TOWARDS AN INTEGRATED ASSEMBLY PROCESS DECOMPOSITION AND MODULAR EQUIPMENT CONFIGURATION

A KNOWLEDGE ENHANCED ITERATIVE APPROACH

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Abstract: In today's increasingly volatile and dynamic global markets it is increasingly important to react to changing market demands and reduce the time-to-market. The design and re-design of assembly systems has a significant impact on the product development time. This paper reports on the effort that has been put into developing an assembly process decomposition and modular assembly equipment configuration methodology that takes advantage of the current trend towards modular equipment solutions and is expected to reduce design time and improve the design process integration. A general framework for the proposed methodology has been outlined and an ontology for the design of modular assembly systems is being discussed.

Key words: Assembly Process Decomposition, Equipment Configuration, Modular Assembly Systems, Ontology, Agent-based

1. INTRODUCTION

The requirements driven specification of assembly process as well as the selection and configuration of equipment for suitable assembly system solutions are central aspects of the assembly system design and redesign process. The assembly process specification should define the temporally ordered activities from the order in which the different components of a product or product family can be assembled to specific actions that need to be performed to facilitate the actual establishment of the individual liaisons between the components. The equipment selection and configuration process needs to find suitable equipment solutions for the required processes and combine them into a working assembly system.

Both the process decomposition and equipment configuration are highly related. The process definition prescribes the required equipment and the available equipment constrains the process decomposition (Rampersad, 1994). Often however these two aspects of the design process are considered separately and equally important constraints are neglected. Hence a methodology is needed that facilitates the dynamic decomposition of assembly processes and the configuration of equipment solutions within a single integrated framework that makes best uses of available expert knowledge.

Currently there is a strong trend towards Evolvable and Reconfigurable Assembly Systems (RAS) that enable enterprises to rapidly respond to changes in today's increasingly volatile and dynamic global markets without having to commit large investments in advance (EUPASS, 2005; Onori et al., 2002; Koren et al., 1999). One of the enabling factors of RAS is the availability of highly standardized modular equipment solutions that can be rapidly configured to deliver different assembly solutions. This opens the scope and need for higher degree of integration and automation during the design of such systems. Configuration methodologies that have been demonstrated in the computer industry which benefit from a higher degree of modularization can be harnessed to solve the challenges of the assembly system design process. Examples of such configuration methods include XCON (McDermott, 1982), MICON (Birmingham et al., 1988), and COSSACK (Mittal and Frayman, 1989).

A number of different frameworks for the configuration and design of products and system has been proposed (Bley et al., 1994; Lu et al., 2000; Boër et al., 2001; Jin and Lu, 2004). Distributed collaborative design frameworks provide clear advantages for the considered design problem as discussed by Rosenman and Wang (2001) particularly when combined with object and component oriented modelling approaches as are commonly used under the CIM paradigm (Schäfer and López, 1999). We propose to use a distributed knowledge based reasoning approach for the process decomposition and equipment configuration and an agent based framework to facilitate their integration.

The paper provides a more detailed definition of the proposed framework. Furthermore, the underlying knowledge model will be outlined and the approach will be illustrated with an example reconfiguration. To conclude the paper, the whole approach will be critically discussed and further work has been outlined.

2. METHODOLOGY OVERVIEW

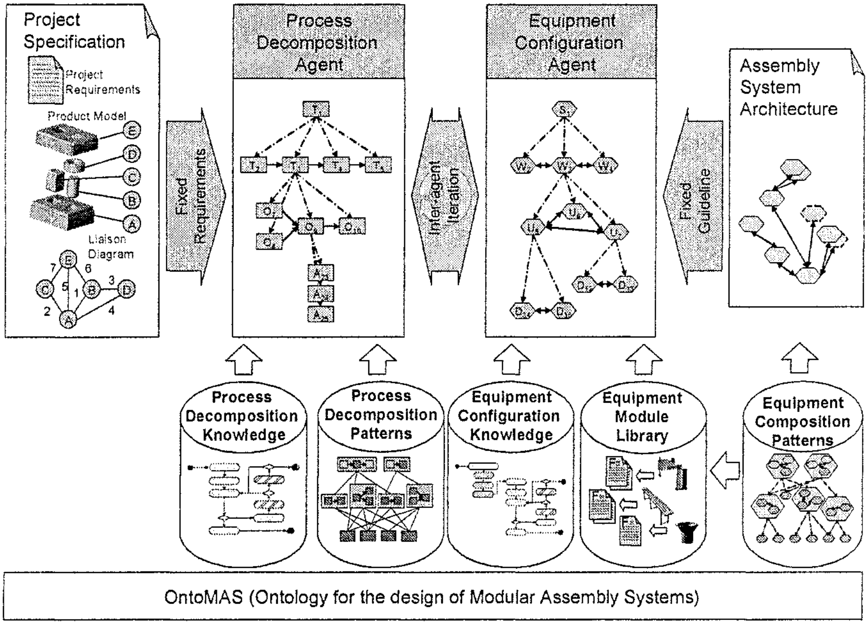

Figure 1. Integrated Assembly Process Decomposition and Equipment Synthesis Framework

Figure 1 shows an overview of the proposed approach. For this work it has been assumed that the product requirements that drive the assembly process decomposition in the first instance are fixed and are none negotiable. Furthermore it was assumed that a set of equipment modules exists that permits at least one viable configuration to fulfil a given set of requirements. However, the framework has been defined to allow for later extensions to include these aspects.

The assembly process decomposition is guided by rule-based patterns that define how different types of assembly activities break down into sub-activities including their temporal and logical relationships. The decomposition is prescribed through the product requirements and influenced by continuous equipment choices. The configuration of suitable equipment solutions is based on a virtual library of available equipment modules. The configuration process is guided by equipment configuration knowledge and constraint by a chosen system architecture for the given product domain. The interaction between the process decomposition and the equipment configuration is defined as an iterative process between cooperating software agents.

2.1 Process Decomposition Methodology

The process decomposition is using a hierarchical decomposition approach guided by rules that capture the decision making process. The foundation for the decomposition is a hierarchical specification of different activity types that can occur as part of the assembly process. Each on elementary activity type is associated to one or more process decomposition patterns. The process decomposition patterns define the required sub-activities for a specific activity type including their temporal and logical constraints. This definition results in an AND/OR graph like structure that links higher level activity types to lower level ones. This approach allows a dynamic integration of new activity types and can also be used as basis for the functional synthesis of newly configured equipment solutions. More detail on the decomposition process can be found in Lohse et al. (2005a).

2.2 Modular Equipment Configuration Methodology

The equipment configuration is using a hierarchical configuration method that addresses the following aspects:

- grouping of activities into conceptual equipment definitions
- specification of required equipment types and their specific requirements
- selection and evaluation of suitable equipment modules
- integration and functional synthesis of selected equipment modules

Each aspect of the configuration process is performed by specific agents presenting domain experts. For example the selection and evaluation of equipment is done by different expert agents for the different types of equipment. There is an agent that provides the capability to select and evaluate grippers, one to do the same for manipulators, etc.

The assembly equipment configuration is guided by predefined module types and interface specifications that are specified as part of a chosen system architecture for a specific product domain. The module specifications defined the required functional capabilities of different module types and their connectivity constraints based on the interface specifications. The system architecture also defines the logical and spatial constraints between the different types of modules. The use of an architecture definition makes the configuration process more effective by reducing the number of possible solutions. This is advantageous as long as there is a mechanism to ensure that the architecture is constantly updated. It is still an open question where the break even point between improved effectiveness and lost advantage due to the restriction of possible solutions is. The approach was designed under the assumption that there exist domain specific architectures that cater for the majority of the needs in their domain.

2.3 Agent-based Interaction/Negotiation

The interaction between the process decomposition and the equipment configuration is defined as an iterative process between cooperating software agents with different design objectives. The agents that facilitate the assembly process decomposition aim to find the best possible fulfilment of the assembly process requirements whilst the agents responsible for the equipment configuration search for the most effective configuration of the assembly equipment. These objectives are naturally contradictive since one is trying to minimise cycle time and process flow and the other cost and space.

Each agent has its own knowledge resources and is associated to a human expert who is responsible for the critical decisions that can not be fully automated. The conflict resolution strategy is based on inter-agent iterative negotiation as suggested by Lu et al. (2000). The interactions between the different agents in the framework are defined in terms of the FIPA interaction protocols (FIPA, 2005). Further detail on the general decision making framework can be found in Lohse et al. (2004).

3. ONTOLOGY FOR THE DESIGN OF MODULAR ASSEMBLY SYSTEM (ONTOMAS)

The decomposition and configuration methods are underlined by an Ontology for the design of Modular Assembly System (OntoMAS) that defines the product, the assembly process, and the assembly equipment domain knowledge models. The ontology is defined based on the general engineering ontology structure suggested by Borst et al. (1997). They suggest a fundamental ontology structure based on mereological, topological, and system theory principles. Their suggested structure has been extended to also include abstraction relationships. This is a knowledge based definition that is closely related to the object-oriented paradigm.

The concepts in the proposed overall ontology are split into three separate domain models; the product, assembly process, and assembly equipment domain models. The product is modelled as assemblies, components, and the liaisons between them; the assembly process as activities and their temporal relationships. The most complex model is used for the assembly equipment. It is modelled as virtual components with a function-behaviour-structure representation (Lohse et al., 2005b).

Functions express the capabilities of an equipment module based on the intentions of the designer and are therefore subjective and domain specific. For example the intended function of a robot is to move end effectors. **Behaviour** characterises how an equipment module reacts to changes in its environment and in turn how its reaction influences the environment based on physical phenomena. For example the high level behaviour of a robot is the transformation of electrical energy into kinetic energy under the guidance of control signals. **Structure** defines the physical aspect of the equipment model with geometric objects and connections. In the case of the robot that would include the links and joint definitions of its structure. The attributes of the three aspect models are all based on a fully parametric model.

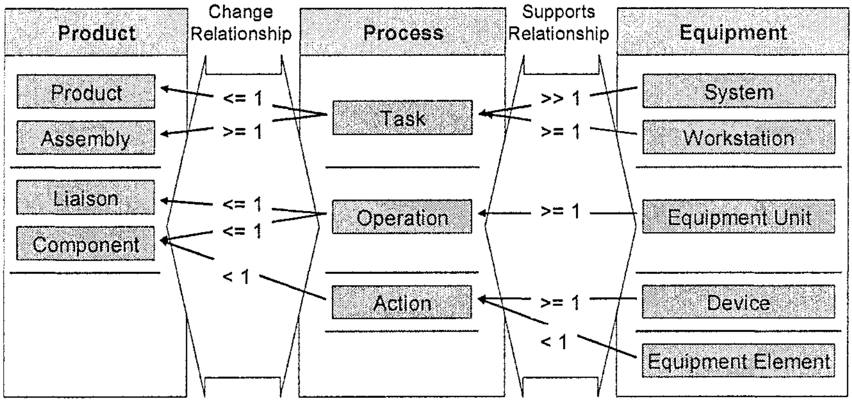

Figure 2. Logical relationships between hierarchical levels of the domain models (extension from Lohse et al., 2005b)

For the hierarchical structure of the three models we suggest that it is advantageous to define a number of distinct levels which have quite rigidly defined relationships. We expect that this will significantly reduce the configuration effort since a straight forward comparison between the required assembly activities and the functional capabilities provided by the synthesised equipment functionally will be possible on each level. Figure 2 shows the proposed levels of hierarchy and how they related to each other.

On the assembly process side, the activities are structured on three levels of hierarchy: task level, operation level, and action level. Actions form the fundamental activities that can be performed by a piece of equipment without the goal to directly influence an object related to the product. Operations are processes that facilitate state changes of entities that are part of a product. Tasks are processes that facilitate clear definable portions of work towards the completion of a product.

The equipment modules are allocated to five hierarchical levels depending on their functional capability. Systems are assembly equipment configurations that perform all the tasks required to assemble the whole product. Workstations are the smallest equipment modules that facilitate the whole assembly of at least two components. Equipment units execute at least one operation and devices at least one action. Equipment elements denote the lowest level of equipment modules that do not have an active function that would enable them to perform an action.

4. ILLUSTRATIVE EXAMPLE

The proposed iterative process decomposition and equipment configuration can best be demonstrated with an illustrative example. The given example here is not entirely based on real data and has been defined for illustration purposes only. Also not all the stages of the design process are shown since this would unnecessarily overcomplicate the example and reduce its explanatory value.

The given example is based on a new design process without any given equipment. The starting point is a set of user requirements for an assembly system including a complete product specification (see Figure 3). The example product is a simple peg-in-hole assembly with a loose fit liaison between component 1 and component 2. From this definition it can be determined that for the required assembly task (T_{A3}) both components need to be supplied, they need to be assembled (O_{A9}), and the completed assembly need to be removed. Furthermore, it can be determined that component 1 needs to be feed (O_{F7}) if component 2 has been defined as base part and also that the assembly operation needs to be an insertion. The classification of the assembly operation as insertion directly entails the specification of a number of required lower level actions.

The first iteration of the configuration can be defined from this initial assembly process specification. An assembly workstation (W_3) is needed to complete the assembly task (T_{A3}). The workstation needs to contain a number of equipment units. In this case an existing feeder unit (U_6) has been found that matches the requirements of the feeding operation (O_{F7}). The assembly operation (O_{A9}) is associated to an assembly unit (U_5) which is configured from a number of lower level devices and elements.

The connection of the feeder unit (U_6) and the assembly unit (U_5) cause the spatial location at the end of the feeding operation (O_{F7}) and at the starting point of the assembly operation (O_{A9}) to be different. This requires an adaptation of the initially defined assembly process which causes new operations to be added. This in turn changes the responsibility of the selected equipment and might cause them to be changed. The process continues until a stable process-equipment solution has been found which can be subjected to performance evaluation.

A re-configuration process would be similar with the only difference that the design process would start with an existing equipment configuration and the required changes need to be established first.

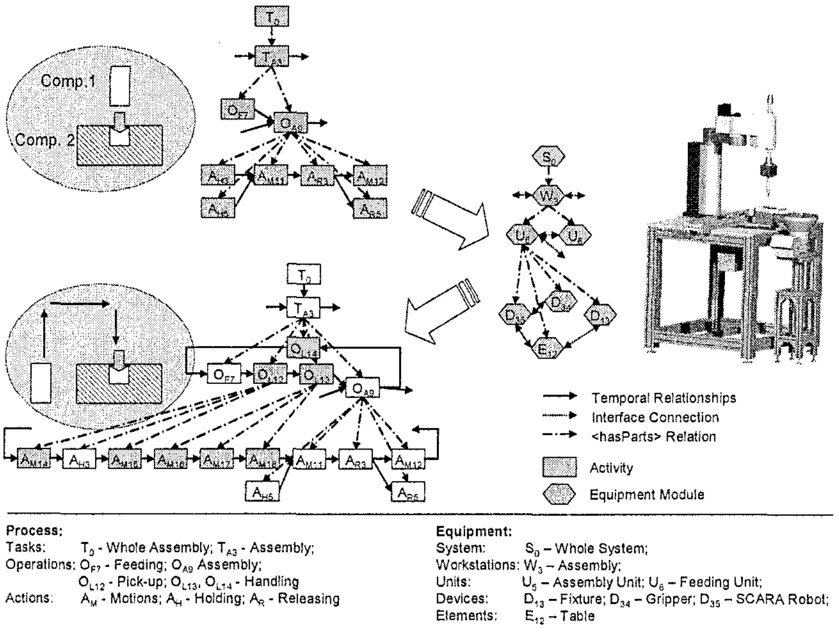

Figure 3. Illustrative Decomposition and Configuration of an Assembly Task

5. CONCLUSIONS AND FUTURE WORK

In this paper we have outlined a new methodology for the integrated specification of assembly processes and modular assembly equipment configurations. The methodology is based on a distributed agent-based reasoning approach that is supported by expert knowledge. The process specification has been defined as a decomposition process using rule-based process specification patterns and the assembly equipment specification as an architecture constraint, hierarchical configuration process. Both methods have been integrated into a common framework with an integrated ontology for the design of modular assembly systems (OntoMAS).

We perceive this methodology to have potentially a significant impact on:

- The reduction of the time-to-market of new products that need automated assembly systems,
- The reduction of the reconfiguration effort permitting more reconfiguration steps
- The improvement of the integration and quality of the design process of modular, automated assembly systems by providing a consistent knowledge infrastructure throughout the whole design process

Future work will be focused on:

- The test of the proposed methodology in industrial use-cases
- Incorporating a wider range of process prototypes and equipment definitions
- Extending the methodology to cover a wider part of the design process to include for example incomplete product definitions

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