Collaboration in Heterogeneous Environments along Product Processes

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ABSTRACT

As collaborative partners in heterogeneous engineering environments work on different life-cycle stages, tasks, and disciplines, they use, by nature, different related ontologies. Thus, the concept of facilitating a shared ontology is pragmatically unrealistic. Based on multiple related product ontologies, we propose an architecture, in which collaboration can be performed without ontological commitment.

The architecture is based on a brokering mechanism, which is communicating with all participating sites through intelligent agents. The brokering apparatus contains the least common denominator information about the participating sites, as well as product modelling-specific mappings across ontologies. Partners can either use a single ontology from the same domain (for instance, two subcontractors providing the same service), or from a related domain (for example, marketing vs. design, or conceptual design vs. embodiment). The collaboration, which can be handled by the system, encompasses the synthesis of the agent protocol based on the core ontology, creation of mappings between agent messages and local protocols, query definition, query mediation, and conflict resolution. The entire system (architecture, ontologies, mappings, and collaboration mechanism) is demonstrated with an example scenario that is based on experience from industrial projects.

INTRODUCTION

The emerging new paradigm of enterprise operation is that of *virtual enterprises*. It sets new challenges to enterprise and system integration, which have to be answered using qualitative requirements, such as:

- in its purest form a virtual enterprise is a consortium that is created through opportunistic negotiations for satisfying unique customer needs;
- an infrastructure is needed for supporting engineering processes across company borders of the dynamic consortium; and
- independent parties cannot be expected to apply centralised or shared data, instead the product and process knowledge lies in distributed and potentially inhomogeneous systems.

Thus, virtual enterprises have to be based on facilities for collaborating across heterogeneous environments and along the various company processes. In order to improve the conditions for such collaboration it is necessary to gain a better understanding of processes, the required infrastructure, as well as related product and process models. In this paper we address these three issues as follows:

1. In order to illustrate problems of a concrete case we have generated a scenario with an example product and related process. The product and participating companies are imaginary, however, they are created in analogy with cases that have been found in industrial projects.
2. We propose an agent broker architecture that provides an open and flexible infrastructure, which is required for virtual enterprises. It reflects the change from exchange of paper or electronic documents towards accessing shared information through mediating brokers.
3. We further suggest an approach for managing multiple related product ontologies and mappings among them. The approach is demonstrated by sample ontologies, which are part of the accompanying example.

The outline of the paper is follows. First, a generic engineering process is described, which covers the product process as well as its customer order satisfaction counterpart. Then, an example scenario is given, which uses a hypothetical product process of thermometer engineering, which is kept a simple as possible for didactical reasons. Next, a prototypical architecture is presented, which consists of participating sites (including ontologies and some product-related data), a broker (including core rules, a mediator, and terminological mappings), as well as agents through which the communication is performed. Then, collaborative aspects are discussed, which concentrate on agent functionality and their interfaces to ontologies and the broker. The paper concludes with a summary of our contribution and outlines further work.

ENGINEERING PROCESSES

For almost all companies the core process is the sequence of activities to make and sell their products to customers. We call it the *customer order satisfaction process,* which typically includes steps such as offering products on a market place, selling them to the customer, engineering the ordered product according to customer specifications, planning the production, buying materials and modules, manufacturing products, and finally shipping and installing them. Another main process of a virtual enterprise is the *product process* for developing products that can be successfully offered to the market through the customer satisfaction process. Figure 1 illustrates these two processes (Mäntylä, Ranta and Kress, 1997). In this paper we focus on the order and product configuration stages of the customer order satisfaction process.

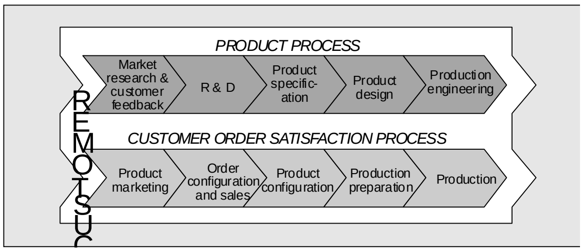

Fig. 1 Engineering processes of an industrial company

In a virtual enterprise customer order satisfaction and product processes do not take place in a single company, but across company borders. An example of such collaboration was studied in the IMS/GNOSIS project that realised a demonstration on the product life-cycle along the product process reaching from conceptual design to manufacturing preparation and simulation (Ranta et al., 1996). The experiment showed that the challenge of system integration lies in linking independently defined inhomogeneous software systems that cannot be assumed to be sharing any central product model or to be based on common standards. It cannot be assumed that collaborating companies would adapt to use the same tools, as even in a single company different disciplines use specific systems and departments may prefer different software for the same functionality.

Furthermore, the demonstration has shown the potential power of using high-level mappings in contrast to the more conventional sharing of neutral low-level product data. Standards such as STEP for product data representation and SDAI protocol for accessing data, and EDI tools for electronic data interchange and XML for electric commerce provide good tools for integrating heterogeneous systems such as CAD, CAM, operation management, product data management, or workflow management. Still, none is covering all the communication needs; various disciplines need their particular standards, new standards and versions are constantly introduced as industries and technologies develop. Furthermore, companies require more than generic means to be allowed to utilise their own product and process concepts instead of being forced to just adapt to commonly agreed standards and ways of operation.

The integration of the product-related processes in a virtual enterprise has to be based on the understanding how to carry out communication among partners that have to apply different product and process concepts, that is across heterogeneous ontologies. The concept of ontology is defined by Tom Gruber (1993), the father of Ontolingua, as follows: *"An ontology is a specification of a conceptualisation [...] That is, an ontology is a description of the concepts and relationships that exist for an agent or a community of agents [...] for the purpose of enabling knowledge sharing and reuse."* Our intention is to form a basis for managing ontologies and their relationships so that the discourse between communicating partners is supported, while allowing that each of them can maintain their individual ontologies. Thus, we base the approach on *mappings between multiple ontologies* instead of other alternatives which insist that partners adapt to commonly shared ontologies.

As a summary our approach is based on the following assumptions that rise from characters of product-related processes:

- It cannot be assumed that partners are using a common standard or a shared ontology in the case of a network of quasi-independent companies. As the companies work on different product life-cycle stages, tasks or disciplines they have different ontologies and an idea of an all covering standard or ontology is unrealistic.
- It cannot be assumed that there will exist a straightforward mapping between the product ontologies of the parties along product processes of a virtual enterprise. This means that mappings between ontology hierarchies are not supposed to cover only leaf nodes, but also relationships to non-leafs.
- Instead of a holistic mapping mechanism, the aim is to find the minimal common ontology mapping that allows communication. Furthermore, we see that the

mappings of the ontologies evolve according to new communication needs.

By looking at the product related processes in Figure 2, it can be noticed that they include collaboration both of parties that come from same or similar domains and of parties that have quite different viewpoints and background. Thus, collaboration in two cases has to be supported:

- parties of the same domain or discipline such as two subcontractors providing the same service, or
- parties from similar or related domains, such as marketing and design, or conceptual design and embodiment.

EXAMPLE SCENARIO

The chosen example scenario is taken from a customer order satisfaction process and a simple thermometer is used as a sample product to demonstrate different ontologies. As we will show that different parties have different viewpoints and ontologies of thermometers, however, the following bill-of-materials gives an understanding our simplified thermometer model:

```
Thermometer
   Case
      Back case
      Scale
   Tube
      Glass tube
      Liquid
```

Fig. 2 Thermometer Bill-of-Materials

The scenario includes seven parties that are shown in Figure 3. They include contractors, subcontractors and subsubcontractors; two of the contractors are competitors offering similar products:

- A Customer is looking for a thermometer.
- A Thermometer Retailer, whose ontology hierarchy is shown in Figure 4, is a company that sells various kinds of thermometers and uses subcontractors for the actual manufacturing.
- Thermometer Manufacturer 1, whose ontology hierarchy is depicted in Figure 5, is a factory that assembles thermometers from parts that are manufactured in its own factory (case) or modules bought from subcontractors (tube).
- Thermometer Manufacturer 2 (Figure 6) is a factory that assembles thermometers and manufactures the parts itself from bought raw materials or basic parts (liquid, glass, metal, PVC, various woods).
- The Thermometer Tube Manufacturer produces the thermometer core that includes the tube and liquid.
- An Industrial Chemicals Provider sells industrial chemicals that include mercury and red alcohol (or spirit) that can be used for thermometers.
- A Glass Manufacturer produces various objects from glass including the tubes with bulb applied in thermometers.

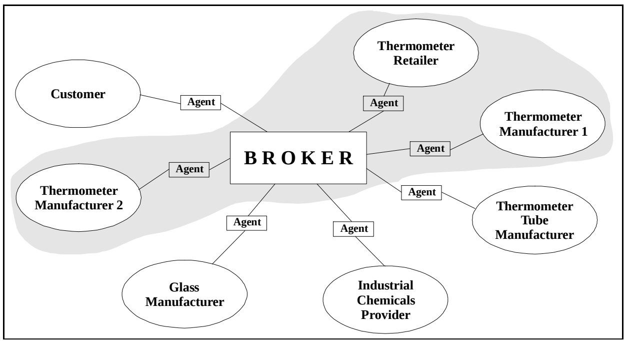

Fig. 3 Example Scenario

The scenario is concerned about the order and product configuration phases of the customer satisfaction process as it is assumed that the thermometer is to be a configurable product that is assembled from existing components without including any engineering or design.

The Customer is sending a request for a thermometer with certain properties to the broker who initiates the process. The broker initially locates thermometer providers that have introduced themselves and tracks down the Thermometer Retailer, then maps the request to the ontology of the it, and forwards the request accordingly.

The Thermometer Retailer processes the Customer request information into a proper sales configuration description; and sends an invitation of manufacturing tenders to the broker.

The broker checks the known thermometer manufacturers, that is Thermometer Manufacturer 1 and Thermometer Manufacturer 2; maps the invitation of tenders into the manufacturing ontologies of; and forwards the tender invitation to the Thermometer Manufacturer 1 and Thermometer Manufacturer 2. Thermometer Manufacturer 1 processes the invitation and notices that it needs a tube subcontractor, sends an invitation for tube tenders through the broker and, again, receives a tender through the broker from the Tube Thermometer Provider, and finally sends the resulting tender for manufacturing the product to the broker.

Thermometer Manufacturer 2 processes the invitation of tenders and becomes aware of the request for liquid and glass providers, uses the broker services to locate the Industrial Chemicals Provider and the Glass Manufacturer as subcontractors, and finally sends the resulting tender back to the broker.

The broker carries out the negotiation using pre-specified ontology mappings and forwards the tenders from the Thermometer Manufacturers 1 and 2 to the Thermometer Retailer. Then, the Thermometer Retailer sends an answer via the broker to the Customer with product information and price, which can be accepted (or refused) via the broker.

After this the process proceeds to production preparation and production, which are not considered in the scenario.

A PROTOTYPICAL ARCHITETURE

We now propose prototypical architecture in which collaboration in heterogeneous environments along product processes can be deployed. Each participating site contains some local product-related data, usually stored in databases or data warehouses, and a product-related ontology. These components are loosely coupled to a broker; the communication is performed through intelligent (transport) agents. The overall architecture is depicted in Figure 4. The outlined architecture has partially been adopted from Mena et al. (1996), and thus can be used as a generic vehicle for interoperation across ontologies, which is not limited to product data environments.

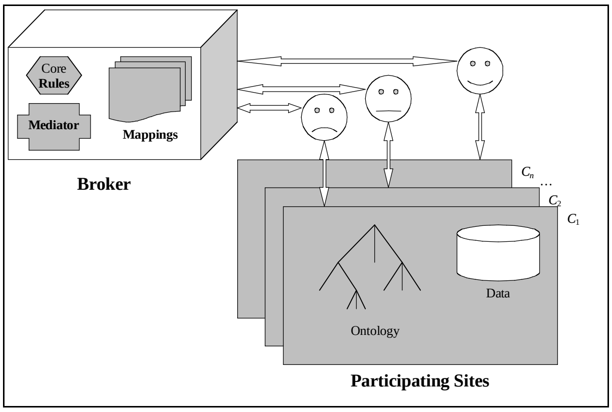

Fig. 4 A Prototypical Architecture

The broker contains a set of core rules, which contain system generic functionality, for instance, how to join a collaboration, how to specify mappings, et cetera. It also contains the mediator itself, which takes requests from the agents and negotiates among other sites based on the mappings, which are also located at the broker. The mappings, as described in (Büchner et al., 1999), provide a mechanism to specify semantically equivalent concepts across ontologies. From an architectural point of view, a mediator is an independent application layer, located between a data source layer and a data source (Wiederhold, 1992; Lee, Madnick and Siegel, 1996). Each mediator has an interface to each boundary, namely a resource access interface to the database (for example, a product catalogue) and a service interface to the application (for instance, production scheduler). The mediator itself contains domain-specific code, which is based on a pre-defined terminology. From a product modelling-centred view, these can be is-a, part-of, generalisation and abstraction. From an ontology modelling viewpoint they are synonyms (end-node – end-node), hyponyms (end-node – node), hypernyms (node – end-node), as well as alternatives (combinations thereof). The update of mappings is also performed through the agents.

The architecture shown above is purely based around the product process. Ideally, it should have close links to other organisational units and functions, which are located in an enterprise-scale system. Manola et al. (1998) have suggested such an OMG-architecture that is based on distributed objects and services, which communicate through an object request broker. For the purpose of this work, we concentrate on the product process outlined so far. Connecting local components of a virtual enterprise to an organisation-wide infrastructure is beyond the scope of this paper.

The remainder of the paper will discuss ontological representation of partner sites, as well as the communication applying intelligent agents. For further information on the mediation mechanism and broker-related operational issues, the reader is referred to Büchner et al. (1999).

ONTOLOGIES

We demonstrate the ontology mapping approach by focusing on the collaboration of the three core partners that are indicated by the grey shading in Figure 2. The thermometer retailer and the two thermometer manufacturers are communicating according to different views to the product configuration.

On the one hand, the retailer is concerned about sales attributes and available designs as shown in Figure 5. On the other hand, the manufacturers see the product as a configuration that reflects the bill-of-materials which differ according to their manufacturing and market orientation.

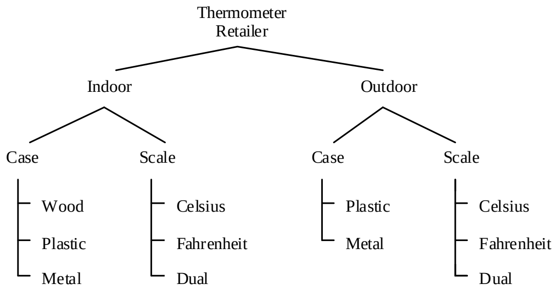

Fig. 5 Thermometer retailer thermometer ontology

Thermometer Manufacturer 1, whose ontology is shown in Figure 6, purchases the tube core for the thermometer from a subcontractor and is not concerned on its detailed structure. Furthermore it is exporting globally and thus offers different scale options, however, only indoor models.

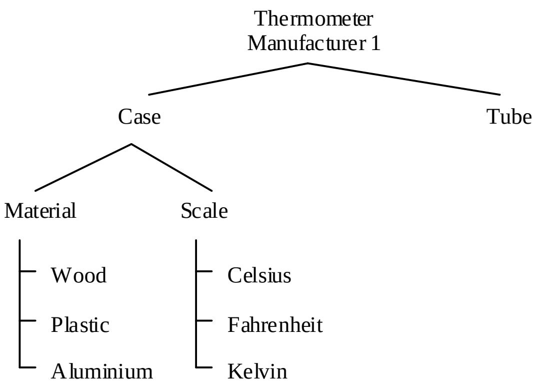

Fig. 6 Thermometer Manufacturer 1 thermometer ontology

Thermometer Manufacturer 2, whose ontology is shown in Figure 6, assembles the thermometer tube in-house and thus the glass as well as two types of liquids are included in its ontology. All thermometers have a domestic Celsius scale and two wood types Oak and Pine are included.

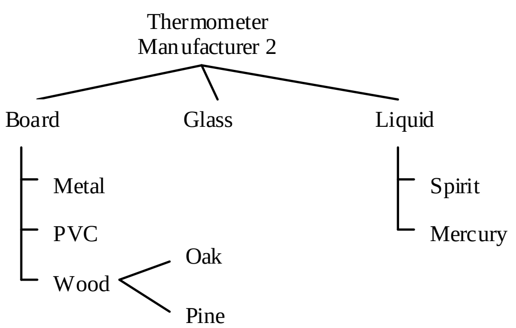

Fig. 7 Thermometer Manufacturer 2 thermometer ontology

The broker maintains mappings between the ontology hierarchies of the collaborating partners as shown in Table 1. The two left-most columns show the mappings from Retailer (*R*) concepts to the concepts of each of the Manufacturers (T_1 and T_2). The third and fourth column show the modelling and relationship types.

Table 1. Retailer — manufacturers ontology mappings

Retailer	Manufacturer	Modelling	Relationship	Conflict
R.Wood	T1.Wood	leaf — leaf	is-a	synonym
R.Wood	T2.Oak _ T2.Pine	leaf — leaf	is-a	alternative
R.Plastics	T1.Plastics	leaf — leaf	is-a	synonym
R.Plastics	T2.PVC	leaf — leaf	is-a	synonym
R.Metal	T1.Metal	leaf — leaf	is-a	synonym
R.Celsius	T1.Celsius	leaf — leaf	is-a	synonym
R.Celsius	T2	leaf — nonleaf	specialisation	hypernym
R.Fahrenheit	T1.Fahrenheit	leaf — leaf	is-a	synonym
R.Case	T1.Material _ T1.Scale	nonleaf — nonleaf	is-a	alternative
R.Case	T2.PVC	nonleaf — leaf	generalisation	hyponym
R.Indoor	T1	nonleaf — nonleaf	specialisation	hypernym
R.Indoor	T2.Wood	nonleaf — nonleaf	generalisation	hyponym

The last column indicates semantic conflicts classified into four types as explained in (Büchner et al., 1999) which describes the ontology mappings and semantic mediation in detail[1]:

Def. 1. Given two ontologies o_1 and o_2, a relationship $r_s(c_1, c_2)$ is defined as **synonym**ous iff $c_1 \in o_1 \wedge c_1$ has outdegree 0 and $c_2 \in o_2 \wedge c_2$ has outdegree 0. ¨

An example of a synonym is T_1.Case.Material.Plastic and T_2.Board.PVC.

Def. 2. Given two ontologies o_1 and o_2, a relationship $r_r(c_1, c_2)$ is defined as **hypernym**ous iff $c_1 \in o_1 \wedge c_2 \in o_2$ and c_1 has outdegree = 0 and c_2 has outdegree ≥ 1. ¨

Def. 3. Given two ontologies o_1 and o_2, a relationship $r_o(c_1, c_2)$ is defined as **hyponym**ous iff $c_1 \in o_1 \wedge c_2 \in o_2$ and c_1 has outdegree ≥ 1 and c_2 has outdegree = 1. ¨

A single example can illustrate the defined symmetric relationships. T_1.Case.Material.Wood is hyponymous to both, T_2.Board.Wood.Oak and T_2.Board.Wood.Pine, whereas T_2.Board.Wood.Oak and T_2.Board.Wood.Pine are hypernymous to T_1.Case.Material.Wood.

Def. 4. Given an ontology space *O*, a relationship $r_a(c_1, c_2, \ldots, c_n)$ is defined as **alternative** iff $c_i \in o_i$ and $c_1 \equiv c_2 \vee c_1 \equiv c_3 \ldots \vee c_1 \equiv c_n$, where the symbol ≡ represents a synonymous, hypernymous or hyponymous relationship. ¨

For example, T_1.Case.Wood can either be T_2.Board.Wood.Oak *or* T_2.Board.Wood.Pine. Equivalently, T_1.Case.Wood is the same as T_2.Board.Wood.

[1] The outdegree of a node *n* is the number of arcs leaving *n*.

In the following the ontology mappings are illustrated by showing how example requests from the retailer are mapped into the ontology hierarchies of the two manufacturers.

Example 1. The Thermometer Retailer requests an indoor wooden Fahrenheit thermometer as shown in Table2. Thermometer Manufacturer 1 can deliver a wooden Fahrenheit thermometer as all its models are suitable for indoor usage. Thermometer Manufacturer 2 cannot deliver since no correspondence to Fahrenheit exists. Notice that the second row of the table shows that R.Wood is hyponymous to T_2.Pine and T_2.Oak; the inverse is a hypernymous relation.

Table 2. Indoor wooden Fahrenheit thermometer

Retailer	Manufacturer 1	Manufacturer 2
R.Indoor.Case.Wood	*T*1.Case.Material.Wood	*T*2.Board.Wood.Pine *T*2.Board.Wood.Oak
R.Indoor.Scale.Fahrenheit	*T*1.Case.Scale.Fahrenheit	
R.Indoor	*T*1	*T*2.Wood

Example 2. The Thermometer Retailer requests an outdoor plastic Celsius thermometer as shown in Table 3. Thermometer Manufacturer 1 can deliver a plastic Celsius thermometer, as all of its models are suitable for outdoor usage. Thermometer Manufacturer 2 can deliver a PVC thermometer as all its models are suitable for outdoor usage and have a Celsius scale.

Table 3. Outdoor plastic Celsius thermometer

Retailer	Manufacturer 1	Manufacturer 2
R.Outdoor.Case.Plastic	T1.Case.Material.Plastic	T2.Board.PVC
R.Outdoor.Scale.Celcius	T1.Case.Scale.Celsius	T2

Example 3. When Thermometer Manufacturer 1 receives an order, it needs to look for a subcontractor from whom to purchase the tube component. For this purpose it will use the services of the Thermometer Tube Manufacturer, who in turn uses the services of the Glass Manufacturer and the Industrial Chemicals Provider.

Analogously, when the Thermometer Manufacturer 2 receives an order, it will need to purchase glass from the Glass Manufacturer and liquid from the Industrial Chemicals Provider.

The ontological hierarchies of the Thermometer Tube Manufacturer, Glass Manufacturer, and Industrial Chemicals Provider are not presented here. However, the Glass Manufacturer among a different glassware concept (viz. tube with a bulb) that corresponds to the glass of Thermometer Manufacturer 2. In an analogous way the Industrial Chemicals Provider provides various metals and spirits (mercury and red alcohol) that correspond to the concepts spirit and mercury of the Thermometer Manufacturer 2. These two cases are examples of how only partial mappings are relevant between ontologies from distant domains.

COMMUNICATION THROUGH AGENTS

The proposed prototypical architecture with respect to the autonomy of the parties along the product related processes preclude the use of standard methodologies, such as shared databases as a basis of integration. Thus, a loose integration model based on agents and a broker is adapted as shown in Figure 3. The objective of the approach is to provide a framework for several independent agents, having their own product ontologies, to collaborate and co-ordinate their activities.

The A3E system (Artefacts-Activities-Actors-Events) provides a co-ordination system that supports virtual enterprise creation and distributed dialogues on the basis of Internet agents (Ranta and Mäntylä, 1998). This system is the basis for our agent approach.

The role of a matchmaker, which has another role and may be a different entity than the previously discussed broker, is to provide an open market place for agents. Through the matchmaker the agents make the services they provide visible to other agents and make their request for services that they request from other agents. The matchmaker facilitates ontology mappings and negotiations between agents. It may also hide or abstract sensitive information in order to providea sufficient degree of security between the agents.

Agents act on behalf of individual parties. They become aware of the other agents and their capabilities trough the matchmaker. Agents exchange information with other agents using a communication protocol such as (UMBC) KQML that is used in A3E.

In addition to provide various kinds of engineering data systems dynamic interface for data exchange and conversion they may be encapsulated by agents. The proposed methods for managing multiple ontologies can be utilised to allow agents to carry out mediation in particularly for legacy systems.

The implemented co-ordination framework of A3E consists currently of three related components:

- matchmaking for locating agents on the basis of their declared capabilities;
- dialogue control for creating and keeping track of dialogues among agents on the basis of replicated model entities; and
- event propagation of replicated entities.

For example, the matchmaking service is required in the example scenario as the thermometer retailer and thermometer manufacturers have to find each other. Figure 8 shows two messages that are related to the matchmaking.

```
(advertise
  :receiver broker
   :sender server1%6
   :language KQML
   :ontology thermo-serv
   :reply-with advertise-1
   :content (offer-activity
 :sender ?client
 :receiver server1
 :ontology ?t-activity-instance
 :content ?activity))

 a) Advertising
```

```
(recommend-one
  :receiver broker
  :sender client%8
  :language KQML
  :ontology contract-customer-client
  :reply-with recommend-1
:content (offer-activity
:sender client
:receiver ?server
:ontology ?t-activity-instance
:content ?activity))

 b) Recruting
```

Fig. 8 Messages related to the matchmaking scenario

The agents presenting these service providers will *advertise* their capability to the broker. Next, the Thermometer Retailer contacts the matchmaker to find an agent capable of processing messages of the type given in the content field of the *recommend* message. To provide the recruiting service the matchmaker scans all its agent models and tries to match the message pattern of the client with the advertised message patterns.

BACKGROUND AND RELATED WORK

The ontology concept, as understood in here, was originally introduced in the artificial intelligence research field for sharing knowledge between independently developed knowledge-based systems. The DARPA Knowledge Sharing Effort conducted in the USA during early 90's developed specifications of tools to facilitate knowledge transfer across heterogeneous systems including the KIF - Knowledge Interchange Format (X3T2, 1995), the KQML - Knowledge Query and Manipulation Language (Finin et al., 1994), and the Ontolingua language (Gruber, 1993). The OKBC - Open Knowledge Base Connectivity proposal of Chaudhri et al. (1998) is a recent significant effort in knowledge sharing. These indicate only the central sources of ontologies for knowledge sharing that have inspired us.

Several research groups have proposed approaches where artificial intelligence knowledge sharing methods are applied in enterprise and process modelling. The Enterprise Ontology of the University of Edinburgh by Uschold et al. (1998) is developed in Ontolingua and is mainly aimed at enterprise modelling and integration. The TOVE - Toronto Virtual Enterprise project (Fox and Gruninger, 1994) aims to develop an ontology that provides a shared terminology that every application can jointly understand and use, and defines the semantics of each term as precisely and unambiguously as feasible. These activities are aimed towards enterprise and process modelling based on shared terminology, whereas our aim is at allowing multiple ontologies.

CONCLUSIONS

We have proposed an architecture, which allows the collaboration in heterogeneous environments along product processes, as they exist in virtual enterprises. The loosely coupled system guarantees the autonomy of each component, which can easily scale up and provide a flexible mechanism for interchanging product-related data. The novel approach of allowing mapping definitions of relevant information across participating sites has justified the work being carried out. The mappings, which form the semantic interface among sites, are based on local ontologies, which are used for mediation purposes. The mediator as well as the querying and responding sites communicate through intelligent agents.

Future work has three directions that are suggested by the current limitations on the collaboration support, product processes and needs of enterprise integration:

- This paper gives a very narrow view to the needs of collaboration in the heterogeneous environments of virtual enterprises. Obviously, the brokering infrastructure must include means for the creation and modification of ontology hierarchies. Furthermore, negotiations that take place during the consortium generation must be supported properly.
- The test scenario was chosen from a customer satisfaction process of configurable products in order to present the basic approach and mechanism in a comprehensive way. However, a future challenge is to study the product development process where collaboration is more intensive and requires more sophisticated negotiations. Product development processes will also provide a good scenario for studying evolving ontologies and mappings.
- In order for members of virtual enterprises to work together, it is insufficient to just exchange product information. It is also necessary to co-ordinate shared activities. Thus, we need to study process ontologies as groundwork for the communication,

co-operation, and co-ordination of virtual enterprises and teams.

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