component assembly
- Identify areas to further develop in order to affect future regulations and technology

## 5. Project realization

In order to evaluate the possibilities to implement human-robot collaborative teams in assembly lines within the automotive industry three different cases have been used. These cases were identified by the automotive industry, here represented by Volvo Cars, Volvo Trucks and Scania. The cases were:

### *Case 1 – Placement of aero panels under a vehicle*

The aero panels limit the reduction of CO<sub>2</sub> when the vehicle is used. This is a standard component in about 6 different variants per vehicle. Furthermore, the panels differ between vehicles due to i.e. size. The panels are stable from a geometric point of view. The panels are large but light-weighted (about 4 kg) since they are made in a polymer.

The assembly work is today performed in a non-ergonomic way with placement with an under-up-work. If a robot in collaboration with an operator could do this placement the process will be very flexible and the ergonomic situation for the operator could be improved. The robot can place the panel with the aim of managing the weight and the operator can use a handhold tool for assemble the clips. There is a need for assemble many clips with high precision.



Figure 1: Manual assembly of aero panels under a vehicle as it is performed today

Here, the case has been simulated in a virtual environment (Figure 2) as well as evaluated in a physical demonstrator cell (Figure 3). The possibilities and challenges have been explored for implementing a robot in the assembly line.

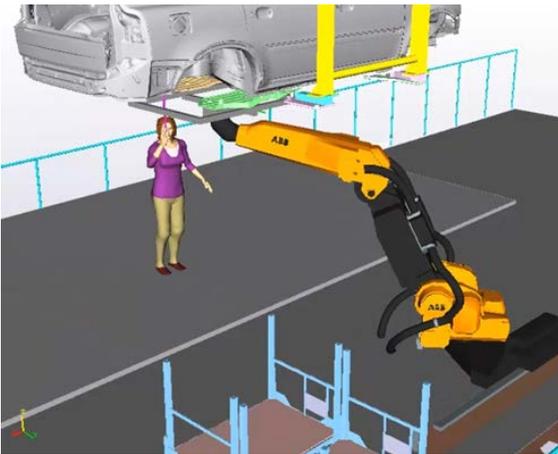


Figure 2: Simulation of case 1



Figure 3: Physical demonstrator of case 1

### ***Case 2 – Heavy and repetitive lifting***

The robot would be used as a lifting device picking and executing a desired trajectory, with the aim to assemble a heavier component and position the object in the right position in relation to guiding pins. The pins will provide a friction that is used in the assembly

and that the robot must manage. Today is the operation done manually and the object is assembled in an angel of approximately 45 degrees to give the operator a more ergonomic situation. However, this operation is still not satisfying from an ergonomic point of view.

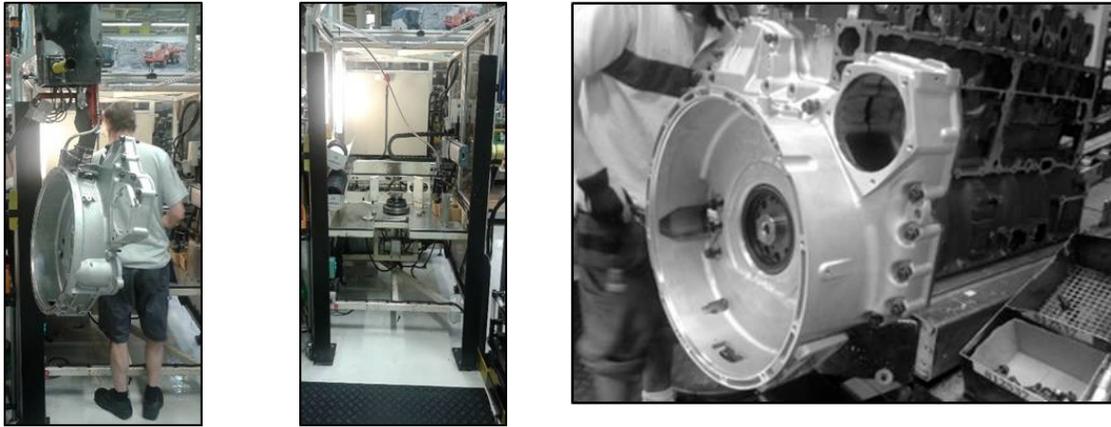


Figure 4: The heavy and repetitive lifting cell as it is arranged today

Here, the case has been simulated in a virtual tool and a first conceptual demonstrator cell has been built in relation to the results from the virtual tool.

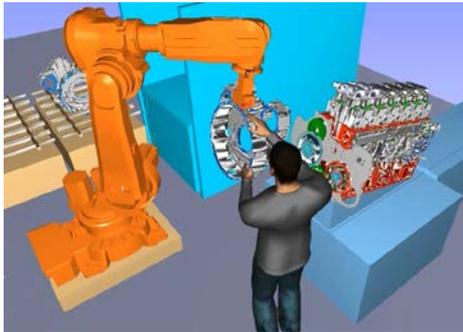


Figure 5: Simulation of case 2



Figure 6: Physical demonstrator of case 2

### ***Case 3 – Interior assembly in truck cab***

Many components that are assembled in a truck cab are large and rather heavy. Examples are dashboard, ceiling lining, beds and various storage drawers. These are to be assembled with the operator inside the cab and another operator is working outside the cab picking up the parts with the lifting device and supporting it to the operator inside the cab. If a robot could perform the picking and furnishing it into the cab the task could be performed as a one person task instead of a two person task.

The add-on difficulty in this case, compared to the first two cases is that the cab is placed on a continuous moving belt conveyor. Is it possible to furnish the parts through the windshield opening when the cab is moving? Does this introduce even more difficulties regarding safety for the operator?



Figure 7: The assembly of huge interior in a truck cab as it is performed today

Here, a virtual analysis has been performed in order to identify the challenges to use a robot as a carrier on a continuous line.

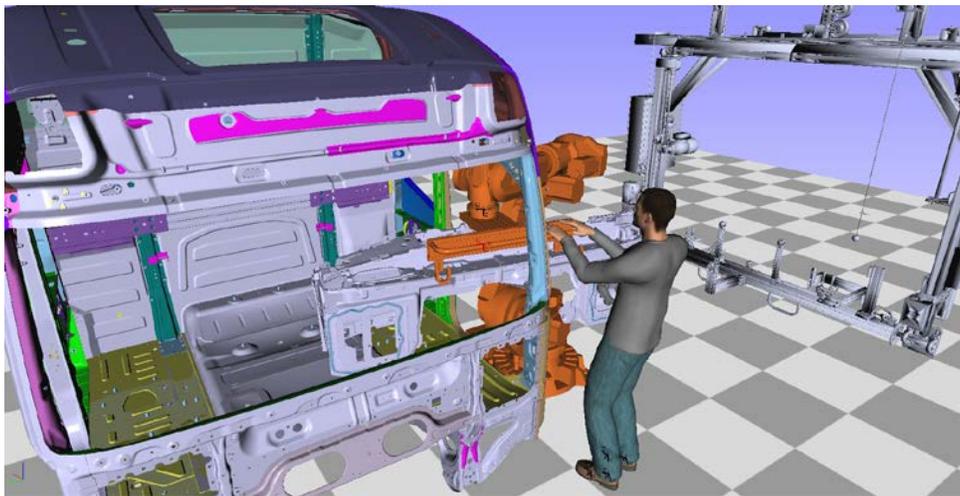


Figure 8: Simulation of the case 3

### *State-of-the-art activities*

In order to support the three cases in the project the researchers and the industry continuously have followed the trend in the area. By attending Collaborative robotics conference in Boston 2014, Automatica in Munich 2014, Robo-Mate in Stuttgart 2015 and the IROS in Hamburg 2015, it is obvious that this area will evolve dramatically over the coming years. This is also shown on Youtube, since the robot suppliers show case their future HRC products, which the participants in the project also have followed. The robot suppliers are developing new robot family's adapted for human-robot collaboration and the regulation work evolves to include more standards. The global community have identified the need for a new standard defining the area of human-robot collaboration, since service robots, industrial robots and other machines all can be more adopted to a

collaborative way of work using other types of safety solution based on emerging technologies instead of physical fences. During the time this project has been running, automotive industries have implemented several light-weighted robots in their assembly lines which they show through different medias.

Project management has used puls-meetings every second Monday in order to share information between and inspire the group of participants continuously during the project. This way of work has been fruitful together with 3-4 physical meetings per year at each other in the different organizations. Furthermore, a sharepoint solution was arranged for sharing data within the project including resumes from conferences and reports. Our approach can be summaries as exploring the following areas:

- Different sensors (Vision, Sound, Force)
- Safety for the operators
- *Machine Learning techniques* to predict operator movement can enhance safety
- ROS - *Robot Operating System* has been explored for the area
- Simulation using the IMMA tool – man and robot sharing the same working area
- Literature study – Different areas are identified based on task identification made by the participating partners and can be exemplified with:
  - Operator controlled robot movement
  - Interaction between human and robot
  - Security systems suitable for human-robot interaction
  - Synchronizing robot – moving line (an existing track motion system is identified)

The work packages in the project are described in figure 9 below:

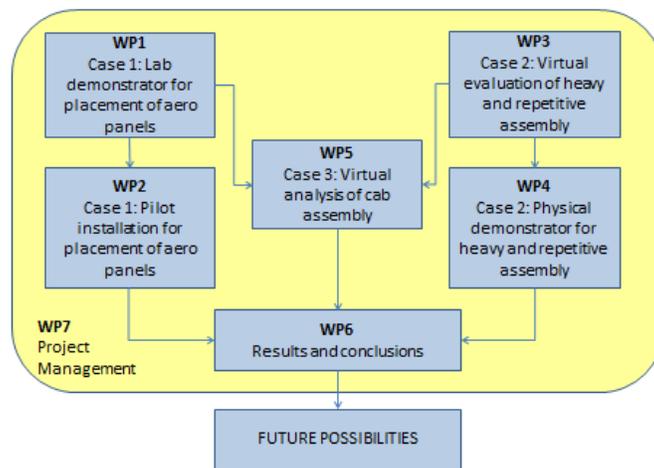


Figure 9: The overall project organization for ToMM with different work packages.

## 6. Results and deliverables

### 5.1 Delivery to FFI-goals

The ToMM project contributes to several of the FFI-goals. The project has explored the possibilities to use a huge robot for performing the more repetitive and heavy tasks in an assembly line including making some simple decisions. This will support a production system that utilizes the operator skill to perform more complex decisions. This will enhance the transition towards a more knowledge based production system through an increased level of automation based on flexible solutions utilizing human-robot in collaboration. This will contribute to the possibilities to have a competitive automotive industry in Sweden.

The project has identified the needs together with the participating companies and through that performed the cases based on problems relevant for the industry. The way of work with industrial cases in order to enhance knowledge in this emerging area is supported by one of the speakers, representing KUKA, at the IROS conference, who mentioned the need to use case tryouts in order to understand the area of Human-Robot collaboration. The robot suppliers need knowledge about the industrial needs in order to develop proper equipment and the customers (i.e. automotive assembly lines) needs knowledge about the emerging technologies that are coming in this area in order to identify how to plan the production / assembly in the most efficient way. Furthermore, this will affect the future operators work and probably also the competence needed in the future assembly line. As the industry during the last 2 years has started to implement light-weighted robots in human-robot collaboration, more understanding and more demands will come in the future, especially related to implementation of heavy robots in collaborative tasks. However, there are still many challenges to solve.

The research environment in Sweden for Human-Robot Collaboration has been established through the ToMM project when it comes to industrial demonstrator related research. Three new persons have started in the area within three different organizations, which contributes to a national dynamic in the area. We have in a way started to establish a knowledge cluster for HRC related to industrial implementation and physical equipment installation. So ToMM has supported our research environment. From an industrial point of view, ToMM has supported the companies in their internal discussions about how to implement Human-Robot Collaboration in their organizations, and today at least VCC has started an internal project about how to implement light-weighted robots in collaborative assembly tasks.

Over all, the ToMM project has increased the collaboration between the academy, institute and automotive industry including involving students in different courses to enlarge the area of knowledge about human-robot collaboration including safety aspects.

## 5.2 Delivery according to project specification

### 5.2.1 Case 1 – Placement of aero panels under a vehicle

Here virtual simulations have been performed in order to evaluate the possibilities to share an assembly task between robot and operator. The physical demonstrator was used to evaluate some initial difficulties and challenges to share an assembly task and for exploring which resource that should do what. Some experiences from this – difficult to reach industrial TRL levels since the regulations are not in place, the operators have different opinions whether they rely on a robot or not. We have made films (both based on the virtual simulation and the physical demonstrator) that we have used in interviews with operators about the new way to share an assembly task. The task time is challenging in this task both from an equipment point of view and also to secure safety for the operator.

### 5.2.2 Case 2 – Heavy and repetitive lifting

Here virtual simulations have been performed and the initial evaluation indicates that there is difficult today to simulate coordinated motions of the robot and the operator. Analysis from the simulation indicates that it will be beneficial to share working task between operator and robot. Physical demonstrator set up is in place and the first tests indicate that it is possible to use the robot as a carrier and the operator as the positioner. However, here it is also a need for proper safety solutions that is possible to implement in an industrial environment.

### 5.2.3 Case 3 – Interior assembly in truck cab

Here virtual simulations have been performed – however, simulation tools are not fully functional especially for simulation of a moving line with the product in combination with a moving robot that is controlled by a moving operator. Here, there are further needs in order to get more reliable results from a simulation. Furthermore, the moving line is a challenge in a human-robot collaboration solution – as also was a result from case 1.

### 5.2.4 General cross-case analysis

It is not possible to simulate a whole cell describing a continuous line with a moving product and a moving robot in collaboration with an operator. To perform simulation it is a need for specific knowledge in the tools, and the tools are complex as they are today.

It is crucial that safety solutions are further developed in combination to the applications and assembly tasks. The regulations that supports existing standards are to be released in December 2015 will

Risk analysis must manage the human safety both during installation and implementation in industrial applications. Here, there is a need for further development of methods for risk analysis related to HRC.

To summaries we have now an increased knowledge about emerging technologies for Human-Robot Collaboration and it is spread both within the automotive industry and in

academy. Our cases have developed physical and virtual demonstrators which have been used to increase our knowledge through discussions and analysis. Areas for further research have been identified and the consortium have collaborated and applied for further funding to continue the research together based on this knowledge.

## 7. Dissemination and publications

### 6.1 Knowledge and results dissemination

Table 1: Overview of result dissemination activities during ToMM

Conference/Meeting	Place	Date	Presenter
Katrineholmskonferensen	Katrineholm	May 2014	Kerstin Johansen with team
Digital Human Modelling Conference	Tokyo, Japan	June 2014	Fredrik Ore
Swedish Production Symposium	Göteborg	September 2014	Varun Gopinath Sten Grahn
Technology day	Scania, Södertälje	October 2014	Fredrik Ore
Monteringskonferensen	Stockholm	March 2015	Fredrik Ore
Presentation at Volvo Trucks	Göteborg	April 2015	Björn Langbeck
Katrineholmskonferensen	Katrineholm	May 2015	Kerstin Johansen with team
Licentiate seminar	Eskilstuna	September 2015	Fredrik Ore
IROS – International Conference on Intelligent Robots and Systems	Hamburg, Germany	September 2015	Varun Gopinath Fredrik Ore

The represents from Volvo Cars have discussed the ToMM project internally at their regular meetings in the organization.

The research area covering Human-Robot Collaboration (HRC) is evolving right now and within the consortium we have other close related projects ongoing. This can be exemplified with the EU project LOCOMACHS (one WP is focusing on this with coordination from LiU in collaboration with aerospace industry). Furthermore, one WP within the application to SweDemo in September 2015 will focus on HRC applicable to aerospace assembly. Research that is more towards simulation in the area with connection to ToMM and i.e. SCANIA is the projects Virtual verification and DYNAMITE. Swerea IVF has identified automation as a strategic area with several internal projects ongoing. Within Volvo internal discussions are ongoing about starting up internal projects in the area. Looking outside the consortium that has worked together in ToMM, the Symbotic project is related to the area HRC and is funded by EU in collaboration with Volvo Cars

and Skövde. Furthermore, the project group has an approved continuation for ToMM in the project ToMM2, where we continue to work together in order to develop the area.

It is focus on develop the standards in the HRC area and Horizon 2020 fund a lot of projects about HRC. To summaries, there is a large knowledge movement in the area, which indicates that the tipping point for industrial implementation is coming soon.

## 6.2 Publications

*Licentiate (partly financed by ToMM):*

Ore, F. (2015) Human – industrial robot collaboration: Simulation , visualization and optimization of future assembly workstations, Mälardalen University, Sweden, Thesis No.211, ISBN 978-91-7485-218-9

*Conference papers:*

Ore, F., Hanson, L., Delfs, N. and Wiktorsson, M. (2014) Virtual evaluation of industrial human-robot cooperation: An automotive case study, Digital Human Modelling, Tokyo, Japan

Gopinath, V., Johansen, K. and Gustafsson, Å. (2014) Design Criteria for a Conceptual End Effector for Physical Human-Robot Production Cell, Swedish Production Symposium, Gothenburg, Sweden

Grahn, S. and Langbeck, B. (2014) Benefits of Collaborative Robots in Assembly – An Evaluation Scheme, Swedish Production Symposium, Gothenburg, Sweden

*Poster presentation:*

Gopinath, V. (2015) Collaborative Assembly Cell – An User Perspective, presented at Late breaking poster session, IROS, Hamburg.

Ore, F. (2015) Simulation of Human – Industrial Robot Collaboration Optimisation of Handover Position, presented at Late breaking poster session, IROS, Hamburg.

*Internal reports:*

Khoshnevis, M., Pehrson, A., Andersson, M., Savén, W., Larsson, N., Qiu, J. and Ganeshan, J. (2014) Evaluation, simulation and prototyping of a Man and Machine collaborative concept, Internal report Linköping university

Christensen, F., Gawell, E., Hjelm, E., Jakobsson, J., Runge J-E., Sjöstrand, G. and Åström, E. (2014) Gripdon, Internal report Linköping university

Andersson, M. (2015) Interview report from operator impression about case result (*Working Paper*)

*Thesis reports:*

Backman, B and S:t Clair Renard, C. (2015) Simulating Human-Robot Collaboration - An example from cab assembly, Master thesis, KTH, URN: urn:nbn:se:kth:diva-169486

Christensen, F. and Runge, J-E (2014) Automatiserad skruvmatning på rörlig end-effector, Thesis report LIU-IEI-TEK-G—14/00677—SE

Jakobsson, J. and Hjelm, E. (2014) Säkerhetsaspekter i en produktionscell där människa och robot ska samverka, Thesis report LIU-IEI-TEK-G—14/00672—SE

Sjöstrand, G. (2014) Design för produktförståelse i en miljö där människa och robot samverkar, Thesis report LIU-IEI-TEK-G—14/00676—SE

## 8. Conclusions and future research

The project ToMM2 will further develop knowledge based on demonstrator based research about how to secure a safe collaborative assembly team of man and machine sharing the same workspace. Some of the identified main areas to further research are how to solve the safety issues while using a large robot instead of the light-weight robots that are entering the market more and more. In assembly tasks where there is a need for a robot with higher payload it seems that there will be a need for an enabling device as part of the safety system. The regulations are still in its referral loop due to safety issues. However, we have identified that there is an increasing trend in the research area and light-weight robots in man-machine collaborative applications have entered the automotive industry in Europe. However, this implementation has been possible based on a careful and deep risk analysis and use of current safety standards. To achieve an industrial implementation using large robots, ToMM2 will focus on cases, common assembly processes in the automotive industry that will be used as drivers for creating concepts for shared tasks between man and robot.

## 9. Participating parties and contact person

	Volvo Cars	Åke Gustafsson
	Scania	Lars Oxelmark
	Volvo Trucks	Lena Moestam
	Swerea IVF	Björn Langbeck
	Linköpings universitet	Kerstin Johansen