Proceedings of DETC'00
2000 ASME Design Engineering Technical Conference
and Computers and Information in Engineering Conference
Baltimore, Maryland, September 10-13, 2000

DETC'00/CIE-14608

REPRESENTING AN ARTIFACT TRANSPORT SYSTEM IN A DESIGN REPOSITORY: A CASE STUDY

R. H. Allen
Department of Mechanical Engineering
University of Maryland
College Park, MD

R. J. Fijol
Department of Civil Engineering
University Massachusetts, Amherst
Amherst, MA

S. Syzkman
Manufacturing Systems Integration Division
National Institute of Standards and Technology
Gaithersburg, MD

R. D. Sriram
Manufacturing Systems Integration Division
National Institute of Standards and Technology
Gaithersburg, MD

KEYWORDS: Design Repository, Artifact Transport System, Function, Form, Behavior, Rationale

ABSTRACT

This paper describes a case study representing the design essence of a prototype ultra-high vacuum artifact transport system (ATS) in an existing design repository (DR). Specifically designed for the purpose of transporting nanometer-scale dimensional artifacts at pressures ~10^{-8} Pa, the ATS consists of a transport cart and an ultra-high vacuum (UHV) system. The artifacts are the result of nanomanufacturing efforts to create atom-based dimensional standards for the semiconductor industry. To populate the design repository, we represent engineering geometry, function and associated behavior, as well as taxonomies of generic functions and flows of the transport system. We model geometry with digital photographs and Virtual Reality Markup Language (VRML) images of actual Computer-aided Design (CAD) drawings, represent function with linked textual descriptions, and capture behavior with mathematical expressions. Through an evolving user interface, this representation serves to capture the more than 50 parts and systems of the ATS in such a way that the information relating to form, function and behavior is accessible *and* browsable to subsequent designers. We conclude that such a representation, or ones similar to it, can provide the basis for a generic database in which specific information—including design rationale—can be easily retrieved by future design teams.

INTRODUCTION

Recent research in design methodology, and recent practice in industry, have shown that collaboration among multidisciplinary teams reduces the time and cost to design and manufacture, and, perhaps more importantly, improves the quality of the end product. To varying degrees, collaborative engineering (CoE) has become the *de facto* methodology for developing products [Lawson & Karandikar, 1994], [Sriram & Logcher, 1993]. In general, design and manufacturing personnel have increased their CoE activities as technology has allowed them to do so. A prime example of this is the recent proliferation of Internet-Aided Design (IAD), where design and manufacturing personnel use the World Wide Web for providing information services on the Internet [Cannon, *et al*.; 1997, Cutkosky *et al*. 1996; Martin, 1997].

In addition to *sharing* information, there is a need for and an increased focus on representing product knowledge in a way that facilitates storage with searchable retrieval and reuse. This is a considerable problem with over 20 billion CAD models in use (Bach et al, 1996). In addition to providing an extensive database to improve the design process, it is also important to provide it in an easily accessible way. The Internet provides a widely accessible and usable platform for conveying information over long distances and to many people at the same time. Internet-related technologies that are beginning to address that issue include digital libraries (Regli, 1999; Pierra and Wiedmar, 1996), active catalogues (Luo and Will, 1996), extended databases (Eastman and Tang, 1997) and design repositories (Szykman et al, 1996; Szykman et al, 2000).

The most recent of these is design repositories (DRs), which have extended the capabilities of traditional databases by being more robust in capturing function, behavior and models. In addition, DRs generally accept more heterogeneous information and incorporate more explicit representation than databases (Szykman, 2000). The National Institute of Standards and Technology (NIST) design repository, started around 1997, is a database that supports representating capturing sharing and reusing design knowledge. The NIST DR can be used to store much of the data created from a generic design and its associated processes so that the information can be shared with future designers and planners.

This paper describes a case study in using the NIST design repository to capture the design and reasoning behind the development of a prototype artifact transport system (ATS) for atomic artifacts [Tsai, *et al*., 1998; Silver, *et al*., 1998]. After briefly describing the rationale behind the ultra-high vacuum ATS project and the associated design and manufacture process for it, we highlight the process of populating the DR with ATS information. We conclude with our assessment of the benefits of, and the bottlenecks to, the representation of the ATS in the DR.

NOMENCLATURE

ATS	Artifact Transport System
CAD	Computer-Aided Design
CoE	Collaborative Engineering
DR	Design Repository
MBE	Molecular Beam Epitaxy
NAMT	National Advanced Manufacturing Testbed
NIST	National Institute of Standards & Technology
STM	Scanning Tunneling Microscope
URL	Uniform Resource Location
UHV	Ultra High Vacuum
VRML	Virtual Reality Modeling Language

ATS DESIGN DESCRIPTION

To support the development of solutions to the standards and metrology issues of information-based manufacturing, NIST initiated a research and development program in 1996 called the National Advanced Manufacturing Testbed. (A web-based description of NAMT can be found at the following URL: http://www.mel.nist.gov/namt.) In brief, this program is a showcase for the future of manufacturing, demonstrating how machines, software and people can be networked together to achieve interoperability at all levels of a manufacturing enterprise. NAMT contains a facility in which scientists and engineers from industry, NIST, academia, and other government agencies work together to solve measurement and standards issues in information-based manufacturing and develop the needed tests and test methods for industry that are part of NIST's mission.

In one part of the NAMT program, an Artifact Transport System (ATS) has been designed and built to transport *atom-based* silicon artifacts from their manufacturing laboratory—the Molecular Beam Epitaxy (MBE), to their measurement laboratory—the Scanning Tunneling Microscope (STM). The atom-based artifacts have dimensional features on the order of a nanometer. To protect the dimensional features, these artifacts need to be preserved in a highly clean environment, an Ultra High Vacuum (UHV) on the order of 10^{-10} torr (< 10^{-7} Pa). To transfer the artifacts between the laboratories, the ATS must be compatible with the MBE apparatus and the STM while maintaining the high vacuum conditions throughout (Allen et al, 1999; Nidamarthi et al, 2000).

Designed using a collaborative Internet-based design system, the ATS is comprised of five sub-systems and 46 major separate parts. Shown assembled in Figure 1, the subsystems include the vacuum system, the transport system, the control system, the transfer system and the jacking system.

Fig. 1. A digitized photograph of the assembled ATS in the STM laboratory.

Major components, most of which are made of stainless steel to ensure adequate seals, include an ion pump and a turbo pump, a drive rod, a vertical shifter, and a support frame. Figure 2 depicts a typical CAD drawing for one component, a mitre gearbox for the jacking system; Figure 3 shows its corresponding VRML image. One reason for using VRML representations was dissemination over the Internet for the design team during the design phase. This representation mode ultimately was also the vehicle by which form was stored in the design repository.

DESIGN REPOSITORY PROJECT

The NIST DR is based on a data language and a design representation language (DRL). The data language consists of four fundamental entities, which include objects and relationships, and object classes and relationship classes. The data language describes the syntax and data

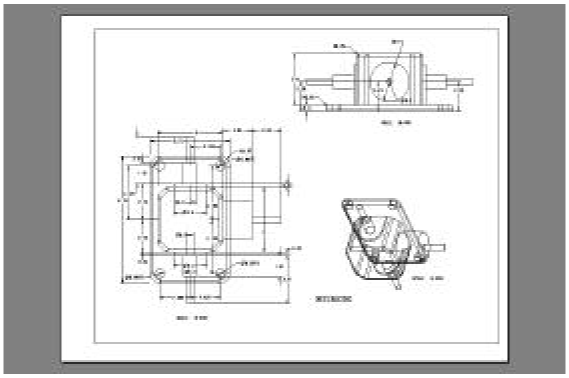

Fig. 2. Typical CAD drawing of a mitre gear box. This component was one of four deployed for the jacking system.

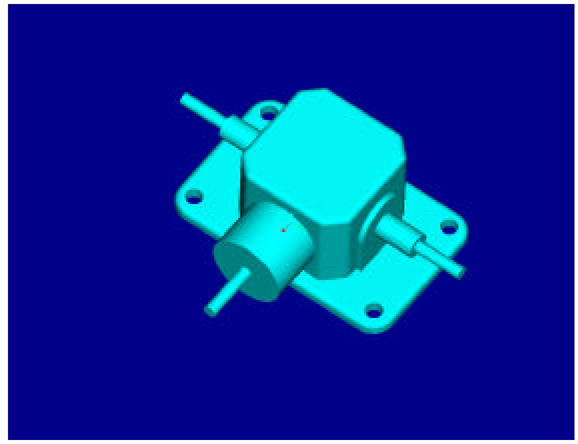

Fig. 3. A VRML image of the gearbox. This representation was used to enable Internet dissemination during the design phase, and ultimately to enable repository storage.

structure for a generic object-oriented paradigm. The DRL combines this language with an engineering context to provide a means for modeling artifacts. An example schema for the ATS is shown in Figure 4. The object shown defines the artifact ATS_artifact_1 as an instance of the class, ATS_artifact. The three attributes—form, function, behavior—are listed with values in brackets. A sample relationship is also listed. Szykman et al (2000) describe these in greater detail.

Object:	
Parent:	[ATS_artifact]
Object ID:	[ATS_artifact_1]
Attributes:	function [ATS_artifact_1_Function]
	form [ATS_artifact_1_Form]
	behavior [ATS_artifact_1_Behavior]
Relation:	[ATS_artifact_Has_part]

Fig. 4. Sample schema for ATS object entity

As indicated earlier, one facet of the DR is capturing form, function and behavior. As such, each system, subsystem and component needs to be explicitly represented in the DR. Each of the UHV components and subsystems were abstracted into this form; Figure 5 shows one example of the ATS. Here, a textual description is provided, as well as links to form, function and behavior. In addition, the parent (in this case, artifact) is specified as are the subartifacts. In this way, the hierarchical nature of the design is captured as it is abstracted.

In brief, the DR paradigm explicitly captures form, function and behavior of each component within a design and maps it onto the data elements discussed above. As an example, the pumping system takes ambient air and reduces it with a turbo pump to a moderate vacuum, which in turn gets pumped down with an ion pump to an ultra-high vacuum. However, both of these are interconnected to the transport system. At the simplest level, we can consider this one mechanism a single artifact, having one input flow whose source is ambient air, and one output flow, whose destination is UHV. However, the functions of this system are more intertwined than that. The turbo pump accomplishes the moderate vacuum by taking air and decreasing pressure in a controlled way to produce a moderate vacuum. This vacuum then passes through several leak-free joints to enter the ion pump chamber. The ion pump is also carefully controlled to ensure that UHV can be maintained. Figure 6 shows a schematic representation of the data structures and associated references for the UHV pumping system as part of the transport system.

```
Object:
parent:     [Artifact]
uid:   [artifact_transport_system]
A:     description "a self contained artifact transport system";
       creation [artifact_transport_system_creation];
       last_update [artifact_transport_system_last_update];
       function [artifact_transport_system_Function];
       form [artifact_transport_system_Form];
       behavior [artifact_transport_system_Behavior];
       subartifacts
        {[support_system]
         [ultra_high_vacuum]
         [instrumentation_and_accessories]};
R:
```

Fig. 5. A textual description of the ATS in the Design Repository. Form, function and behavior are integral part of the artifact object.

Shown in Figure 7 is the user interface of the design repository browser (Szykman, 2000). In this view, there are three active windows. The upper right shows a VRML image of the entity at hand; in this case, it is the entire assembly. The lower right window displays the information contained in the abstraction—description, form, function, behavior,

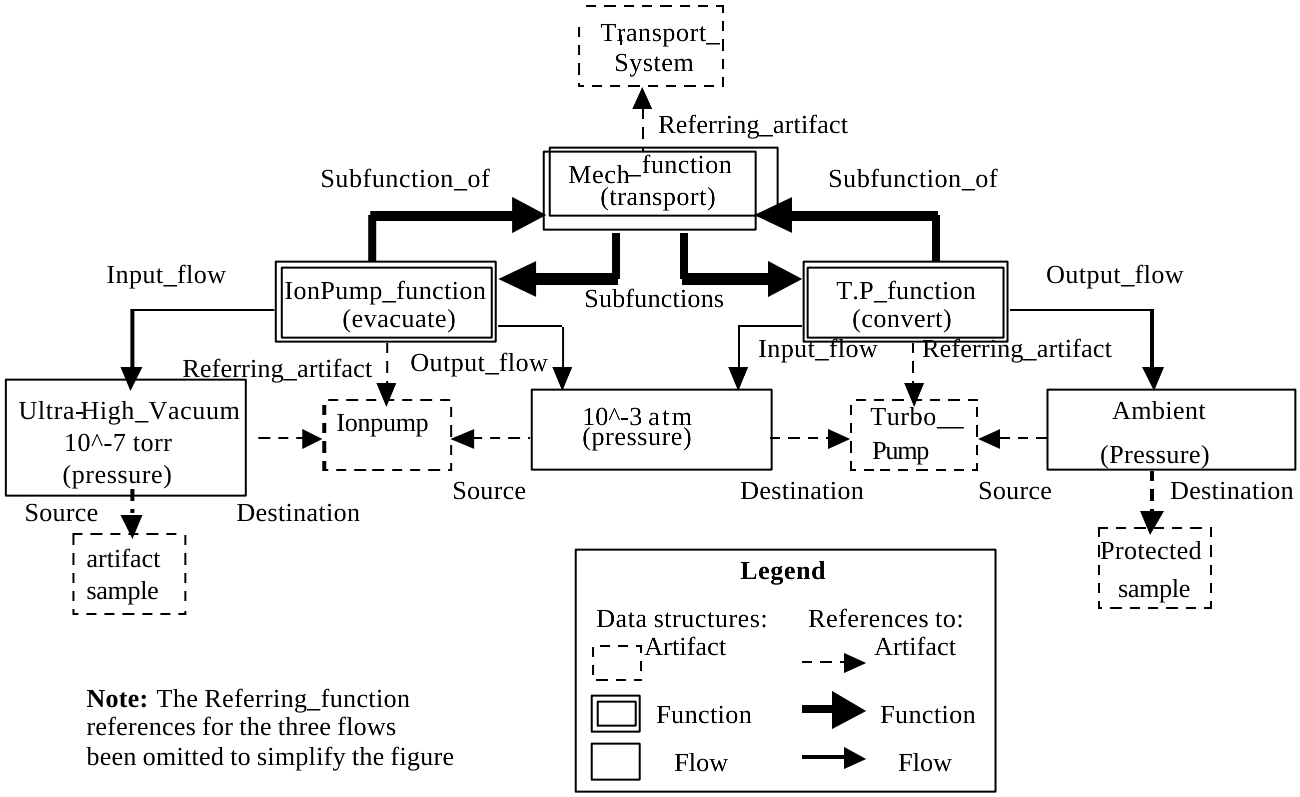

Fig. 6. Graphical representation of ultra-high vacuum pump function.

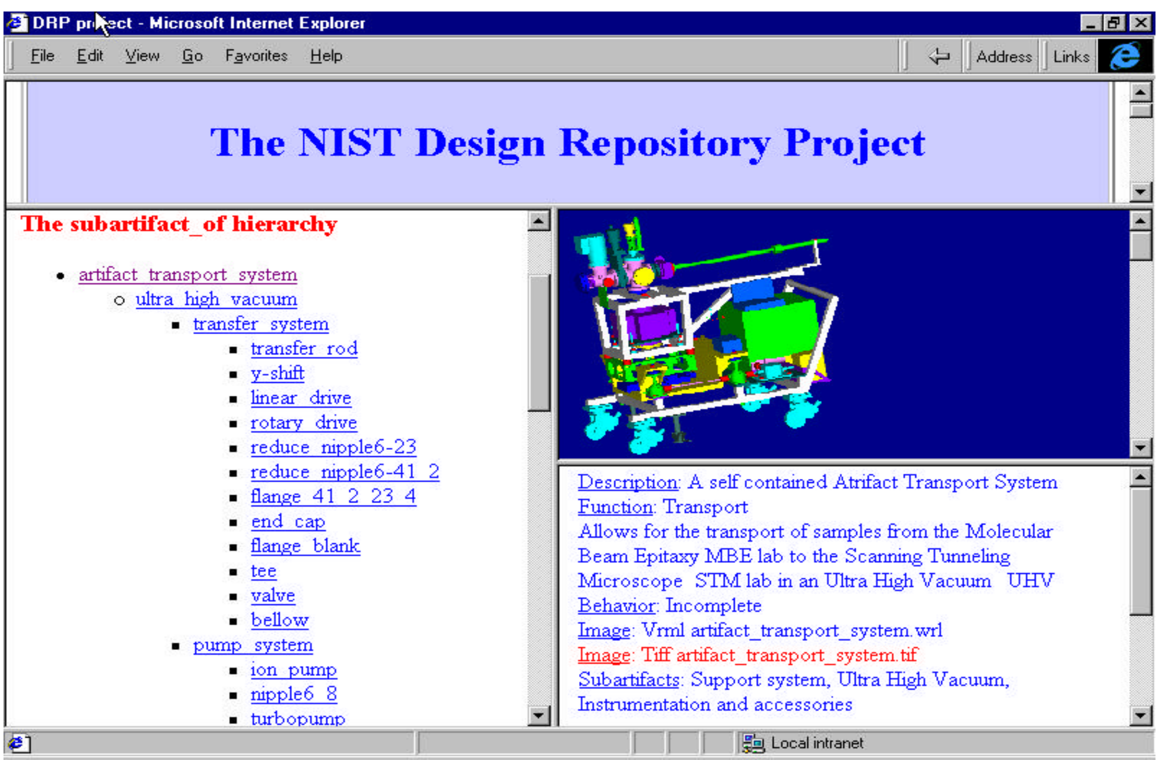

Fig. 7. A sample user interface. The graphical screen depicts one VRML view of the overall system. The lower screen describes the system, its basic function and its subartifacts. The system hierarchy is listed on the left.

Subartifacts and parent. Each abstraction—being an object itself—is accessible to the user. The left window lists the system hierarchy allowing the user to view other aspects of the design at his/her discretion. Although the ATS consists of 46 major parts, the representation of the ATS in the NIST Design Repository included many more data entities (objects and relationships). It is these additional objects that model artifact functions, associated flows, physical decompositions, and other relationships between parts of the artifact. It is these entities that allow design repositories to capture a more comprehensive representation of an artifact than would be included in a traditional design database.

SUMMARY AND AREAS FOR FUTURE RESEARCH

We represented the function, form and geometry of an ultra-high vacuum artifact transport system in the NIST Design Repository. The hierarchical abstraction of the prototype can now be accessed and browsed through the Internet. Subsequent design teams can view and browse the design for specific instances of components or system, for rationale in selecting them, or for the specific dimensions of one part. Preliminary data with the system suggests that having this information readily available can reduce subsequent design cycle time.

Our purpose in this paper was to explore the feasibility of populating an existing design repository with the ATS as a case study. To this end, we achieved our goal, however, doing so came at a cost. In particular, we went through a process by which the design data and design intent could be elicited from the actual artifact, from design drawings and from the designers themselves. This was a separate task requiring considerable effort. Even if steps were taken to elicit the DR data during the design, more effort would have been needed than was expended without obtaining the granularity required. The efficacy of the DR approach, therefore, should be judged not only by the ability of the system to search and browse existing design data, but by the additional effort necessary to achieve DR representation.

Another issue is the representation itself. To be useful to many, any representation scheme needs to be as standardized as possible to ensure that data can be reused and assimilated on successor projects. Doing so would also ease the burden of undue documentation on the designer while he or she is designing. Such standardization requires consensus with input from the design and the research community. Researchers at several universities are making use of representations developed for the DR project providing useful feedback. NIST is continuing its industry workshops to gather additional information regarding needs associated with data reusability.

ACKNOWLEDGMENT

Part of this work was funded under the National Advanced Manufacturing Testbed (NAMT) program at NIST.

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