Stefanie Angerer (Autor)

Skill-Based reconfiguration of industrial mobile robots

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Chapter 1

Introduction to Reconfigurable Industrial Mobile Robots

In this thesis a skill-based reconfiguration mechanism for industrial mobile robots is proposed. The presented MobComm (Mobile Commissioning) approach utilises the holonic paradigm and has a basic division between a Standard Holon for routine executions, and a Reconfiguration Holon, where reconfiguration tasks are accomplished to provide high productivity. The goal of every reconfiguration is to generate a new Composite Skill Agent, containing the answer to functional process changes. The robot hardware is able to immediately use this new skill and thus to satisfy the changed manufacturing process needs.

The motivation of the thesis is explained in section 1.1, followed by the vision of industrial mobile robots in automotive industry in section 1.2. The research structure of the thesis is presented in section 1.3. A short overview of the scientific fields of influence is given in section 1.4, followed by the thesis overview and organisation in section 1.5.

1.1 Motivation

Car manufacturers, like most manufacturing companies, face a rising mass customisation of their products. Mass customisation requires the manufacturing system to be highly flexible [Pollard et al., 2008] because of the high trim level of cars, shortened product life cycles, and an instant satisfaction of customers' demands [Bussmann and Schild, 2000]. As presented in figure 1.1, the car industry itself changed tremendously in the last decades.

Besides increased mass customisation, the decreased time-to-market, and the increased level of complexity are the most considerable changes in this sector.

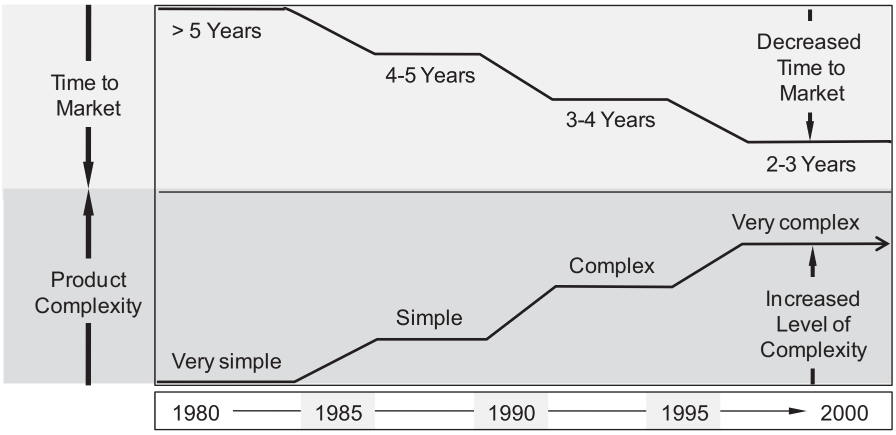


Figure 1.1: The evolution of car industry in the last decades. Adapted from: [Bi et al., 2008].

Following [Bi et al., 2008], the time-to-market decreased from over 5 years in the 1980s to around 2 years in year 2000 whereas the complexity of the cars advanced from very simple to very complex. These characteristics of automotive industry require changes in a broad set of operational sequences in the factories. This thesis contributes to a more flexible manufacturing component level.

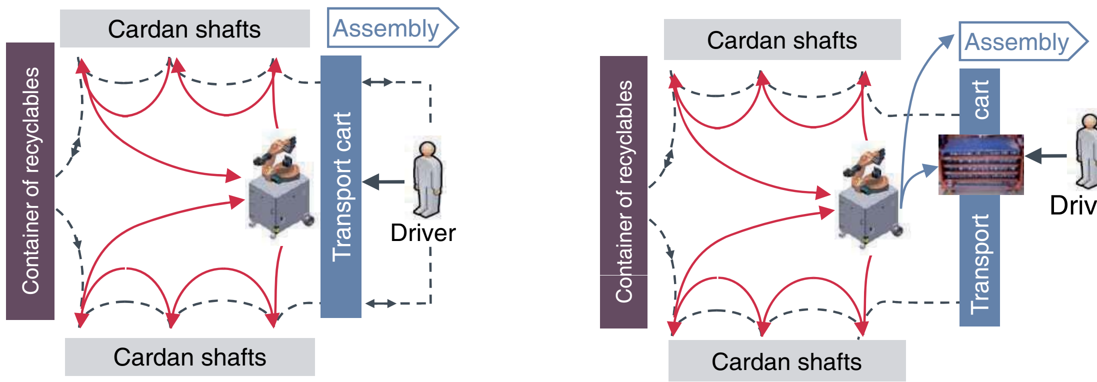
Mass customisation, decreased time-to-market, and the increased level of complexity require changes in hardware systems, control structures and software engineering processes for manufacturing systems. As stated in [Lepuschitz et al., 2010], current and future manufacturing systems must be able to rapidly reconfigure under changed environment conditions.

Not only must a superior manufacturing system provide a high degree of flexibility and reconfigurability, but the single manufacturing components are required to be more adaptable to changes in the production process as well. Single manufacturing systems are traditional industrial robots, conveyors, or drilling machines, to name just a few examples.

Even if the research area of mobile robots provides already a wide range of reconfiguration tools for a changed environment like a dynamic behaviour adaptation of mobile robots (cf. Saphira [Konolige and Myers, 1996]), mechanisms given in literature cannot be applied to industrial mobile robots as they face a different set of requirements for their productive use in factories.

As service robots mostly aim to dynamically adapt to unknown or upcoming environment settings, temporal constraints or the need of a high predictability do not feature significantly in this area. In contrast to that, industrial mobile robots face an environment with a strict cycle time and exact process descriptions. For this reason, industrial mobile robots must provide a very high level of robustness and predictability during standard process execution.

But nevertheless the use of industrial mobile robots is very reasonable to automate for example logistic pick and place tasks, called commissioning. An example application for a mobile robot in logistics is given in figure 1.2(a) where the commissioning of cardan shafts is presented. The robot robustly provides the functionality to pick and place different types of cardan shafts. It ultimately places these components in the provided transport cart in the order as desired by the assembly process.



(a) Example process with industrial mobile robot: Commissioning cardan shafts.

(b) Requirement of process change: Follow transport cart.

Figure 1.2: Use case for mobile robots in car manufacturing: Example commissioning of cardan shafts.

Additionally to the compliance of industrial requirements like robustness or availability, the mobile robot must be able to dynamically react to process changes that occur in the context of model changes or further derivatisation of existing models. An example process change is described in figure 1.2(b) with the required tracking of a transport cart to the assembly line.

Due to the dynamic environment, this robust mobile robot must be adaptable to the new process requirement by a skilled worker to avoid follow up costs for software changes. Figure 1.3 overviews the total commissioning process including manual and automated workplaces. A reconfiguration of the mobile robot is required if the set of provided functionalities (i.e. Skill Agents) is not sufficient any more to comply with the defined manufacturing process. This type of functional reconfigurability cannot be covered in the context of the set industrial requirements by approaches given in literature.

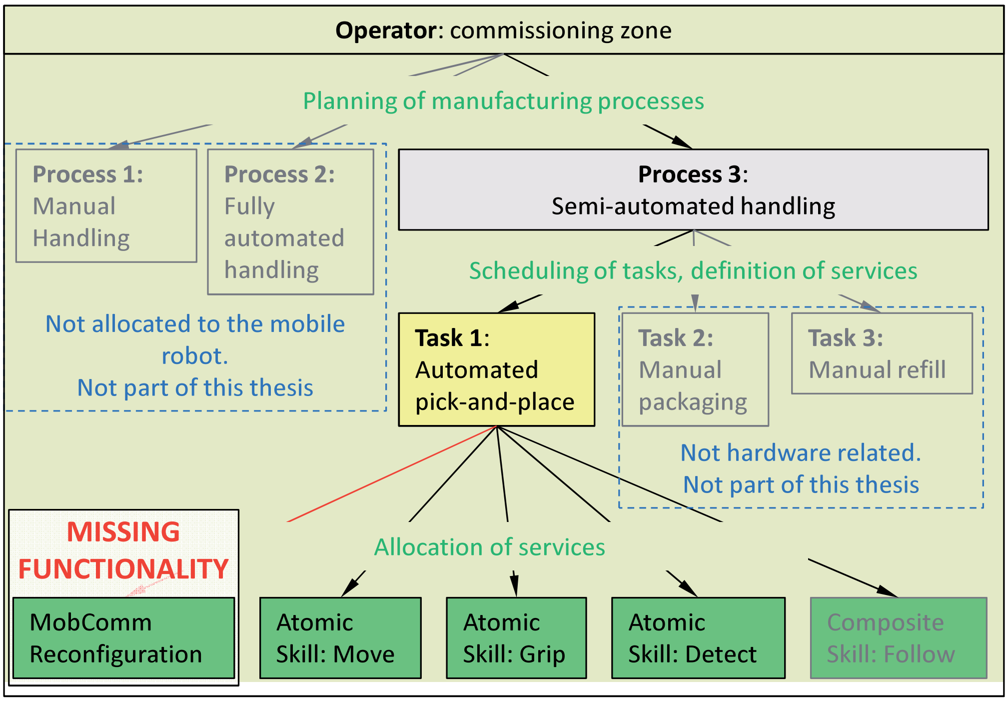


Figure 1.3: Integration of MobComm reconfiguration in total commissioning process.

The need of a robust standard process execution and a dynamic skill reconfiguration without programming effort after functional process changes motivates the proposed skill-based reconfiguration mechanism. The presented work contributes to a higher benefit of flexible mobile robots in car factories of the future.

Following the 2010 Technology Market Survey of Gartner, mobile robots are an emerging technology able to be adopted by the mainstream in more then ten years [Chip Online, 2010]. As highlighted in figure 1.4, mobile robots have already passed the technology trigger and are approaching the peak of inflated expectations.

Flexibility applicable to industrial mobile robots is investigated in different research areas. Reconfigurable, flexible, holonic, and evolvable manufacturing systems are discussed in section 2.2. Especially the use of Holonic Manufacturing Systems (HMS) leads to a high level of flexibility in production flow control. By the application of a hybrid manufacturing control with both hierarchical and heterarchical structures, flexible resource management and the dynamic allocation of production units can be provided by this research area (e.g. [Van Brussel et al., 1998]). A flexible adaptation of temporal process changes can be further reached through dynamic scheduling mechanisms within the holonic principle.

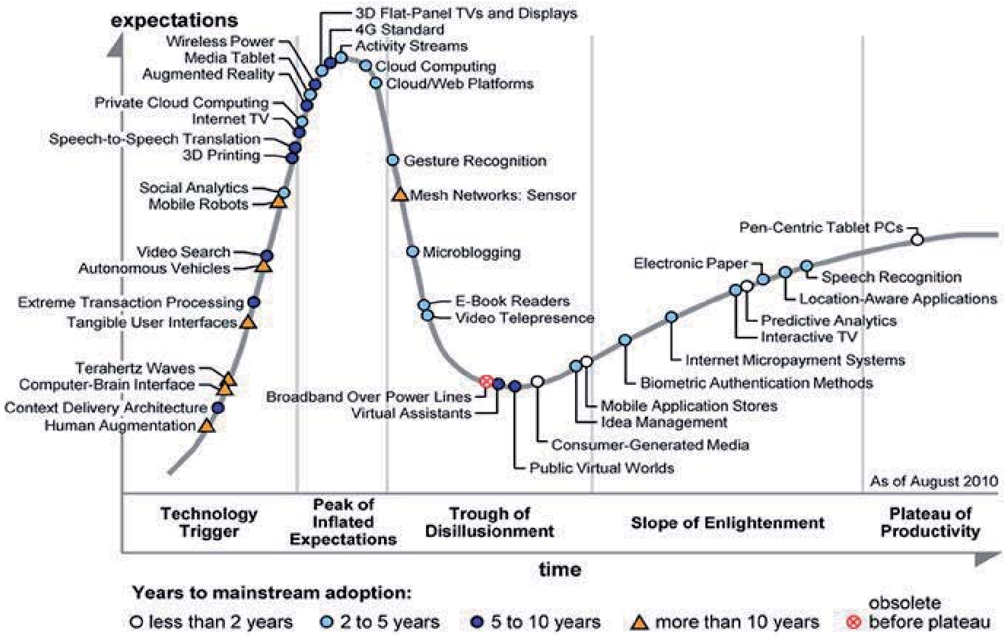


Figure 1.4: Market survey of Gartner Inc. including the technology level of mobile robot technology. Source: [Chip Online, 2010].

A dynamic reaction to hardware failures in manufacturing systems is pictured in a set of approaches such as the Restore Invariant Approach [Guedemann et al., 2006]. In this approach, a hardware failure violates a logical formula, the invariant, and allows to dynamically restore it by the allocation of a different task to this formula.

But neither HMS nor the Restore Invariant Approach are able to react to functional process changes on manufacturing component level as desired for industrial mobile robots in car manufacturing. On that account, this dissertation presents a reconfiguration mechanism for industrial mobile robots using a novel approach to react to these changes. The motivation for the MobComm approach and the different types of flexibility are summarised in figure 1.5.

FMS mostly reach their goals by the use of agent technology that is characterised by autonomy, pro-activity, and location-independence [Huhns and Buell, 2002, Wooldridge, 1998]. In turn, applying agent technology leads to a rise of system and program complexity, and proofs of reliability are harder to provide in real-world applications. This is one reason for the lack of real automation implementations of agent technology as described in [Leitão and Restivo, 2008]. This dissertation includes the implementation of the proposed MobComm reconfiguration mechanism. The real-world evaluation as described in 7 is accomplished at the German car manufacturer Audi where test environment and hardware are provided.

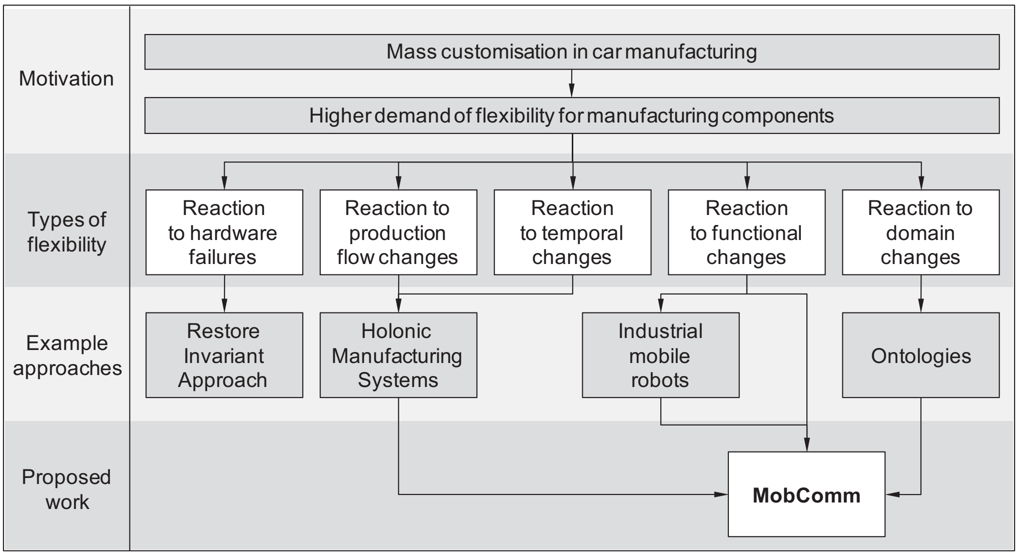


Figure 1.5: Motivation for MobComm reconfiguration mechanism.

1.2 Vision

The vision behind this thesis agrees with the market survey presented in figure 1.4 and imagines a mainstream adaptation of mobile robots. The distribution of industrial mobile robots is viewed as the enhancement of traditional industrial robots in car manufacturing.

Based on a holonic or flexible manufacturing control, an armada of mobile robots is available for the use in different areas in car manufacturing. These mobile robots are applicable to a set of different applications in the factory. As presented in figure 1.6, the superior manufacturing system manages the necessities of mobile robots in the different areas and distributes tasks to the individual robots.

The range of tasks executed by an industrial mobile robot, consisting of a mobile platform, a manipulator, a gripper and a sensory system, is broad and not limited to the given examples. Logistic handling or pick-and-place tasks are the core applications, followed by worker assistance or bring-and-delivery tasks between different areas in the factory.

Especially tasks of worker assistance for industrial mobile robots are focused on in the LOCOBOT (Low cost robot co-workers) project funded by the European Commission's 7th Framework Programme [Profactor GmbH, 2010]. With partners like the Heriot-Watt

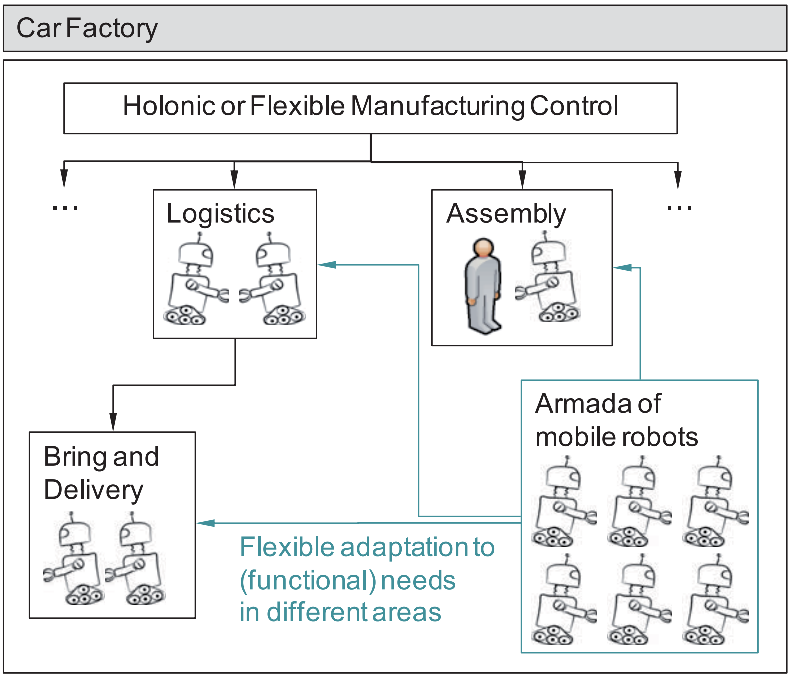


Figure 1.6: Vision for industrial mobile robots in car manufacturing.

University, the University of Edinburgh and Audi, a modular and collaborating mobile robot is investigated aiming at combining reconfigurability in manufacturing with cost effectiveness.

To flexibly adapt the functionalities needed by the mobile robots, a scheduling and reconfiguration mechanism is required. Generic mobile robots have to be able to self-adapt to the upcoming tasks in the factory. A step towards this self-adaptation of generic industrial mobile robots in a productive environment is the reconfiguration mechanism proposed in this thesis.

1.3 Research Structure

The research overview is structured into thesis contribution and hypothesis, resulting research objectives, and finally a set of research assumptions, as presented in the following sections.

1.3.1 Contribution and Hypothesis

The contribution of this thesis can be divided into three aspects: the proposal of a novel reconfiguration mechanism after functional process changes, a hardware-abstract system with maintenance of productivity, and the novel agent design for dependability and self-organisation in productive environments.

Reconfiguration mechanism after functional process changes

The presented reconfiguration mechanism is based on [Angerer et al., 2010b] and is a novelty regarding its self-organised reaction to functional process changes. Extending the hardware-related or temporal reconfiguration aspects as given in [Guedemann et al., 2006] or [Frei et al., 2007c], MobComm proposes the conversion of a semantic description of a functionality into a new agent that represents this robot skill. This reconfiguration mechanism, implemented on manufacturing component level, contributes to the extension of manufacturing flexibility.

Hardware-abstracted system with maintenance of productivity during reconfiguration

The proposed system is novel due to its basic structure of two separated parts in the system, implemented as Reconfiguration and Standard Holons allowing the complete separation of task execution and reconfiguration for the maintenance of productivity. The presented system extends the suggestion given in [Angerer and Pooley, 2009], and is based on [Angerer et al., 2010a].

The segregation and reintegration of reconfiguration results is based on the holonic principle as given in ADACOR [Leitão and Restivo, 2008] or PABADIS [Feng et al., 2007]. Adapted from the hybrid control structures of Holonic Manufacturing Systems, where both robust hierarchical and adaptive heterarchical structures can be applied, the MobComm mechanism consists of a robust Standard Holon and creates a changed skill configuration in a heterarchical organised Reconfiguration Holon.

Besides maintaining productivity, the novel aspect is the configuration-independent reconfiguration while providing a hardware abstraction layer. Configuration independence is achieved by the on-line access of reconfiguration knowledge and the migration of agent clones, whereas hardware abstraction is based on the use of a resource agent layer providing defined interfaces for a broad range of hardware components.

Agent design for dependability and self-organisation in productive environments

According to the requirements of a productive environment, a novel agent design for dependability and self-organisation is presented. Corresponding the definition 2.12 on page 45, self-organisation includes self-management structure adaptation and the provision of decentralised control. The Standard Holon, used for routine executions, is realised by behaviour-based agents using a service-based communication. This aspect of the MobComm agent ensures dependability for the executed processes in cycle time. Agents used in Reconfiguration Holon, however, are designed as BDI-agents and able to support self-organisation and self-awareness. The reconfiguration mechanism draws on reasoning and planning of the BDI principle, nevertheless the outcome of a successful reconfiguration is a behaviour-based agent, suitable for the use in Standard Holon. By using this novel combination of behaviour-based and BDI aspects, the agent design in MobComm is suitable for a dependable execution of tasks and a self-organised handling of process changes in productive environments.

Based on these three aspects of thesis contribution, the research hypothesis is formulated as follows:

1. Functional process changes are inserted as semantic descriptions by a user. The proposed reconfiguration mechanism transforms these descriptions self-organised into the desired robot functionality.
2. MobComm reconfiguration mechanism can be executed without disturbing the running manufacturing process.
3. The reconfigured robot functionalities provide a high dependability for their permanent use in the standard process.
4. The used mobile robot is expandable by further hardware components that implement the MobComm specification.

1.3.2 Research Objectives

This section presents the research questions derived from the research hypothesis. By using the provided contribution and hypothesis, the main thesis question is determined as follows:

How is it possible to reconfigure industrial mobile robots self-organised in their hardware limits after functional process changes?

The thesis question includes that the reaction to functional process is handled self-organised by the reconfiguration mechanism. This covers a self-managed execution of computational steps without the need of external control by following the definition of self-organisation on page 45. The hardware components of the provided mobile robot are further regarded as fixed and thus not used as a source of reconfiguration or failure.
Based on the thesis question and the research hypothesis, a set of research objectives is outlined as goals for this work:

Objective 1: Self-organised reconfiguration with maintenance of productivity during reconfiguration.

Objective 2: Dependable integration of new skills.

Objective 3: Handling of functional process changes with an abstraction of given hardware.

1.3.3 Research Assumptions

MobComm requires a set of system requirements and environment premises to be implemented as stated in the thesis contribution.

Assumption 1: The used hardware operates as specified. No communication or bus errors are regarded during reconfiguration.

Assumption 2: No hardware failures occur during reconfiguration. Hardware breakdowns are not regarded in this approach.

Assumption 3: Descriptions of new functionalities are inserted by the operator and regarded as semantically correct. No feedback loop between the user and the resulting system configuration after a reconfiguration is provided. This feedback loop is not within the scope of the thesis.

Assumption 4: New functionalities are within the example domain that allows to keep system ontology valid during reconfiguration. In case a new domain is desired, the according ontology must to be updated by using expert knowledge.

The list of research assumptions finalises the research structure section that has focused on the thesis contribution and the deduction of a set of research objectives. While an overview of structure and organisation of this work is given in section 1.5, the following section introduces the scientific fields of influence.

1.4 Scientific Fields of Influence

To detail the relationship between the research objectives and the approaches provided in literature, a set of research fields is evaluated in chapter 2. Figure 1.7 introduces the relation between research objectives and related work. The key fields for MobComm are mobile robots (cf. section 2.1) and manufacturing systems (cf. section 2.2) including their self-organisation (cf. section 2.2.2). As it is desired that a mobile robot is able to handle process changes, mobile robot research is of high interest. Further the used robot hardware, environment and executed processes are highly related to manufacturing systems. Comprehensively, related work concerning agent-oriented software engineering techniques is surveyed in section 2.3, as the relevant approaches presented in section 2.1 and 2.2 emphasise the use of agent technology for MobComm.

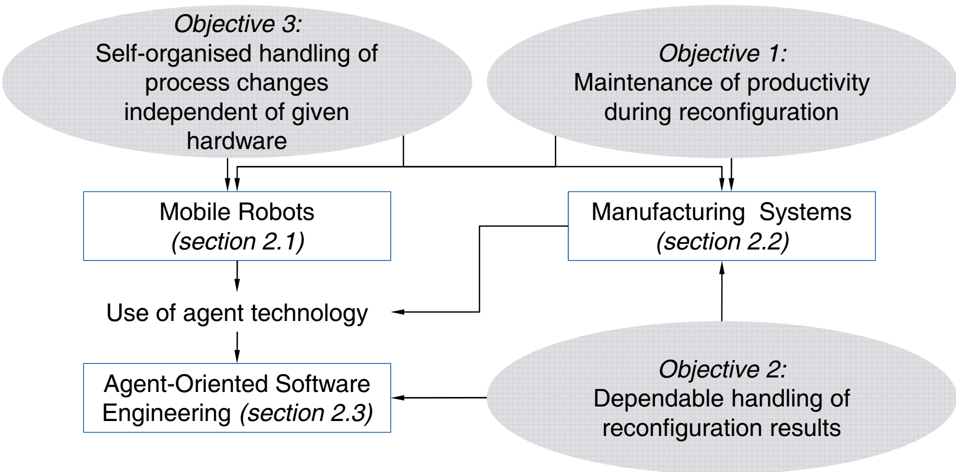


Figure 1.7: Relationship between research objectives and related work.

1.5 Thesis Overview and Organisation

In this thesis a reconfiguration mechanism dealing with functional process changes is proposed for industrial mobile robots. The scope of the dissertation comprises the design of a reconfiguration mechanism after functional process changes, followed by its implementation and evaluation.

A complete overview of the MobComm approach is presented in figure 1.8. The system is divided into a single Standard Holon (SH) and [1..n] Reconfiguration Holons (RH). Holons are autonomous and at the same time co-operative building blocks in hierarchies as futher defined in definition 2.11 on page 37.

The Standard Holon maps the routine executions of the system in cycle time and is divided into four layers. Process and Task Layer provide a global and local schedule for the actual process. Skill Agents form the key layer as they hold all functionalities executable in the system, encapsulated in agents. Resource Layer, meanwhile, represents the connection to the real-world and includes the interfaces to the underlying robot hardware. The semantic level of the Standard Holon is represented by an ontology that contains all domain vocabularies.

The insertion of a New Skill Description (NSD), arising from a process change in the manufacturing system, leads to the initialisation of a Reconfiguration Holon. Compared to the hierarchical structure of Standard Holon, agents in Reconfiguration Holon are organised heterarchical and follow the Belief-Desire-Intention (BDI) principle. As pictured in figure 1.8, the main purpose of a reconfiguration is the processing of the NSD in Reconfiguration Holon and its reintegration as a new Composite Skill Agent in Standard Holon. The according flow of reconfiguration is summarised in figure 1.9.

The insertion of a NSD is handled and analysed by a Generic Task Agent (GTA), described in chapter 4, and is sent forward to the Reconfiguration Holon for reconfiguration purposes. Inside a Reconfiguration Holon, an Initiator Agent (I-IA) defines its goals and beliefs according to the incoming NSD. All Execution Agents (I-EA) link themselves to the knowledge and agent behaviour of Standard Holon to execute the reconfiguration mechanism. The outcome of the algorithm, executed by collaborating I-EAs, is a New Skill Input Data (NSID). The NSID is comparable to a construction plan of the new agent which includes all knowledge about the new Composite Skill Agent. This structure cannot be used until a Generic Skill Agent (GSA) converts this data into the Composite Skill Agent format. The resulting agent is identical in shape and behaviour to the already existing ones in Standard Holon. Thus, it can be easily integrated into Standard Holon. For an immediate use, its service has only to be registered at the Directory Facilitator (DF), the yellow pages of Standard Holon. Every reconfiguration process finishes with a

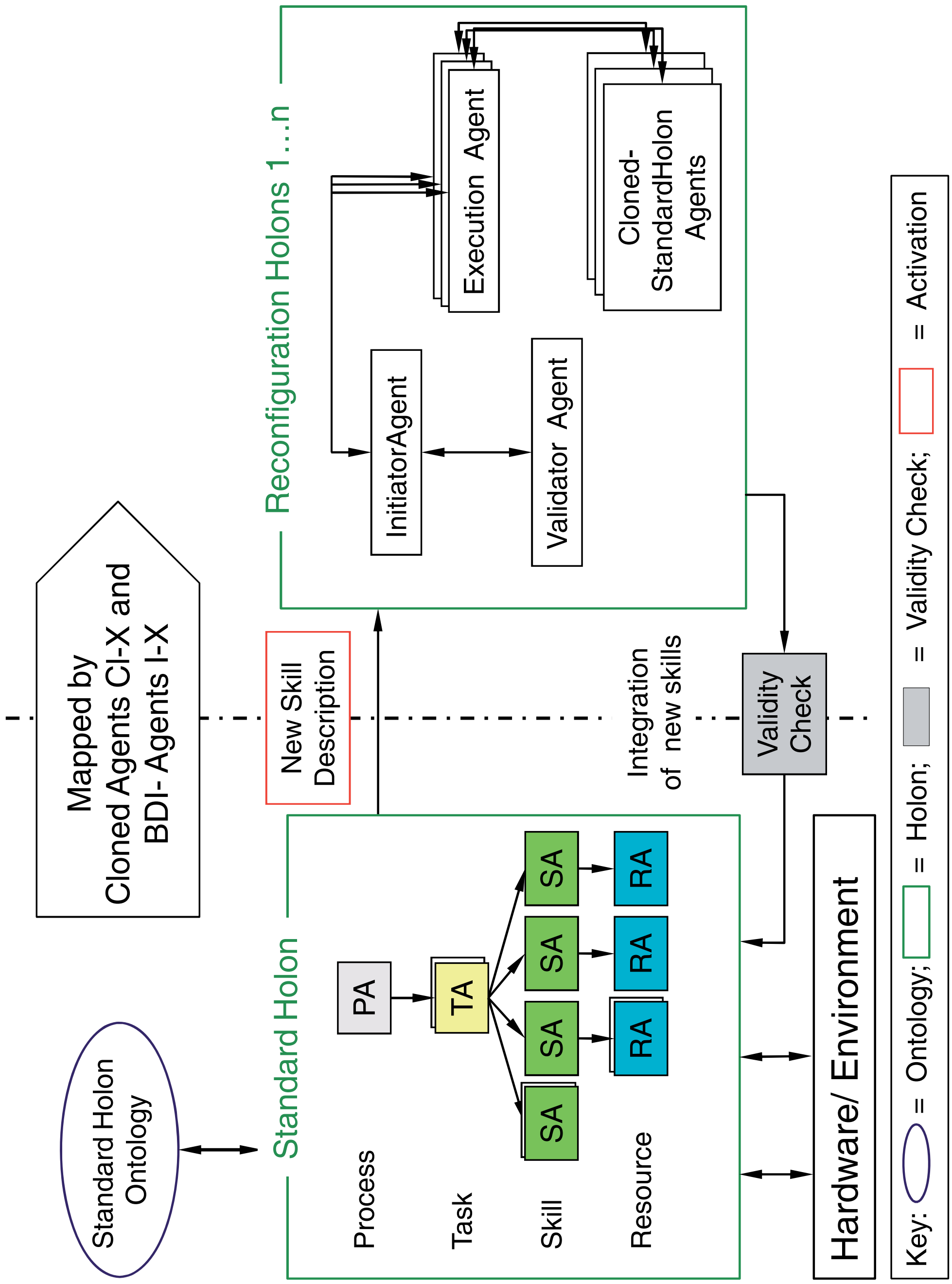


Figure 1.8: Block diagram of MobComm reconfiguration approach.

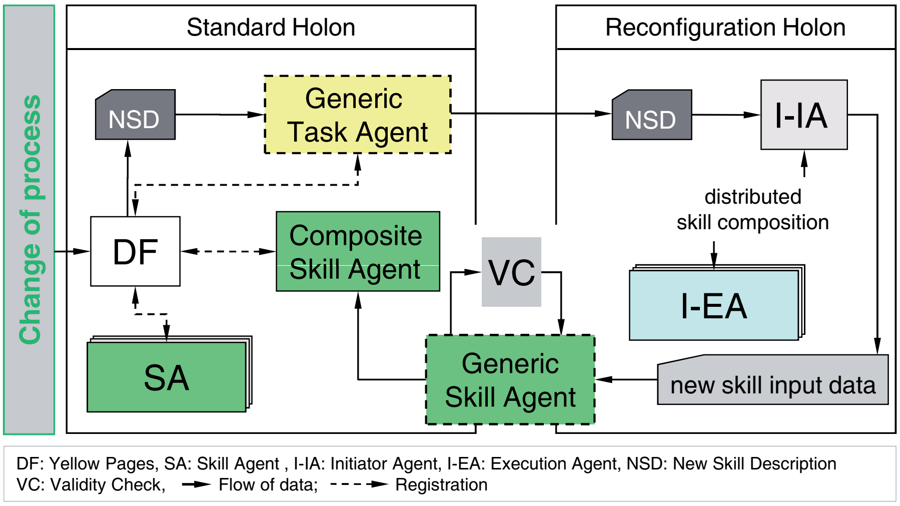


Figure 1.9: Overview of reconfiguration flow and the basic principles of the MobComm reconfiguration.

Validity Check that ensures that no unwanted or harmful operations are executed by the

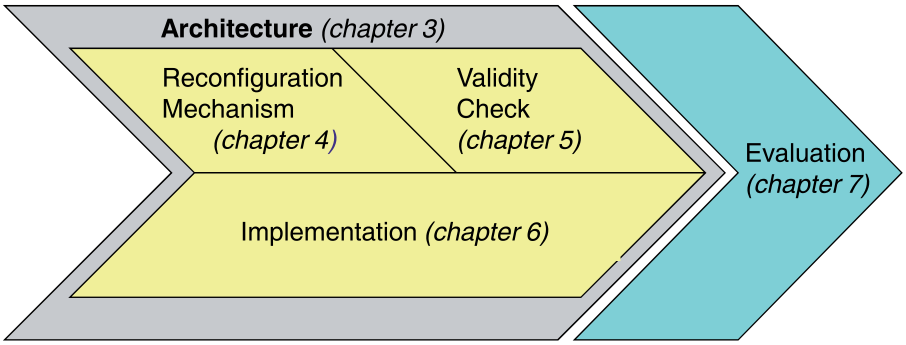


Figure 1.10: The organisation of the dissertation.

Passing over from the flow of reconfiguration to the organisation of the described system in this thesis, chapter 2 reviews related work as described in section 1.4. The main part of the thesis is organised in chapters corresponding to figure 1.10 and basically divided into three parts.

The MobComm reconfiguration as the core part starts in chapter 3 with the supporting architecture and focuses on the reconfiguration mechanism itself in chapter 4 and the Validity Check in chapter 5. The resulting MobComm implementation is given in chapter 6 and the MobComm approach is completed by its evaluation in chapter 7.