A MODEL FOR VISUALIZING MECHANICAL ASSEMBLY SITUATIONS

Madhusudanan N[a] and Amaresh Chakrabarti[b]

Virtual Reality Laboratory, Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore, India.
Email: [a]*madhu@cpdm.iisc.ernet.in,* [b]*ac123@cpdm.iisc.ernet.in*

In order to acquire and use expert knowledge about potential issues in an assembly, knowledge based systems are utilized. To automate the process of acquisition of assembly knowledge from experts and contextualize this knowledge, we use assembly situations in which the acquired knowledge applies. For the knowledge acquisition system to be able to locate where each piece of knowledge acquired from experts applies, an assembly situation is visualized in our work as a set of assembly states separated by the processes that change the states. The paper proposes an assembly situation model as a simple and flexible means of visualizing an assembly process, and explains how this visualization may be utilized in knowledge acquisition for assemblies.

Keywords: Assembly situation, mechanical assembly, knowledge acquisition, situation model.

1. INTRODUCTION

In the realm of manufacturing, mechanical assembly, referred to in this paper as assembly, is different from other manufacturing processes in that it is an integrative process [1]. Assembly helps to put together a number of parts and allows them to work as a system. Given the importance of assembly in the product development cycle, it is important to understand the process of assembly and possible causes of defective products and difficult assembly processes. Guidelines are available for designing assemblies that are easier to assemble [1]. However, these guidelines may not always address or predict all possible issues with assembly, particularly those which may be very specific to certain domains only, or are come across by specific experts only.

1.1. Overview of paper

This paper presents a unique way of visualizing an assembly situation for supporting acquisition of expert knowledge about the situation. Here, the word assembly is used in both noun- and verb-sense — to mean the collection of physical components and subassemblies in a product that constitute the assembly (noun-sense), and the processes necessary in developing the subassemblies, and putting these together into the final assembly (verb-sense). The intent here is not so much to develop a means of modeling the components and processes mathematically, as to develop a means for conceptually representing and visualizing an assembly process and using this as a framework for hanging various pieces of knowledge associated with various aspects of the assembly. It first develops a representation for visualizing the smallest event of assembling — a single subassembly — and then expands this to encompass the entire assembly.

Research into Design — Supporting Sustainable Product Development. *Edited by* Amaresh Chakrabarti

ISBN: 978-981-08-7721-7

2. BACKGROUND

2.1. Objective of research

The overall objective of this research is to develop an automated knowledge acquisition system that, by means of conducting a systematic dialogue with a human expert, can acquire knowledge, structure it and utilize this to build conducting a systematic up a knowledge base. This knowledge can then be used to predict potential issues that could arise during assembly in the context of a given assembly situation, and to suggest suitable remedies for these issues. The expert here is a person possessing considerable experience in the assembly of mechanical components.

2.2. Use of knowledge based systems

For acting as a medium that is capable of handling, storing, retrieving and utilizing the knowledge, knowledge based systems, otherwise known as expert systems, are used. Knowledge based systems have been previously used in a variety of applications, ranging from diagnosis of meningitis, to identifying possible sites for mineral deposits, to interpreting tax laws [2]. Practical implementations of such systems can be constructed using expert system shells. The expert system shell currently used for this research is the C Language Integrated Production Systems (CLIPS) [3]. The expert system used determines the knowledge representation that needs to be adopted.

2.3. Acquisition of expert knowledge

A major challenge in constructing knowledge based systems is the acquisition of knowledge that a domain expert or a set of experts possess. This knowledge needs to be processed and put in a form suitable for an expert system to utilize in its reasoning. Knowledge acquisition is a sequence of processes that involves extensive interaction with experts, compilation of expert knowledge, and verification of the acquired knowledge. Knowledge acquisition has been seen as a bottleneck in setting up a knowledge base [4] and has traditionally been a manual process [5].

However, in the broader scope of our research, it is our hypothesis that given a systematic way of questioning and a suitable knowledge acquisition and representation approach, diagnostic expert knowledge could be acquired, structured and used without the continuous presence of an intermediate knowledge engineer. Hence, a questioning procedure is used to conduct a dialog with an expert by presenting an assembly situation and to acquire knowledge about potential issues, potential constraints related to these issues, and possible solutions to the issues. An assembly situation used for knowledge acquisition is shown in Figure 1, and is used for sake of explanation in this paper.

As a preliminary investigation, a set of interviews were conducted with experts from academia, in order to acquire knowledge about possible problems that might arise in a given design — the example situation used was that of a cantilever beam. From these interviews, it was concluded that for

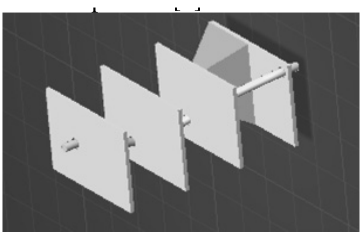

Figure 1. One of the assembly situations used for the interviews and knowledge acquisition. It shows four different plates with equal sized holes and a box component, and a cable bundle is assembled through the holes.

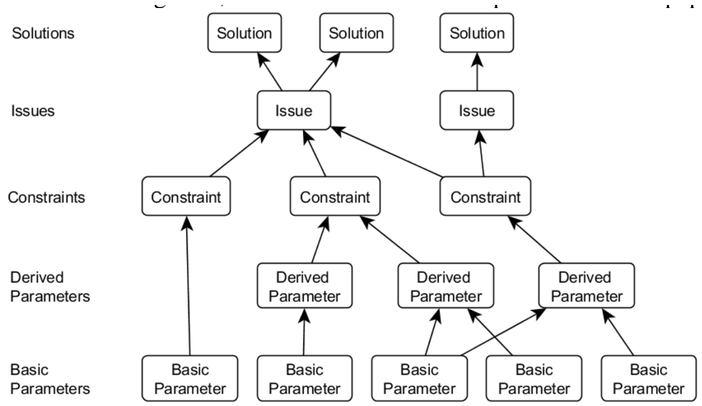

Figure 2. The different types of knowledge that are part of the expert knowledge about potential assembly issues. The possible relations between these types of knowledge are also shown.

acquisition of knowledge about a given situation, we need to acquire the following types of knowledge (See Figure 2):

- *Issues*: These are the potential issues that can be identified with the current assembly situation e.g. for the assembly shown in Figure 1 a potential issue might be 'the weight of the assembly is too much'.
- *Constraints*: These are the constraints on the system, which when violated, would lead to the above issue(s) e.g. 'the weight of the assembly should not be greater than the maximum specified weight of the assembly'.
- *Parameters*: These are the identifiable/measurable characteristics of a system that are necessary to determine whether a constraint has been violated, e.g. 'weight of the assembly' and 'maximum weight of the assembly' are the parameters needed to ascertain whether the constraint 'the weight of the assembly should not be greater than the maximum weight of the assembly' is violated. Such parameters may be
  a) *Derived Parameters*: These are the parameters whose values are not directly available from the situation, but must be calculated or otherwise determined from other parameters, e.g. 'weight of plate = (volume of plate) × (density of plate material)'.
  b) *Basic Parameters*: These are the parameters whose information is directly available from the situation e.g. 'the length of the plate'.
- *Solutions*: These are the suggestions to avoid the potential issues that have been identified by the expert, e.g. 'in order to avoid the potential issue that the weight of the assembly may exceed the maximum limit, remove material where it is possible to do so'.

The questioning procedure is intended to identify the above types of knowledge shown in Figure 2 with respect to a given situation. It consists of a series of questions that systematically acquire these various types of knowledge. The questioning procedure (shown in Figure 3) starts by asking what potential issues are present in a situation (e.g. 'the cable bundle may bend too much'), and for every issue, what is the cause and effect (e.g. Cause: 'the radius of cable bundle is less than minimum bend radius'; Effect: 'the cable bundle may be damaged'). The cause of the issue is further asked to be put in a form that provides a relation between two parameters (e.g. 'radius of cable bundle *is less than* minimum radius of cable-bundle'). Questions are then asked to identify how the parameters involved in these constraints can be found: whether these are basic parameters, or need to be computed using a relation. Finally questions are asked to identify potential solutions to the issues (e.g. increase the length of the cable).

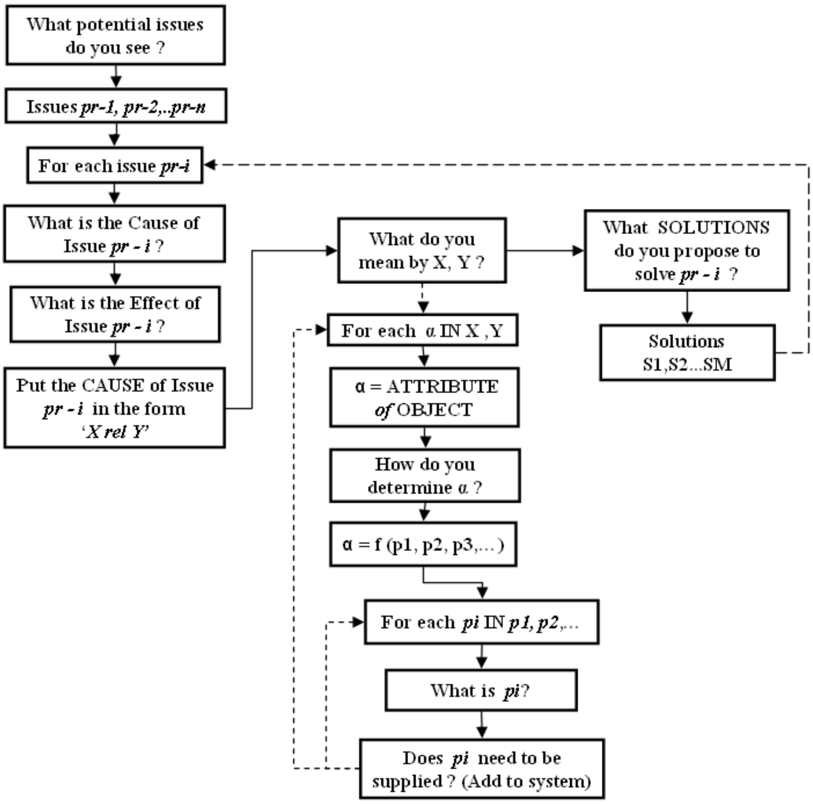

Figure 3. Questioning Procedure to acquire knowledge from the expert.

3. ASSEMBLY SITUATION MODEL (ASM)

3.1. Need for a Situation Model

The preliminary phase of interviews mentioned earlier was conducted with the experts using the questioning procedure (Figure 3) to verify if knowledge about potential issues and solutions in a given engineering situation can be obtained from experts. The situation used was that of a simple cantilever beam subjected to a load at its free end. Later on, this questioning procedure was implemented in a computer-based tool titled ExKAV (an acronym for Expert Knowledge Acquisition and Validation), and tested with experts from industry using assembly situations.

For instance, when presented with the assembly situation shown in Figure 1, some of the issues identified by the industry experts during their interaction with ExKAV were,

"*cable bundle may bend too much*" (1)

"*cable bundle may not fit into the hole*" (2)

"*the hole edge may damage the cable bundle surface*" (3)

Finally a third questionnaire based interview was conducted using two assembly situations. One situation is the one shown in Figure 1. The other situation was a physical model of a simple ball-point pen, and all its components were laid down in front of the subject. The following three questions were then posed to a set of Master's level students:

1. Describe the situation shown in your own words
2. Describe how one can assemble the components shown in the figure
3. List down any problems that you think may be faced during assembly

For the third question above (regarding potential issues), some of the responses were:

"*placing the box first may require more effort while assembling the rest*" (4)

"*if there is insufficient space for access to the cable holes, then passing*" (5)

"*them through each successive hole may be difficult*"

A preliminary observation of the different responses regarding the potential issues in an assembly situation shows that the issues pertain to

i) the point where the process of assembly is yet to begin e.g issue (2) above, or,
ii) when the assembly is taking place e.g. issues (4), (5) or,
iii) when the process of assembly has been completed e.g. issues (1), (3)

More importantly, from the usage of the questioning procedure, it was observed that the knowledge to be acquired is two-fold, namely

– Knowledge about potential issues and their solutions in the assembly situation
– Knowledge about the aspect in the assembly in which the above knowledge of potential issues and solutions applies.

It was also found that the knowledge about the potential issues and solutions can be obtained from the questioning procedure in Figure 3 alone. To obtain the knowledge about where this acquired knowledge applies, it is necessary to identify certain locations in the assembly situation itself, which might serve as pointers to aspects of the assembly at which the knowledge is applicable. For this, we need to systematically model an assembly situation as a set of various steps, so that this knowledge too can be elicited from experts during knowledge acquisition.

3.2. Objectives of the Assembly Situation Model

From the point of view of our research, where the goal is to advise on potential assembly issues and their resolutions, an assembly situation model is expected to achieve the following objectives:

– In order to know where the knowledge acquired about an assembly situation applies, the assembly situation model must enable the expert to point to any suitable stage of the assembly, belonging to any level of abstraction, where (s)he can place his/her knowledge.
– The model should be possible to be used within the constraints of the information available about an assembly situation, i.e. the geometry of the components and the assembly processes involved.
– In view of the same situation being presented to assembly experts as well to as assembly planners, the same model should be possible to be used for interactions of the knowledge acquisition system with both these groups.
– Since a situation may have to be modified at any point of time, e.g. change in components, sub assemblies or the sequence or processes with which these are assembled, the situation model must also be able to accommodate such changes.

3.3. Literature Survey

Previous attempts to model or characterize situations for various applications utilize a variety of methods ranging from probabilistic methods to Petri nets. Delius *et al.* [6] characterize situations in road traffic using Situation Hidden Markov Models (HMM), in which, given data about location of a trailing vehicle, and relations defined beforehand, Bayes' factor is used to judge the most likely maneuver. However, the dynamic nature of the scenario in this application is different from that of assembly situations handled in the context of our work. Second, the above technique cannot be used to model combinations of assembly processes, and the states between these processes. Third, representing uncertainty is not important in assembly situations. Other approaches used to model situations that are dynamic in nature include a probabilistic frame based representation language for modeling and hypothesizing possibilities and types of cyber-attacks [7].

For modeling aircraft assembly operations, Scott [8] models operational procedures and assembly personnel resources using discrete event simulations. The focus in their work is to model crew resources and operations during assembly, as opposed to model assembly components and processes which is the focus of our work. A notable model of an assembly as an artifact uses an integrated, object-oriented definition of an assembly model [9]. This assembly model contains details about parts and assemblies contained in a product, part and assembly features, assembly constraints and kinematic relationships. However, this model does not include assembly processes and related information, nor does it include the relationships between the assembly and its processes. In our research, the information that is common to both the assembly planners and the experts is the information about the assembly components/subassemblies, and their assembly processes. Overall, existing literature does not seem to have a model that can represent this combination of assembly components and subassemblies, and their assembly processes, which covers these necessary details for both the assembly planners and experts.

3.4. Proposed assembly situation model

In order to meet the objectives in Section 3.2, a means for systematically visualizing the whole assembly process as a number of recognizable pieces is necessary. Here, we propose an assembly situation model to help visualize the entire set of components (or subassemblies) that constitute the product, and the processes that combine these components (or subassemblies) together in order to assemble the product. Consider the assembly of a cabinet, consisting of 18 parts shown in Figure 4(a). The first step of this assembly is to assemble the tower-bolt to the door using two rivets, resulting in the first sub-assembly shown in Figure 4(b). What results after the assembly process is a sub- assembly which represents the combination of all three different components as a single piece. The final cabinet assembly after all parts are assembled is shown in Figure 4(c).

This first assembly process from Figure 4(a) to Figure 4(b) depicts an elementary assembly process, and represents a typical sub-step in the process of assembling a large assembly. This can be represented in terms of three different sections as shown in Figure 5, namely

– An Initial State, where the components to be assembled are represented
– An Assembly Process, which combines the components to a (sub) assembly
– A Final State representing the assembled components as a single (sub) assembly

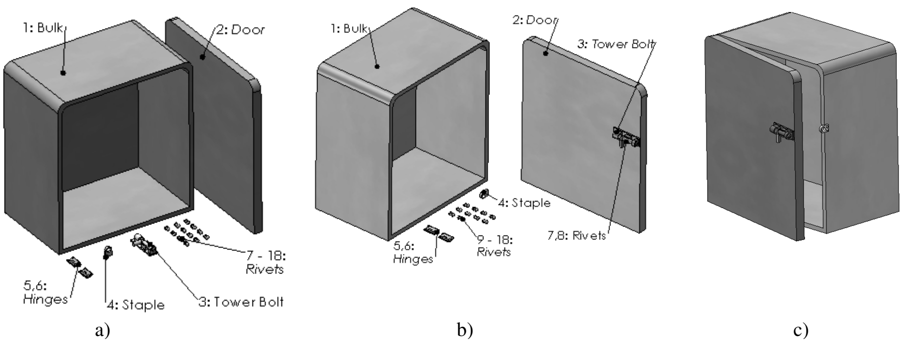

Figure 4. a: Initial State of components before Assembly b: After the first step of assembly — attaching the Tower Bolt to the Door c: Final Assembly.

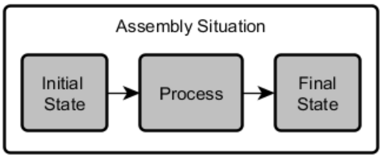

Figure 5. Visualizing an assembly situation as a sequence of three different elements.

The assembly of the parts shown in Figure 4(a) shows the initial state of the parts before they are assembled; the final state of the assembly in shown in Figure 4(b). The process of assembly involves placing the tower bolt to the door in the right configuration, marking out the rivet holes and drilling them, and performing riveting. The resulting sub-assembly is shown in Figure 4(b). Thus we can clearly see the three distinctive phases of the assembly situation in this case. It is to be noted that the intent here is not to mathematically model the assembly processes, but rather to visualize them as a combination of easily understandable states, which is used to structure the domain knowledge about assemblies gathered through knowledge acquisition and structuring.

3.5. Extension of the model to represent complex assemblies

The assembly situation model (ASM) shown in Figure 5 represents an atomic process within a larger, complex assembly. The situation model could be extended to either directions to incorporate a set of atomic processes (or their composites), wherein the Initial State of the current ASM would be the Final State of a previous ASM, and the Final State of the current ASM would be the Initial State of the next ASM. The two major distinctive features of the ASM are: (1) every state of the ASM contains the entire set of parts, albeit in various states of assembly, and (2) multiple aggregations are used to describe the assembly in a hierarchy of levels. Petri Net representation [10], has been used to represent individual parts/subassemblies in the assembly and the intermediate processes between these states. However, it does not explicitly contain multiple aggregations, nor does it carry the parts through the states. As a result, much possible expert knowledge cannot be hung in the appropriate context. Also, in our model, the grouping of various parts is identified as a single state, which helps to visualize the set of all parts that are involved at any given step in the assembly. A semantic model of virtual assembly is also reported [11], which contains information about assembly objects (parts/subassemblies), operations (e.g. translation/rotation), and processes, so as to identify possible assembly sequences, and help in detailed modeling of the assembly states and processes. However this model too describes the assembly process only at the most atomic level of detail, thereby losing out on richness in contexts that could be provided with multiple aggregations. ASM provides a more direct means of interacting with an expert rather than presenting a set of data using the semantic model. Table 1 presents a detailed comparison of these three models.

The assembly tree for the assembly shown in Figure 4(c) is shown in Figure 6. The parts are represented using numbers from 1−18. The subassemblies formed using these components are shown as letters from *A.D*. The final assembly is represented as *A*. Note that a given subassembly, e.g. subassembly *C* is merely a representation of the parts.2, 3, 7, 8 together with the assembly relationships (e.g. mating conditions, liaisons) between them. To represent the assembly tree in Figure 6 using the ASM proposed in this paper, every atomic assembly process is visualized as a single ASM. In Figure 7 each ASM is shown as a box, consisting of the initial state, process and final state as three blocks within the box. The corresponding parts concerned with an initial state or final state are shown inside a white box e.g. during the assembly process of sub-assembly C, the initial state consists of the components 2, 3, 7,8. After the assembly process *Proc1*, subassembly *C* results. This is the final state for this assembly process, and forms part of the initial state for another sub-assembly process — resulting in sub-assembly *B*. Similarly the blocks of ASM for each subassembly are shown until the final assembly *A* is formed.

Table 1. Comparison of the various models with respect to our objectives.

Objective (Section 3.2)	Assembly Petri-Net	Integrated Semantic Model	Assembly Situation Model
Does the model allow an expert to place his/her knowledge at any suitable stage of the assembly belonging to any level of abstraction?	No	No	Yes
Can the model be used within the constraints of available information –geometry of parts and assembly processes?	Yes	No: Details like translation/ rotation needed	Yes
Can the same model be used for interactions with experts as well as with assembly planners?	No	No	Yes: same situation is used for both
Can the model accommodate any changes to the assembly in terms of parts and/or processes?	Yes	Yes	Yes

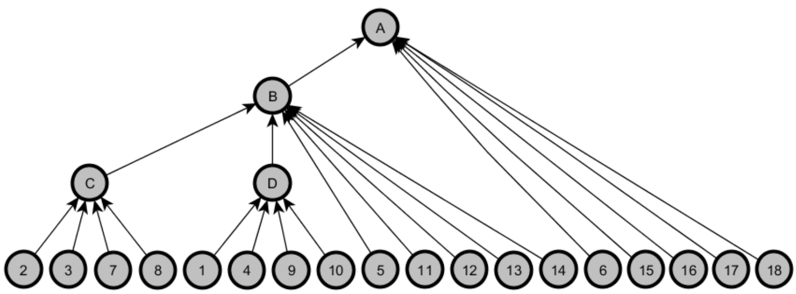

Figure 6. Assembly Tree for the assembly example shown in Figure 4.

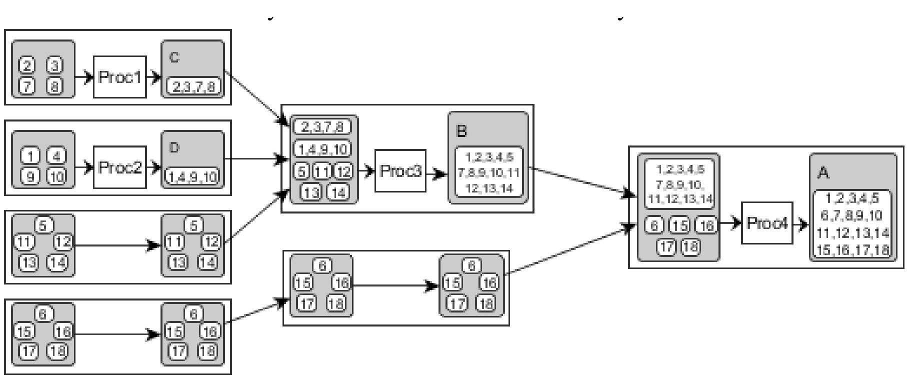

Figure 7. The ASM extended to the whole assembly.

4. UTILIZATION IN KNOWLEDGE ACQUISITION

The Assembly Situation Model is intended to serve as a placeholder for the knowledge being acquired by the knowledge acquisition system described in Section 3.1. If the expert expresses his knowledge about an issue about the assembly in Figure 4, (s)he can rather attach this issue to a particular step of the whole assembly process in Figure 7. We believe this is one step closer to specifying the context in which the knowledge gets used by the knowledge based system, since it makes the knowledge more specific to a single step in its application, rather than the whole assembly.

5. CONCLUSIONS

ASM — a new model for describing assembly situations has been proposed. It helps visualize both atomic and composite steps of assembly of a set of components or sub-assemblies, and provides details of each assembly step, both in terms of the artifact before and after the assembly, and the processes responsible for the transformation. Revisiting the expectations for ASM, we see that this model has the potential to describe necessary details about all assembly components/subassemblies involved and their assembly processes, for presenting assembly situations to assembly planners or experts. This, we argue, would help assembly experts to suitably place their knowledge about assembly situations, which in turn would help assembly planners to identify and resolve potential issues in such situations leading to better assembly plans. Given that the geometric models of the components and sub-assemblies within an assembly are available as CAD models, and information about their assembly processes is available from the assembly process specifications, the proposed model can be made compatible with information typically available on CAE systems. However, for this, a means of updating and maintaining these situation models has to be devised.

6. FUTURE WORK

The situation model proposed is planned to be used to identify the location of issues, constraints, and solutions in given assembly situations, and help better locate these within an assembly. This is planned to be achieved by developing an updated questioning procedure, to be used in conjunction with the situation model for the entire assembly.

ACKNOWLEDGMENTS

Inputs from the industry experts involved in validation of ExKAV tool, and the participation of students from Indian Institute of Science (IISc), Bangalore, India in the questionnaire survey are acknowledged. We also thank the Boeing Company for financial support under contract PC36016 at SID, IISc, and Dr. Al Salour and his colleagues from The Boeing Company, USA for their valuable support.

REFERENCES

1. Whitney D E, 2004, *Mechanical Assemblies*, Oxford University Press.
2. Hart A, 1986, *Knowledge Acquisition for Expert Systems*, Kogan Page.
3. CLIPS Advanced Programming Guide and User's Guide, CLIPS homepage: http://clipsrules.sourceforge.net/ accessed March 22, 2010.
4. Savory S, 1988,Artificial Intelligence and Expert Systems, '*Some views on the state of the art in AI, Nixdorf Computer AG, Paderborn*', Ellis Harwood Books.
5. Noelke U, Artificial Intelligence and Expert Systems, Edited by Stuart Savory, '*The Essence of Knowledge Engineering, Nixdorf Computer AG, Paderborn*', Ellis Harwood Books, 1988.
6. Meyer-Delius D, Plagemann C, Georg von Wichert, Feiten W, Lawitzky G and Burgard W, *A Probabilistic Relational Model for Characterizing Situations in Dynamic Multi-Agent Systems*, Data Analysis, Machine Learning and Applications, Springer Berlin Heidelberg, Part IV, DOI : 10.1007/978-3-540-78246-9_32, *p*. 269–276.
7. D'Ambrosio, B., Takikawa, M., & Upper, D., 1999. *Representation for dynamic situation modeling*. Tech. rep., Information Extraction and Transport, 28, 47, 161.
8. Scott H, 1994, *Modeling Aircraft Assembly Operations*, Proceedings of the 1994 Winter Simulation Conference.
9. Sudarsan Rachuri, Young-Hyun Han, Sebti Foufou, Shaw C. Feng, Utpal Roy, Fujun Wang, Ram D. Sriram, and Kevin W. Lyons, 2006, *A Model for Capturing Product Assembly Information*, J. Comput. Inf. Sci. Eng., Volume 6, Issue 1, 11 doi:10.1115/1.2164451.
10. Zha XF, Du H, Qiu JH (2001) *Knowledge-based approach and system for assembly oriented design,Part I: the approach*. Eng Appl Artif Intell 14:61–75.
11. Fan, J and Ye, Y and Cai, J, 2004, *Design and Implementation of Integrated Assembly Object Model for Intelligent Virtual Assembly Planning*, Lecture Notes in Computer Science, Computational Science — ICCS 2004, Springer Berlin, p.435–442, v.3037.