SAND2007-2386C

Semantic Web Technologies for Knowledge Management of Small-Scale Virtual Manufacturing Enterprises

John S. Bowers[1], John M. Linebarger[2], J. Cecil[3]
[1]Concurrent Design and Manufacturing Program, Sandia National Labs, Albuquerque, NM, jsbower@sandia.gov
[2]Integrated Knowledge Management Solutions, Sandia National Labs, Albuquerque, NM, jmlineb@sandia.gov
[3]Center for Information Based Manufacturing, New Mexico State University, Las Cruces, NM, jcecil@nmsu.edu

Abstract: **Enabled by advances in global information infrastructure, businesses have adopted an organizational paradigm known as a Virtual Enterprise (VE). A Virtual Manufacturing Enterprise (VME) is a type of VE that is focused on the manufacture of products. Information Technology (IT) and knowledge management (KM) often function as the glue that hold VEs together. The larger the number of partners the greater the knowledge management problem, because of differences in technology, terminology, and data formats. These knowledge management issues can be subdivided into three categories: standardization, automation, and integration. The adoption of common standards for technology, terminology, and data is an ideal solution to this problem, but is rarely achievable across organizational boundaries in practice. This is especially true when the VME is relatively small-scale, has heterogeneous information technology systems, and accounts for a small percentage of each of their suppliers' business. The contribution of this paper is to review VME-related research work in an emerging area called "the Semantic Web;" to note that existing research has not focused specifically on the use of the Semantic Web for small-scale VMEs; and to propose several strategies for using Semantic Web technologies for small VMEs to address the three knowledge management issues identified above.**

Keywords: **virtual manufacturing enterprises, information based manufacturing, knowledge management, Semantic Web, ontologies**

I. VIRTUAL ENTERPRISES

The global information infrastructure (*e.g.*, the Internet) and business practices continue to advance and mature. Consequently, businesses and organizations, which are enabled by these advances, are now able to consider a new organizational paradigm known as Virtual Enterprises (VEs). A VE is an organizational model that is an opportunistic (or temporary) network of core competencies throughout several independent, geographically dispersed organizations, which include suppliers and customers that perform as a single enterprise [1,2,3]. Another definition is that a VE is a consortium of companies with diverse resources and expertise that forms a temporary partnership in order to respond quickly to changing global market opportunities [4].

Key characteristics of a VE include partnering, collaboration, and cooperation; agility and adaptability; world-class capabilities and technologies; geographic distribution and borderless operations; trusting and trustworthy behavior; and integrated business development, project management, systems engineering, and information technology capabilities [1,3]. Core capabilities are maintained within each partner, and other activities (*e.g.*, inventory, warehousing, and staffing) can be externalized [5].

II. VIRTUAL MANUFACTURING ENTERPRISES

As outlined in [6,7], the manufacturing industry strives to be lean, agile, and global. This tendency leads to the concept of a VE with several sub-production units that are strategically and geographically dispersed worldwide as branches, joint ventures, subcontractors, and alliances. In order to effectively meet today's challenges, a VE must be formed based upon core-complementary competencies, organized to manage change and uncertainty, and able to leverage people and information [7].

A Virtual Manufacturing Enterprise (VME) is a type of VE. In a VME, the focus of interest is a product, which is the outcome of collaborations among various VE partners. The characteristics of a "true VME" (as well as a "true VE") have been identified as follows [4]:

- Partners in a VME should belong to different organizations with different areas of expertise;
- Partners should be geographically distributed;
- The computer-based systems used must be heterogeneous;

- The software applications used must be implemented in a variety of software languages (*e.g.*, Java, C, and C++);
- The Information Technology (IT) used must support seamless information exchange.

III. INFORMATION BASED MANUFACTURING

Information Technology (IT) and knowledge management (KM) often function as the glue that hold VEs together. This is especially the case for virtual manufacturing enterprises (VMEs) because of the large amount of richly interconnected information and data that needs to flow seamlessly between the customer and its suppliers. Since the customer does not actually make or test the product, it is the information that serves as the proxy for knowledge and control during the entire product development life cycle (which can include design, manufacturing, assembly, and testing). The larger the number of suppliers the greater the knowledge management problem, because of differences in technology, terminology, and data formats. These knowledge management issues can be subdivided into three categories: standardization, automation, and integration. The adoption of common standards for technology, terminology, and data is an ideal solution to this problem, but is rarely achievable across organizational boundaries in practice. This is especially true when the VME is relatively small-scale, has heterogeneous information technology systems, and accounts for a small percentage of each of their suppliers' business.

In recent years, research in an emerging interdisciplinary subject called Information Based Manufacturing (INBM) has catalyzed the adoption of cutting edge IT to support VMEs [8,9]. INBM can be described as a field which emphasizes the study and use of techniques, frameworks and technology dealing with (1) modeling; (2) visualization and simulation; and (3) exchange of information as it pertains to product and process design activities across a range of domains (from traditional parts manufacturing to advanced micro assembly applications). INBM principles, concepts and practices are beginning to have a substantial global impact on the way in which products are designed and manufactured. Semantic Web technologies, the focus of this paper, fall under the category of Information Exchange within INBM. Additional discussions of the various computing architectures and collaborative frameworks used in manufacturing can be found in [10,11].

IV. SANDIA NATIONAL LABORATORIES' VME

Sandia National Laboratories (SNL) utilizes the VME concept for one of its component manufacturing organizations. Currently, the collaborators include a site in New Mexico where complex high reliability electronic components are designed, approximately twelve supplier sites where the components are designed and produced, and a production site in Missouri where the components are used in the resulting assemblies. A conceptual view of SNL's VME is shown in Figure 1.

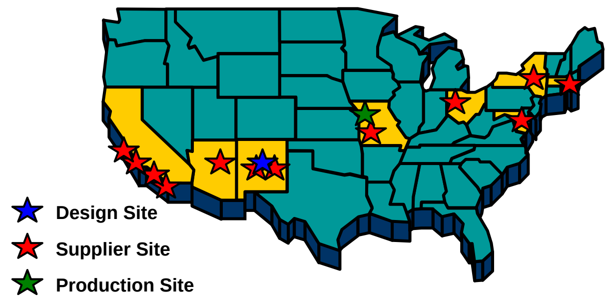

Figure 1. Sandia's Virtual Manufacturing Enterprise

A distinguishing characteristic of SNL's VME is that it is small-scale. The supplier network includes approximately twelve suppliers. The total number of unique components that are produced by this VME is approximately 100. Typical lot sizes are between 100 and 300 units. Production of these lots is discontinuous. Each component is unique, and has stringent quality and reliability requirements. As a result, SNL accounts for a relatively small portion of the business of each of its suppliers.

V. SEMANTIC TECHNOLOGIES

The Semantic Web is the brainchild of the inventor of the Web itself, Sir Tim Berners-Lee. Berners-Lee envisions the Semantic Web as a Web of meaning, not just a Web of data. Currently, the World Wide Web consists of trillions of pages of text marked up using HTML (Hypertext Markup Language). As a markup language, HTML controls the format of the information on the screen. Thus HTML is display-oriented; the intended audience is human. However, HTML has no way of specifying the meaning (or semantics) of the data on the Web page, merely its format. Neither do XML (Extensible Markup Language) and XHTML (Extensible HyperText Markup Language), the successors of HTML. These markup languages allow the structure of the data to be user-defined, but are unable to specify the semantics of the information.

Unlike the current Web, which is display-oriented and intended for a human audience, Berners-Lee has proposed that the Web of meaning be semantics-oriented and intended for a mixed audience, which would consist of both humans and computers. In his famous 2001 Scientific American paper entitled "The Semantic Web," which inaugurated the Semantic Web field, a scenario was presented in which automated Web search programs (called "Webbots") used information on semantically marked-up Web pages to make medical appointments under tight constraints of time and proximity [12]. Such a capability is simply not possible using HTML; some way of indicating the semantics of a Web page is needed.

The semantics of a Web page are specified by tagging them with entries taken from a shared ontology. The word "ontology" was taken from the domain of philosophy, where it means *existence*. However, in Computer Science contexts, ontology generally means *essence*, a characterization of the structure and vocabulary of a particular domain. A well-known definition of ontology can be found in [13], where it is defined as "a specification of a conceptualization." The one that the present authors prefer is that an ontology is a network map of terms in a shared concept space, made logically rigorous to enable automatic inferencing. Intuitively, an ontology can be conceived of as a network representation of the key terms in a domain, and the logically precise nature of the relationships between the terms. In that sense, an ontology forms a shared cognitive model for a domain. In philosophical terms, when a Web page (or any other data item) is semantically marked up in terms of an ontology, that Web page or data item "commits" to that ontology, to that particular way of structuring the world.

Several computational representations, each based on XML, have been developed to encode ontologies for the Semantic Web. These representations build on each other in a layered fashion, and have been standardized by the World Wide Web Consortium (otherwise known as W3C). The first is the Resource Description Framework (RDF), which builds on XML to allow semantic metadata to be represented in a network (or lattice) fashion. The second is RDF Schema (RDFS), which builds on RDF and allows concept and property hierarchies to be created. Concepts are called classes, and instances of a class are called individuals. Properties represent relationships between individuals. For example, a Web page tagged with the ontology class "Manufacturing Process" is considered an instance or individual of that class. Currently, the top of the ontology layer cake is the Web Ontology Language (OWL), which builds on RDFS. OWL adds formal reasoning constructs to the ontology, which allows other facts to be inferred from the asserted facts. For example, suppose a class called "Problem Areas" is logically defined as the set of all manufacturing projects where either the projected cost is greater than the budgeted cost, or the schedule date is greater than the desired date. By running the reasoner against the asserted facts, those manufacturing projects that met the definition criteria would automatically be inferred (and thus tagged) as members of the Problem Area class. OWL comes in three flavors, OWL Lite (which has limited semantic extensions to allow greater tool support), OWL DL (the "Description Logic" version, which adds decidable inferencing capabilities, and is the level of OWL chosen for many Semantic Web applications); and OWL Full (the most expressive and powerful version of OWL, but one in which inferencing is no longer computationally tractable).

Typical applications of ontologies and semantic technologies include information integration (also known as Enterprise Information Integration, or EII) and ontology-driven search (also known as semantic navigation). Information integration is accomplished by using a shared ontology to integrate disparate heterogeneous data sources. A query is made in terms of the shared ontology, which is mapped to the intermediate ontologies of each of the data sources. The relevant data is retrieved from each data source, and the results are combined and presented in terms of the shared ontology. For example, the 45th Space Wing of the United States Air Force is using a shared ontology to integrate numerous databases from over 20 programs to deliver what they call a Single Integrated Range Picture [14].

Semantic navigation is a form of information integration that is generally applied to the browsing of Web sites. It is generally seen as much more intuitive than keyword search, but it is often combined with keyword search to increase its power and flexibility. An ontology is divided into several orthogonal facets, and artifacts on the Web site are tagged with ontology values from each of the facets. Each ontology facet is organized hierarchically, and is in effect a small taxonomy. For example, a museum might divide information about its artifacts into several different ontology facets, such as artifact type, material, manufacturer, place of manufacture, date of manufacture, user, place of usage, and situation of use. Generally, each artifact is tagged with a single ontology value from each of the facets, but depending on the application domain, multiple (or even zero) ontology values from a particular facet may be applied to an artifact. The initial search screen displays all of the ontology facets as well as a single level breakdown of each of the facets; attached to each of the entries in the breakdown is a count of the number of artifacts that have been tagged with that facet value. Navigation then proceeds at the "speed of click" as facet values are chosen, results are displayed, and the facet counts recalculated to reflect the facet breakdown of the result set. A history of the facet choices that apply to each result set (called "breadcrumbs" because they reflect how the user has arrived at that particular result set) is displayed on the top of the result set screen. An example of a Web site that uses semantic navigation is the archives of the Environmental Health News [15]. Experiments have indicated that if a user is not familiar with the contents of a particular Web site, a desired artifact can be retrieved more quickly using semantic navigation than keyword-based search [16].

VI. RELATED WORK

Some of the work on the use of semantic technology in the engineering and supply chain domains predates the Semantic Web. The Mediator system by Gaines *et al.* [17] and the Active Catalog work of Kim *et al.* [18] are examples of such work. Roche *et al.* [19] briefly discuss the role of ontologies in virtual manufacturing enterprises, but their focus is more on multi-agent systems that use ontologies to communicate. An upper-level (or foundational) ontology for manufacturing, called MASON, has recently been proposed [20]; a portion of the top-level is depicted in Figure 2.

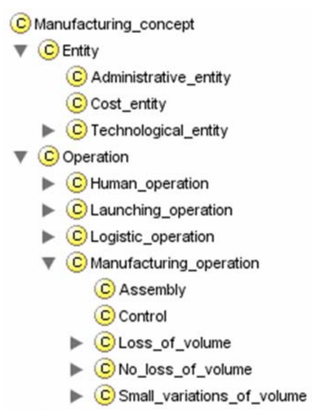

Figure 2. Portion of Top-Level of MASON Ontology

Research work in a manufacturing context can be grouped into three categories: (1) research highlighting the need for ontologies and information sharing; (2) research focusing on using ontologies for a segment of the manufacturing life-cycle; and (3) research which provides a detailed implementation based on Semantic Web technologies to support the complete life-cycle of products in a specific domain. Papers such as [21,22] that have highlighted the role of ontology and knowledge sharing fall under category 1. In category 2, papers have been published dealing with production planning issues, distributed manufacturing and teaming. Karageorgos *et al.* [23] briefly discuss the use of ontologies for communication between agents in doing production planning in a virtual enterprise collaboration network. In [24], the use of a Manufacturing Systems Engineering (MSE) Ontology is outlined to achieve a common understanding of manufacturing terminology used by virtual manufacturing teams. In [25], a framework to support the accomplishment of distributed process planning tasks is outlined. While the paper presents a detailed design of the collaborative process achieved using a Semantic Web Service approach, it does not address the implementation issues demonstrating the manufacturing of parts using such an approach. In [26], a segment of the paper outlines the implementation of a Semantic Web approach to accomplish distributed process planning. A three-step process is outlined including Automatic Web Discovery of services (for addressing the process planning problem input by users); Automatic Web Service Execution (where software agents can automatically execute the discovered Web Services); and Web Service Composition and Interoperation (where agents select web services, compose and interoperate them to perform process planning tasks). However, like the previous work mentioned, this paper also does not demonstrate the physical manufacturing of target parts and focuses only on distributed process planning issues.

In category 3, very little work been published detailing the design and implementation of a Semantic Web-based approach that encompasses the entire manufacturing life-cycle (from design through manufacturing or assembly). In [11], the design and implementation of a VE for micro assembly is detailed using Semantic Web technologies; the VME domain is an emerging area known as "micro devices assembly." The life-cycle of interest includes the planning, simulation, analysis, and physical assembly of micro devices. The resources in the VE are modeled as software agents that possess their own knowledge about the environment, their actions (basic and complex), their set of practical rules, and their own goals. The key agents include an User Agent, a Virtual Enterprise Agent, an Ontology Agent, a Service Directory Agent and a collection of Service Provider Agents. The agents are implemented using 3APL (Abstract Agent Programming Language), which is a relatively new agent oriented programming language for developing agents with cognitive capability [27]. The VE Agent facilitates the communication between the various agents and develops plans based on specific user requests. When a user inputs a specific micro device design, the VE Agent facilitates the communication between the various agents and builds a plan to address the user's need. The Ontology Agent in the collaborative system provides the necessary meta-information for the VE agent to further process the inputs from the User Agent. The ontologies developed (using OWL) for the collaborative system are deployed on Tomcat Web servers. The Service Directory Agent maintains a service directory (using the emerging OWL-S standard for Semantic Web Services [28]) where service provider agents publish their services, which range from assembly planning, path planning, simulation and physical assembly. After the appropriate partners are identified, the proposed plan is implemented and the life-cycle tasks are executed. Then assembly plans are proposed (including detailed 3D path plans) which are then validated by virtual reality-based simulation agents. Finally, the target micro parts are assembled by physical micro assembly cells based on the part design details and respective assembly capabilities.

A more comprehensive discussion of research publications dealing with Semantic Web-based approaches can be found in [29]. Based on the literature review presented above, it should be noted that no previous work has focused specifically on using Semantic Web technologies for *small-scale* VMEs. Additional research is needed in this promising area. The next section will present several proposals for using Semantic Web technologies for knowledge management of small-scale VMEs.

VII. SEMANTIC WEB FOR SMALL-SCALE VME'S

Semantic Web technologies are a promising mechanism for ontology-driven integration of heterogeneous data sources in a VME. Such technologies enable integration at a deeper, semantic level of common meaning, instead of just at a shallower, syntactic level of common data formats. An important observation is that not every approach to using the Semantic Web for information integration is appropriate for *small-scale* VMEs. In particular, imposing a normative ontology on all of the suppliers in the supply chain is likely to be unsuccessful, since the percentage of the suppliers' business represented by the VME is so small. The burden thus falls on the customer to perform the semantic integration, and even to generate the semantic metadata required for such integration. An *ontology mapping* approach (such as the one outlined in [11]), as opposed to an *ontology imposition* approach, may be an effective semantic integration strategy for small-scale VMEs. In ontology mapping, a reference or normative ontology is created from the standpoint of the customer, and separate descriptive ontologies are developed for each supplier. The ontologies for each supplier are then mapped to the reference ontology for the customer. Because the mapping is bidirectional, queries against the reference ontology can be decomposed into queries against the data from each of the suppliers, and the results combined and displayed in terms of the reference ontology. In the general case, ontology mapping is a difficult problem; a certain amount of simplification or scope restriction may be required to ensure that the mapping is tractable.

A beneficial side effect of an ontology mapping approach to semantic integration is that the existence of multiple ontologies can be exploited to provide multiple views on the same data. Since an ontology structures a domain, it can be considered a view of that domain. Dynamically swapping out one ontology for another allows the same data to be viewed from the perspective of a new ontology. For example, allowing user-selectable ontologies on a semantic navigation screen could allow suppliers to look at data from their own perspective as well as from the perspective of their VME customer.

Additional approaches to semantic integration are also appropriate for a small-scale VME. The use of lightweight ontologies that cover only the most critical areas of information interchange between customer and supplier, instead of heavyweight ontologies that span the entire business, are particularly applicable. Such lightweight ontologies are useful not just as a starting point for an initial implementation, but perhaps for a goal state as well. Reuse of other industry standard ontologies, such as the Dublin Core Metadata ontology for document interchange [30] and the FOAF ("Friend of a Friend") ontology for people information [31], will leverage the ontology creation process and increase the interoperability of information exchange. The use of open source or free community edition tools, such as Protégé (for ontology creation), Jena (for programmatic access to ontologies with the Java language), Pellet (for Description Logic reasoning), and MySQL (for database management of ontologies and metadata), will help reduce the cost footprint of the adoption of such technology. For small-scale VMEs, cost containment is always an important consideration. Existing information services can be exposed on the Semantic Web by creating a Semantic Web service interface for each of them, using the emerging OWL-S standard [28]. Findings from the multi-year Manufacturing Interoperability program at the Manufacturing Engineering Laboratory in the National Institute of Standards and Techology (NIST) [32], whose charter is to develop an ontology and Semantic Web tools for manufacturing interoperability, could also greatly benefit a small-scale VME by allowing them to adapt and expand on proven ideas and approaches.

ACKNOWLEDGEMENTS

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a

Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

REFERENCES

1. J. A. Byrne, R. Brandt, and O. Port. (1993). "The virtual corporation." *Business Week*, Feb. 8, 98-103.
2. W. M. Fitzpatrick and D. R. Burke. (2000). "Form, function, and financial performance realities for the virtual organization." *SAM Advanced Management Journal* 65.3, 13-20.
3. S. L. Goldman, R. N. Nagel, and K. Preiss. (1995). *Agile competitors and virtual organizations: strategies for enriching the customer*. New York: Van Nostrand Reinhold.
4. J. A. Cecil. (2003). "Virtual Enterprises." In Hossein Bidgoli, ed., *Internet Encyclopedia*, Vol. 3 (New York: John Wiley & Sons), 567-578.
5. W. B. Werther. (1999) "Structure-driven strategy and virtual organization design." *Business Horizons* 42.2, 13-18.
6. Y. Tu. (1997). "Production planning and control in a virtual one-of-a-kind production company." *Computers in Industry* 31.3, 271-283.
7. A. Gunasekaran and Y. Yusuf. (2002). "Agile Manufacturing: a taxonomy of strategic and technological imperatives." *International Journal of Production Research* 40.6, 1357-1385.
8. J. Cecil, A. Trivedi, and J. Jones. (2006). "An Information Based Manufacturing framework for Nanomanipulation." *World Scientific and Engineering Academy and Society (WSEAS) Transactions on Information Science & Applications* 3.2, 462-470.
9. J. Cecil. (2004). "Curriculum Innovation in Information Based Manufacturing." *Proceedings of the 2004 American Society for Engineering Education Annual Conference & Exposition*, June 20-23, Salt Lake City.
10. J. Bowers and J. Cecil. (2006). "Internet based Frameworks for Virtual Enterprises." *World Scientific and Engineering Academy and Society (WSEAS) Transactions on Information Science & Applications* 3.8, 1601-1606.
11. N. Gobinath, J. Cecil, and T. Son. (2006). "A Collaborative Framework to Realize Virtual Enterprises Using 3APL." In M. Baldoni and Ulle Endriss, eds., *Declarative Agent Languages and Technologies IV* Lecture Notes in Artificial Intelligence 4327 (Berlin: Springer), 191-206.
12. T. Berners-Lee, J. Hendler, and O. Lassila. (2001). "The Semantic Web." *Scientific American* 284.5, 34-43.
13. Tom Gruber, http://www-ksl.stanford.edu/kst/what-is-an-ontology.html
14. http://colab.cim3.net/file/work/SICoP/EPADRM2.0/view_pdf.asp.pdf
15. http://www.environmentalhealthnews.org/archives.jsp
16. K.-P. Lee, K. Swearingen, K. Li, and M. Hearst. (2003). "Faceted metadata for image search and browsing." *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI 2003), 5-10 April, Ft. Lauderdale, FL, 401-408.
17. B. R. Gaines, D. H. Norris, and A. Z. Lapsley. (1995). "Mediator: an Intelligent Information System Supporting the Virtual Manufacturing Enterprise." *Proceedings of the 1995 IEEE International Conference on Systems, Man, and Cybernetics*, 22-25 October, Vancouver, BC, CANADA, 964-969.
18. Jihie Kim, S. Ringo Ling, and Peter Will. (1997). "Ontology Engineering for Active Catalog." Technical Report, The University of Southern California, Information Sciences Institute.
19. C. Roche, S. Fitouri, R. Glardon, and M. Pouly. (1998). "The Potential of Multi-Agent Systems In Virtual Manufacturing Enterprises." *Proceedings of the 9th International Workshop on Database and Expert Systems Applications*, 26-28 August, 913-918.
20. S. Lemaignan, A. Siadat, J.-Y. Dantan, and A. Semenenko. (2006). "MASON" A Proposal for An Ontology of Manufacturing Domain." *Proceedings of the IEEE Workshop on Distributed Intelligent Systems (DIS 2006)*, 15-16 June, Prague, 195-200.
21. O. Nabuco, J. M. Rosário, J. R. Silva, and K. Drira. (2004). "Scientific Collaboration and Knowledge Sharing in the Virtual Manufacturing Network." *Proceedings of the 11th IFAC Symposium on Informatics Control Problems in Manufacturing,* Salvador, Brasil.
22. Baltazár Frankovič and Ivana Budinská. (2006). "The Role of Ontology in Building of Knowledge Systems for Industrial Applications." *Proceedings of the 4th Slovakian-Hungarian Joint Symposium on Applied Machine Intelligence,* 15-25.
23. A. Karageorgos, N. Mehandjiev, G. Weichhart, and A. Hämmerle. (2003). "Agent-based optimization of logistics and production planning." *Engineering Applications of Artificial Intelligence* 16, 335-348.
24. H.-K. Lin, J. A. Harding, and M. Shahbaz. (2004). "Manufacturing system engineering ontology for semantic interoperability across extended project teams." *International Journal of Production Research* 42.25, 5099-5118.
25. B. Kulvatunyou, H. Cho, and Y. J. Son. (2005). "A semantic web service framework to support intelligent distributed manufacturing." *International Journal of Knowledge-based and Intelligent Engineering Systems* 9, 107-127.
26. J. Cecil and N. Gobinath. (2004). "Mobile agent and semantic web based frameworks for the realization of virtual enterprises." *Proceedings of the International Mechanical Engineering Congress and Exposition (IMECE 2004)*, 16-19 November, Anaheim, CA.
27. K. V. Hindriks, F. S. De Boer, W. Van Der Hoek, and J.-J. Ch. Meyer. (1999). "Agent Programming in 3APL." *Autonomous Agents and Multi-Agent Systems* 2:4, 357–401.
28. http://www.w3.org/Submission/OWL-S/
29. N. Gobinath. (2007). "A Collaborative System to realize Virtual Enterprises using 3APL." Master's Thesis, Department of Computer Science, New Mexico State University, Spring 2007.
30. http://dublincore.org/
31. http://xmlns.com/foaf/0.1/
32. http://www.mel.nist.gov/proj/pdf/mi.pdf