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Autonomous Industrial Mobile Manipulation (AIMM):
From Research to Industry

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Abstract: This paper presents "Autonomous Industrial Mobile Manipulation" (AIMM) as a research topic and emerging technology for modern industry. The motivation for this work is that the underlying concepts and required technologies exist; now it is time to put the AIMM technology to the test in real-world industrial environments. The context for AIMM is mobile manufacturing assistants in industrial environments with three main application areas: logistics, assistive and service. The paper presents a technology transfer approach for bringing automation of today towards the transformable factory of the future. The approach is based on Front End of Innovation methodologies, including "New Concept Development" (NCD), "Technology Push Manufacturing Technology" (TPMT) and "Modules and Skills Extraction" (MSE). The paper is focused on supporting the collaboration between research and industry and how to get a mutual understanding/common vocabulary for an emerging technology. Furthermore, the paper looks into the domain of mass customization, especially modularization and re-configurability, to realize a feasible system architecture. Finally, the methodologies presented are exemplified by an industrial case study, a full-scale AIMM demonstration in a real-world manufacturing environment.

Keywords: Autonomous Industrial Mobile Manipulation, Industrial robotics, Technology transfer, Front End of Innovation, Transformable production, Innovation and user driven research

1. Introduction

1.1. Motivation

Today, robots are widely used in industry to perform dumb, dangerous, dull and dirty tasks. Furthermore, robot-based manufacturing increases product quality, improves work conditions, and leads to an optimized use of resources. Therefore, robotics forms an essential part of the manufacturing backbone in high-wage countries (EUROP, 2009). However, the industrial robots of today are rather inflexible as they are often dedicated and/or fixed. In recent years the inflexibility and inadequacy of industrial robotics has become more and more evident due to globalization of markets, trade instability, and explosion of product variety. Also the shift in paradigm from mass production to customized production (down to one-of-a-kind) and the resumption of production in industrialized countries have created industrial needs for agility and flexibility, especially in the field of automation and robotics (Jovan et al., 2003) (Wucherer, 2003). Furthermore, today's automation paradigms make it difficult, time consuming, and costly to change the type of products manufactured and to scale the production up and down in response to market volatility. With the increasing market uncertainties, it becomes consequently more and more difficult to justify new automation lines. In general, production systems are either fully automated or strictly manual. While the former is very efficient in high volumes, but less flexible, the latter is very flexible, but less cost-efficient, especially in high-wage countries. To improve the production systems, it is rational to combine the best of both worlds; hereby creating *transforma-ble* production systems (see Figure 1). In this way, it is possible to enable a profitable production regardless of changes in production volume and/or product type (Bischoff, 2010).
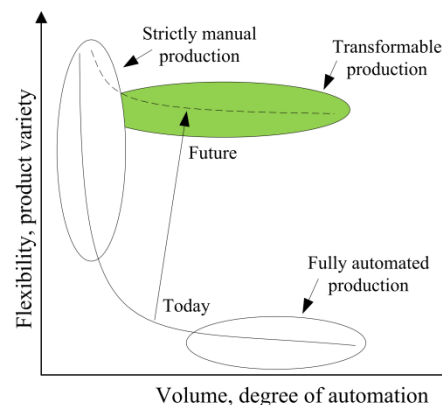

Figure 1 Illustrating the need for transformable production systems (Bischoff, 2010).

A novel automation technology, which can contribute to realization of transformable production systems, is Autonomous Industrial Mobile Manipulation (AIMM). This technology extends the application prospective of industrial robotics by combining locomotion capabilities with manipulation abilities. The conventional architecture of AIMM is a robot manipulator mounted upon a mobile platform, extended by a vision and tooling system, respectively (Hentout et al., 2010). An overview of state-of-the-art AIMM platforms is shown in Figure 2.

The mobility extends the workspace of the robot manipulator, which increments its operational capability and flexibility. Compared to traditional industrial robots it is easier for autonomous mobile manipulators to adapt to changing environments and perform a wide variety of manufacturing tasks (Hamner et al., 2009). Furthermore, the industrial environments do not have to be altered or modified as in the case of AGV's, where permanent cable layouts and/or markers are required for navigation (Datta et al., 2008).

1.2. Related work

The concept of mobile manipulation dates back to 1984, where the MORO (MObiler ROboter) was navigating freely in the shop floor delivering and handling tools and work pieces (Schuler, 1987). However, high system costs and lack of processing power prevented its actual use and implementation at that time. Since then, a lot of research has been carried out (Figure 2), and still today there are many ongoing mobile manipulation projects within different domains, e.g. space exploration, military operations, home-care (domestic service), health-care (professional service) and industry (manufacturing, construction, etc.). Worldwide, research and development efforts are being made to use autonomous mobile manipulators to relieve human operators of tedious, repetitive, and hazardous tasks. Despite considerable attention within the manufacturing domain, real implementations of mobile manipulators have been limited - e.g. (Helms et al., 2002), (Stopp et al., 2003), (Katz et al., 2006), (Datta et al., 2008) and (Hentout et al., 2010) - although the needs for autonomous and flexible automation are present. In addition, the necessary technology entities are, to a large extent, commercial off-the-shelf components (Cardeira & Costa, 2005). The lack of implementations is mainly related to the conservatism in the manufacturing industries (Mekid et al., 2007). Furthermore, within the field of industrial mobile manipulation the main focus has been on optimization of the individual technologies, especially robot manipulators and tooling, while the actual use and application have been neglected. Therefore new initiatives are required in order to realize industrial acceptance and maturation of AIMM.
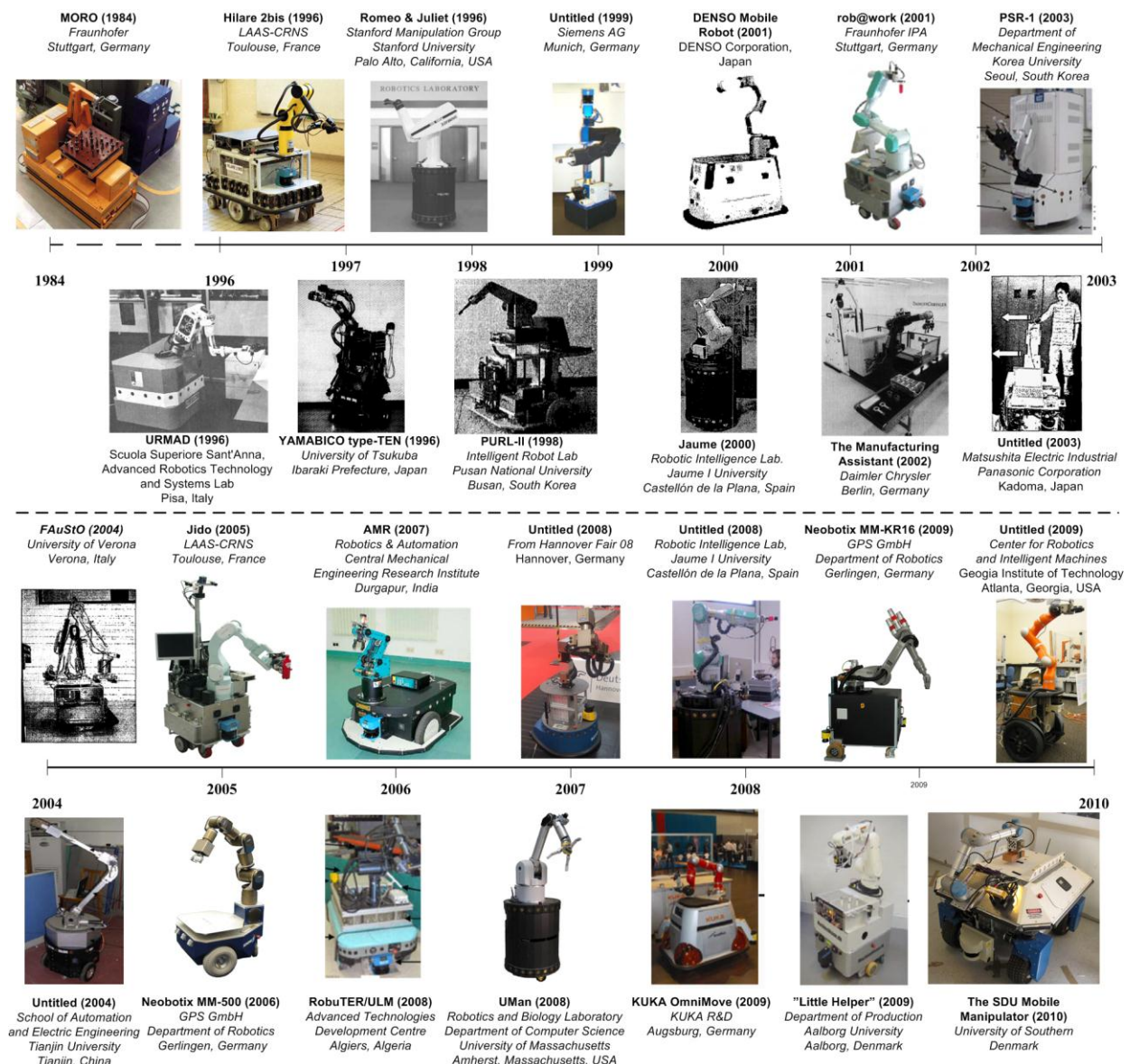

Figure 2 An overview of state-of-the-art AIMM platforms.

1.3. The context and concepts of AIMM

AIMM is intended to be a flexible and versatile automation technology, that is simple to use, so it becomes Plug-and-Play and Out-of-the-Box. Moreover, AIMM is an autonomous manufacturing assistant, which can be easily integrated into various applications in diverse manufacturing environments, as it is able to:

- Work with or alongside people
- Serve usual production equipment/machinery
- Carry out operations at different workstations
- Operate fully-automatic and -autonomous

The general context and concepts of AIMM are shown in a representative industrial environment, in Figure 3. In this environment mobile manipulators carry out their missions by navigating between the workstations and performing diverse manufacturing tasks.
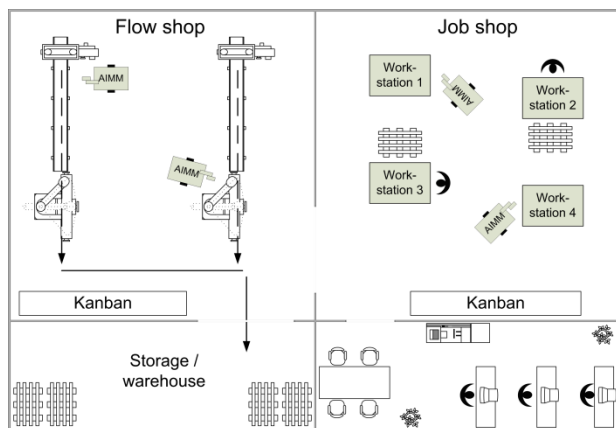

Figure 3 A representative industrial environment.

AIMM robots must be able to communicate with the manufacturing and ICT equipment (machine-machine) and the operators (human-machine), including the Enterprise Resource Planning and Warehouse Management Systems. This is realized by integrating the AIMM on the general industrial network (see Figure 4).
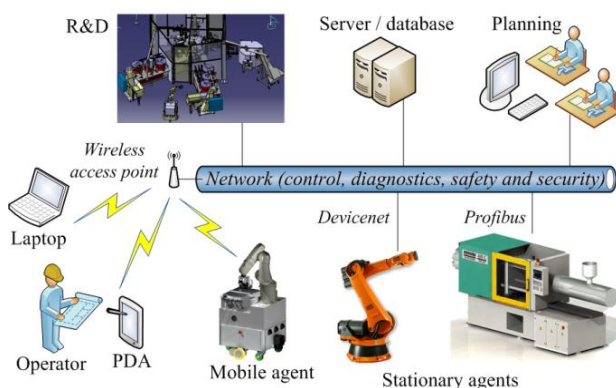

Figure 4 Agent based industrial network architecture.

The overall vision of AIMM is illustrated in Figure 5, which depicts a typical work schedule. The mobile manipulators can be used for fetch and carry tasks, preparatory and post-processing work, and even (pre)assembly.

Another essential aspect of AIMM is that it will be able to work autonomously in a third shift. In this way, manufacturing enterprises can make the most efficient use of expensive machinery (Bischoff, 2010).
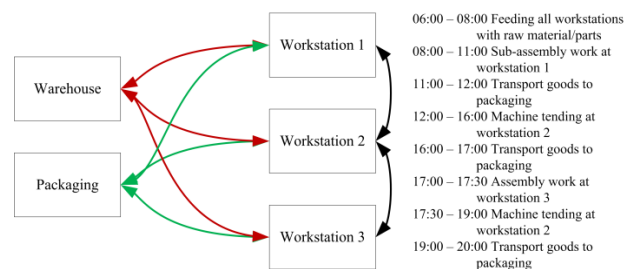

Figure 5 A typical AIMM work day (Bischoff, 2010).

1.4. Paper outline

The previous sections show that the underlying concepts of AIMM are in place, and the technology has been tested in several laboratory experiments. Now it is time to put the technology to the test in real-world industrial environments, to explore the actual potential of AIMM. The rest of this paper is focused on aspects related to moving the AIMM technology from research to industry. First of all, it is necessary to identify suitable tasks and applications for AIMM in real-world industrial environments, to link the conceptual ideas (academia) to actual manufacturing needs and requirements (industry). Furthermore, it is essential to look into the domain of mass customization, especially modularization and re-configurability, to realize a feasible system architecture.

The remainder of the paper is organized as follows. Section 2 gives an overview of the transformation procedure from research to industry, based on an industrial AIMM case study. Section 3 presents results from a full-scale AIMM experiment in a manufacturing environment. Finally, a conclusion is presented together with outlines for future work in Section 4.

2. From research to industry

The distance between research and industry is called the Technology Transfer (TT) gap (Figure 6), which needs a bridge if economic development is to take place. One way to realize this, is to combine backward (market pull) and forward (technology push) methodologies.
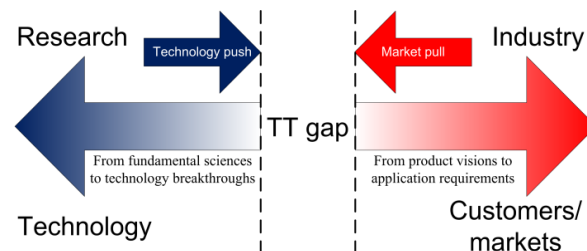

Figure 6 Bridging the gap between research and industry.

In the following, a procedure for moving AIMM (a technology push manufacturing technology) from research to industry (manufacturing enterprises) is presented. The procedure is exemplified by the "Little Helper" project –

an ongoing research project between Aalborg University and Grundfos A/S[1] – with the aim to develop a modular and scalable AIMM system (Hvilshøj et al., 2009). The "Little Helper" project is based on user and innovation driven research methodologies.

2.1. Join forces with the industry

The Technology Transfer "gap" can only be "bridged" by truly effective collaboration between research and industry. As a starting point, it is essential to find and team up with the right industrial partner(s). The partner(s) must be representative for the general domain under consideration. In this way, it is ensured that needs and requirements (e.g. applications) identified at the industrial partner(s) are of general relevance. In the "Little Helper" we have teamed up with Grundfos A/S, as their production facilities are versatile in relation to process discrepancies, parts variation and production strategies. This corresponds to general manufacturing industries. In addition, Grundfos possess a visionary and innovative culture and tradition.

2.2. New Concept Development (NCD) model

When the industrial partner(s) has been chosen, the next step is to achieve a common vision and vocabulary between the application requirements (industry) and the technological possibilities (research). This can be realized by looking into the domain of Front End of Innovation (FEI). The most widely used FEI model is the New Concept Development (NCD) (Figure 7), which provides a common language for the front end activities.
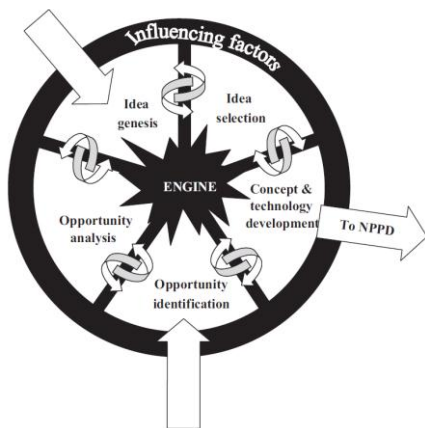

Figure 7 New Concept Development (Koen, 2001).

The circular shape of the NCD model shows the non-sequential and flexible flow, circulation, and iteration of ideas within the five core elements (opportunity identification, opportunity analysis, idea genesis, idea selection, and concept and technology development) and surrounding influencing factors, based on a chosen leadership (the engine). It is important that the leadership is measurable. In the "Little Helper" project, the leadership is based on

three areas related to the factory of the future. An excerpt is shown in Table 1. The exact goals have been removed due to confidentiality issues.

Table 1 Leadership from the "Little Helper" project

Sustainability	• **Improve work environment, i.e. minimize repetitive and burdensome work** • **Prevent outsourcing**
Agility	• Increase the speed with which new products and production technologies are implemented • Provide cost effective automation
Capacity	• Increase production capacity (on same area) • Enable flexible capacity • Increase uptime and OEE

In the NCD model, a fundamental distinction is made between opportunities and ideas, representing the two possible entrances to the model. Finally, a formal plan or project proposal indicates the change over to new product and process development (NPPD) (Koen, 2001).

2.3. Technology Push Manufacturing Technology (TPMT) methodology

The TPMT methodology (Figure 8) contributes to the phases of opportunity identification and opportunity analysis in the FEI activities. The methodology provides a practical tool for identifying and evaluating suitable applications for novel automation and robot technologies in industrial environments, based on a comprehensive analysis at task level. In this way, it is possible to map representative industrial tasks to the new technology.

The general TPMT model consists of four interdependent variables (input/output, environment, technology and process) which, taken together, describe the framework of a manufacturing task. By applying the TPMT methodology at the industrial partner(s) it is possible to identify suitable manufacturing tasks and applications for the new technology, and evaluate these in terms of short-, mid- and long-term implementation goals.
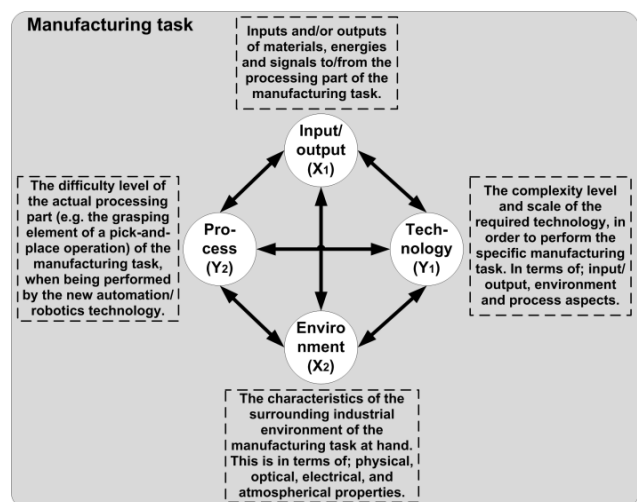

Figure 8 The TPMT methodology and model.

As a starting point, it is necessary to choose a number of general application categories for the specific domain considered. In the "Little Helper" project, the application

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[1] Grundfos A/S is the world's largest manufacturer of circulator pumps. More information at; http://www.grundfos.com.

categories are based on research roadmaps focusing on the future use of robotics, e.g. (EUROP, 2009). An overview is provided in Figure 9, based on the overall categories: assistive, logistics, and service.

AIMM applications		
Assistive tasks	**Logistics tasks**	**Service tasks**
Machine tending	Transportation	Maintenance, repair and overhaul (MRO)
Assembly/ pre-assemby	Part feeding (multi)	Cleaning
Inspection	Part feeding (single)	
Process execution		

Figure 9 Application categories for AIMM.

After this, the actual analysis and assessment of the manufacturing tasks are carried out. All aspects are embedded in an interactive Microsoft Excel spreadsheet[2]. Results from the TPMT analysis in the "Little Helper" project (based on 566 manual manufacturing tasks from five distinct Grundfos factories) are shown in Figure 10. From Figure 10 it is seen that the application categories with the highest immediate AIMM potential are logistics, i.e. transportation and part feeding (multiple and single).
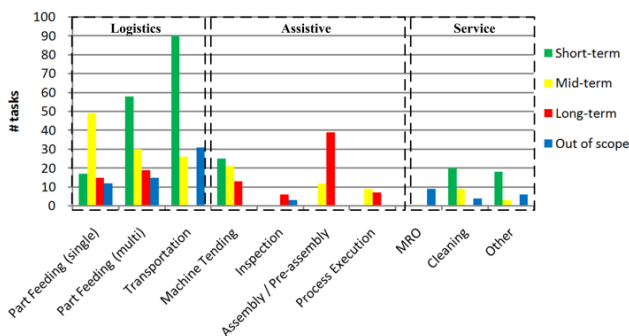

Figure 10 AIMM suitability of the application categories.

2.4. Application scenarios

Based on the TPMT analysis, it is possible to generalize the identified needs and requirements. While each task has specific requirements, e.g. dimensions of work pieces, communication protocols, and environmental characteristics, it is important to find similarities and common challenges in order to realize a modular and scalable AIMM architecture. This corresponds to the creation of general application scenarios for the AIMM technology. In the following, we focus on identified Grundfos scenarios from the "Little Helper" project.

2.4.1. Logistics

Logistics tasks cover the process of transporting parts between workstations and storages, and the process of loading components (several or one at a time) into feeders and machines. A combined application scenario is shown in Figure 11.
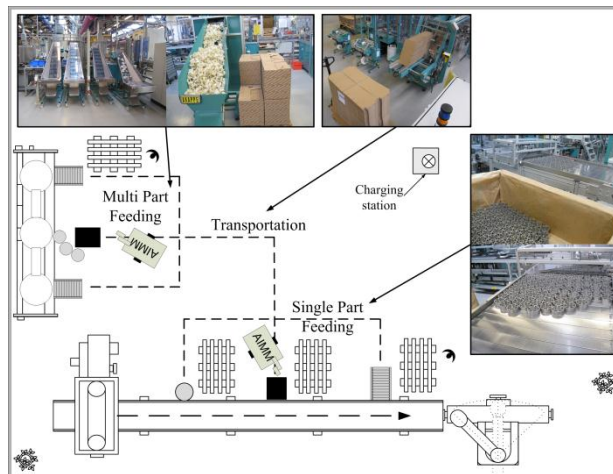

Figure 11 Application scenario for logistics tasks.

2.4.2. Assistive

Assistive tasks cover the processes of loading/unloading materials into machinery for processing, (pre)assembling of components, observing and comparing parts to identify and correct defects, and actual processing tasks (e.g. welding, bending, etc.). A combined application scenario is depicted in Figure 12.

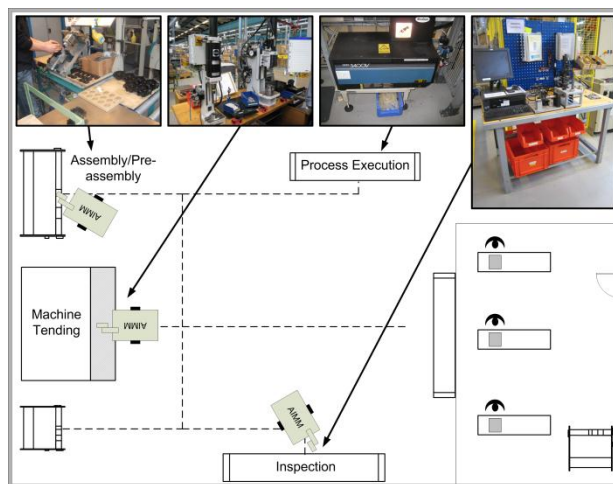
Figure 12 Application scenario for assistive tasks.

2.4.3. Service

Service tasks cover the processes of maintenance, repair and overhaul (MRO) of production machinery, and cleaning (e.g. the removal of waste and scrap). A combined application scenario is illustrated in Figure 13.

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[2] The TPMT spreadsheet template can be downloaded here: www.machinevision.dk/interactive_spreadsheet.
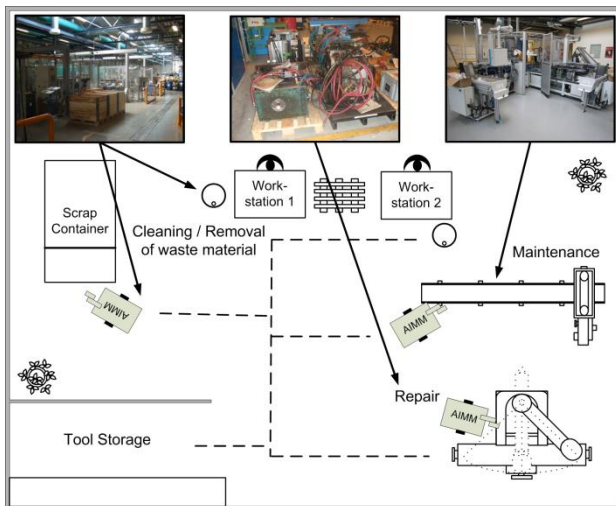
Figure 13 Application scenario for service tasks.

2.5. Mass customization

As the AIMM technology is intended to be a versatile automation solution, it is desirable to maximize the flexibility of the system. However, it is not possible to create a universal autonomous mobile manipulator that can solve all the identified industrial applications within the areas of logistics, assistance and service. Furthermore, it is unacceptable to have a specific AIMM configuration for every single task. In the "Little Helper" project we address this by looking into the domain of mass customization, which aims to satisfy individual customer needs by introducing product proliferation, while taking advantage of mass production efficiency (Pine, 1993). Key methodologies are *modular* product architectures, families and platforms (Sundgren, 1999). Modularity makes it easy to customize the mobile manipulator system by tailoring the module combination or by changing, adding, and/or removing modules. A modular AIMM architecture can be created by use of functional elements (individual operations and transformations contributing to the performance) and chunks (building blocks consisting of a collection of physical elements). Based on mapping relations between functional elements and chunks, modular product architectures can be realized (Ulrich & Eppinger, 2000). Different viewpoints (Figure 14) are needed to describe a product architecture and family (Andreasen, 1980).
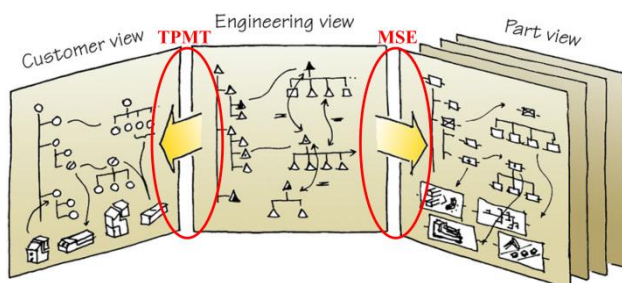

Figure 14 Principle model of a product family, including three different views/domains (Harlou, 2006).

Product family decision-making involves a series of "what-how" mappings between different views (Figure 14). The three views are related in the sense that the product family (i.e. the engineering view) shows variety to the markets (i.e. the customer view) and commonality to the production system (i.e. the part view) (Harlou, 2006). The mapping between the customer and engineering view can be described by the TPMT methodology, whereas the mapping between the engineering and part view can be described by Modules and Skills Extraction (MSE), as shown in Figure 14.

2.6. Modules and Skills Extraction (MSE)

A module is a basic building block with pre-defined interfaces (e.g. mechanical, electrical, mechatronics, software, and man-machine), which can be compared to the well known LEGO bricks (Harlou, 2006). In the context of product architectures, a module is a subsystem designed for re-use. A module is characterised by its skills, which represent the functionalities in relation to the process (Ribeiro et al., 2010). In Figure 15, the correlation between modules and skills is illustrated.
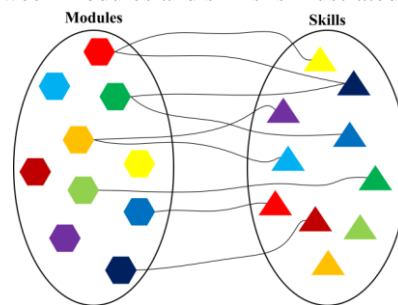

Figure 15 Correlation between modules and skills (Ribeiro et al., 2010).

In the "Little Helper" project, we have applied the MSE for the Grundfos application scenarios, in order to realize a modular AIMM architecture and to obtain manufacturer independency (COTS). A partial overview of modules and related skills is shown in Figure 16.
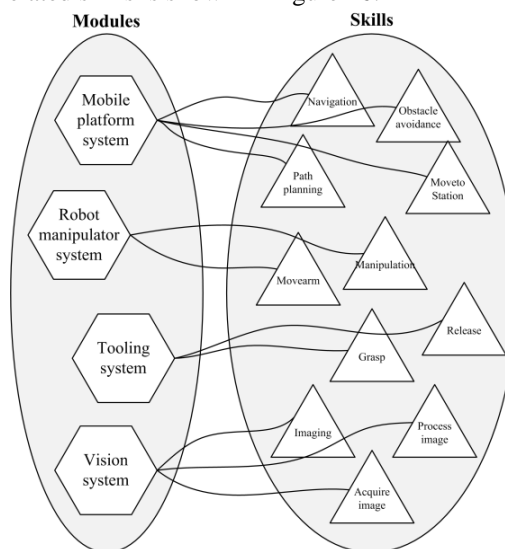

Figure 16 Partial MSE overview for AIMM.

3. Real-world AIMM demonstration

3.1. Theory guides, real-world experiments decide

An important aspect of the proposed technology transfer procedure (Section 2) is to make use of early and successive demonstrations, as illustrated in Figure 17.
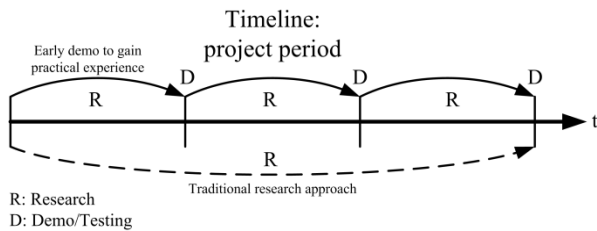

Figure 17 Technology transfer procedure versus traditional research projects.

Laboratory testing is not enough; the technology must be tested in real-world industrial applications and environments. Compared to traditional research projects, where a large demonstration is typically postponed to the end, we find it crucial to complete several smaller demonstrations during the project period.

3.2. Multiple Part Feeding demonstration

By using the proposed technology transfer procedure, we perform real-world demonstrations to identify the necessary generic modules and skills for "Little Helper". The first demonstration concerns multiple part feeding and is carried out in Grundfos' production facilities. These production facilities consist of several automatic production lines, where the feeding of components is performed manually. The mission of the AIMM is to retrieve parts from a storage and subsequently transport them to different feeders. When parts are needed, the mobile manipulator is requested via wireless network, and then it retrieves the parts from the storage. The planning and scheduling are based on data from the ERP system. A 3D simulation is shown in Figure 18.
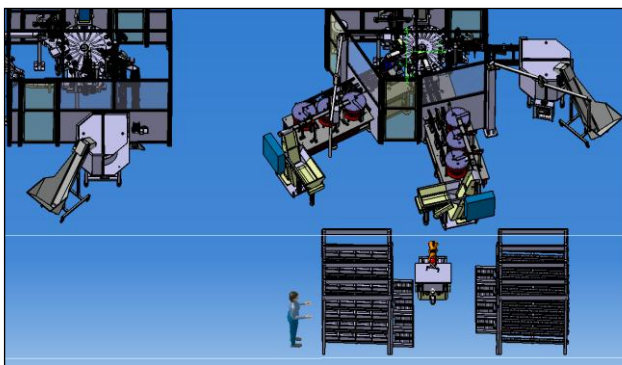

Figure 18 3D simulation of multiple part feeding.

The real-world multiple part feeding scenario at Grundfos' production facilities is shown in Figure 19. This demonstration provided useful insight in challenges when moving the AIMM technology from the laboratory to the factory floor, e.g. related to safety aspects, communication problems, and robustness issues.

Figure 19 Real-world demonstration at Grundfos.

Based on the performed demonstration, it is possible to extract the required modules and skills for multiple part feeding, as illustrated in Table 2. In the long run, the necessary modules and skills will be identified for all application scenarios within logistics, assistive and service tasks. By comparing the different scenarios, it is possible to discover their similarities and varieties. In this way, we are able to find a suitable modular AIMM platform ("the white LEGO figure" or "highest common factor") and an acceptable number of configurations.

Table 2 AIMM mission decomposition: tasks, modules and skills correlation, based on multiple part feeding.

Task description	Tasks	Skills	Modules
Receive mission from ERP/MES-system			
Move to storage shelf-system. Fetch container with objects/parts from shelf. **Fetch container X from storage**	Go to storage	- Move arm to safe/home position. - Platform move to station - Communication: Arrived at storage	Robot manipulator Mobile platform
	Localize X	- Move arm to location - Acquire and process image - Communication: Container X located	Robot manipulator Vision system
	Pick up X	- Move arm to location - Close gripper - Move to "Place" location - Open gripper	Robot manipulator Tooling system
Deliver container with objects to feeder/machine/magazine. **Unload container X at workstation**	Go to workstation	- Move arm to safe/home position. - Platform move to station - Communication: Arrived at workstation	Robot manipulator Mobile platform
	Unload X	- Move arm to "Pick up" location - Close gripper - Move arm to "Unload" location and Unload X	Robot manipulator Tooling system
	Place empty X on platform	- Move arm to "Place" location - Open gripper	Robot manipulator Tooling system
Move AIMM to storage. Deliver empty container at storage **Deliver empty container X to storage**	Go to storage	- Move arm to safe/home position. - Platform move to station - Communication: Arrived at storage	Robot manipulator Mobile platform
	Place empty container X at storage	- Move arm to "Pick up" location - Close gripper - Move to "Place" location - Open gripper	Robot manipulator Mobile platform
Send report to ERP/MES-system			

4. Conclusion and Future work

In this paper we have presented "Autonomous Industrial Mobile Manipulation" (AIMM) as a research topic and emerging technology for modern industry. We present a technology transfer approach for bringing automation of today towards the transformable factory of the future. The approach is based on Front End of Innovation methodologies, including "New Concept Development" (NCD), "Technology Push Manufacturing Technology" (TPMT) and "Modules and Skills Extraction" (MSE). We believe that our approach supports the collaboration between research and industry and helps in getting a mutual understanding for an emerging technology. To achieve maximum benefits from the approach, it is necessary to perform successive demonstrations, and preferably early in the project. Finally, the methodologies presented have been exemplified by an industrial case study, which proved that the approach worked as intended. By using the approach, the path from research to industry becomes more structured and attainable.

In our ongoing research we investigate further aspects of increasing the usability of the approach. These aspects include the use of more visual tools and models in order to bridge the gap between academia and industry. Furthermore, the approach will be utilized in teaching, at other research institutes and at different companies.

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