# An Integrated Testbed for Reverse Engineering of Aging Systems and Components

Kuang-Hua Chang, Zahed Siddique, Mangesh Edke and Zhiqiang Chen

University of Oklahoma, khchang@ou.edu

## ABSTRACT

This paper presents an integrated testbed that supports defense logistics centers to conduct reverse engineering of aging systems and components. This testbed constructed using commercial off-the-shelf (COTS) software and equipment supports three major engineering tasks: the reverse engineering that supports recovering of technical data from worn sample parts, re-engineering that alters design for better performance or lesser cost, and fast prototyping that incorporates advanced manufacturing technologies to produce functional or physical prototype of the part in small quantity in a short turnaround time. A number of examples obtained from logistics centers are employed to illustrate and demonstrate the reverse engineering, re-engineering, and fast prototyping (RRF) process using the testbed. Further tasks for research and development are also presented.

**Keywords:** reverse engineering, re-engineering, fast prototyping.

## 1. INTRODUCTION

Many weapon systems in the U.S. Armed Services and around the world were developed forty, even fifty years ago. After the Cold War ended, the U.S. Department of Defense (DoD) decided to extend the service life of existing weapon systems for a prolonged period, rather than spending billions of dollars for development of new systems. Logistics centers face a major challenge in maintaining weapon systems originally designed half a century ago—systems that are approaching, or have already reached the end of their intended service lives. The challenge stems from the premise that the existing systems designed using outdated technology simply cannot keep the systems in service consistently. In addition, the original technical data packages, including engineering drawings, of the failed parts in weapon systems are either incomplete or completely missing [1]. The situation creates serious problems in either acquiring parts externally or conducting in-house manufacturing.

For some time, logistics centers have adopted various reverse engineering approaches that replicate original parts from physical samples. These approaches have provided some success in supporting logistics centers to accomplish its MRO (maintenance, repair, and overhaul) missions for the past two decades. Recently, some logistics centers, such as OC-ALC (Oklahoma City Air Logistics Center), have attempted to accelerate the process by implementing an aggression of modern scanning devices with surface construction technology [9]. However, the discrete point clouds created using modern scanning devices are often in millions, which usually require a great deal of human efforts to convert them into useful forms. Furthermore, the accuracy of the restored part geometry often was not characterized quantitatively due to lack of adequate tools.

Among many engineering problems encountered in logistics centers, the problem of fatigue and fracture, often present in critical impact load-carrying subsystems, such as landing gears, suspension components, etc., is the most technically challenging task. Especially, fatigue and fracture cause mechanical failures and safety hazard that often ground the weapon systems. In order to address the fatigue and fracture issues, excellent experimental facilities and engineering expertise have been established in some logistics centers to conduct fatigue and fracture tests. However, no computational and design methods have been employed to re-engineer and improve reliability of the failed components. Moreover, parts were designed with experience and engineering intuition. Even though, they work out extremely well, some of the parts were over-designed, and could be optimized to reduce weight and material consumption.

In manufacturing, some of the technology initially employed is out-of-date, and many vendors discontinue their supplies to support logistics centers. In addition, to maintain fleets of small quantities, for example, Air Force AWACS, only small quantity of parts are usually acquired by the logistics centers, which severely narrows the options of viable manufacturing methods and often leads to no-bid after a prolonged acquiring process.

With such a formidable challenge on the horizon—extending the service lives of aging systems—advanced computer-based design and manufacturing technology, unavailable half a century ago, provides logistics centers a great opportunity to confront and overcome the challenge. Products and processes can be re-engineered for more durable and reliable alternatives, with faster and more cost-effective manufacturing options. For example, the E-3 torque tubes shown in Figure 1 were re-engineered for both reliability and manufacturing process [2]. Sample torque tubes were first measured for critical geometric dimensions using coordinate measurement machine (CMM) and FaroArm. The measurement data were employed for constructing parametric solid models manually using CAD system, in this case, *Pro/ENGINEER*. Once the parametric solid model is available, the product and process re-engineering activities are conducted concurrently. In re-engineering the tubes, strength analyses were conducted for both magnesium and aluminum solid models. In order to reduce the weight of the aluminum tubes while maintaining their strength, the tube geometry is changed using shape optimization technology. A sample aluminum tube was machined and delivered to OC-ALC for material strength test. The aluminum tubes are both stronger and more corrosion-resistant than the magnesium tubes they will replace. More importantly, the cost of the tubes is reduced by more than 50% and the manufacturing lead-time is cut down more than tenfold. The key step that allows for product and process re-engineering is constructing parametric solid models. With parametric solid models, advanced design and manufacturing technologies are readily employed for creating durable and economical replacements. In addition, a well-organized process with necessary tool set in place will make the RRF process more systematic and effective. The success and lessons learned from the tube examples prompt the idea of developing an RRF testbed.

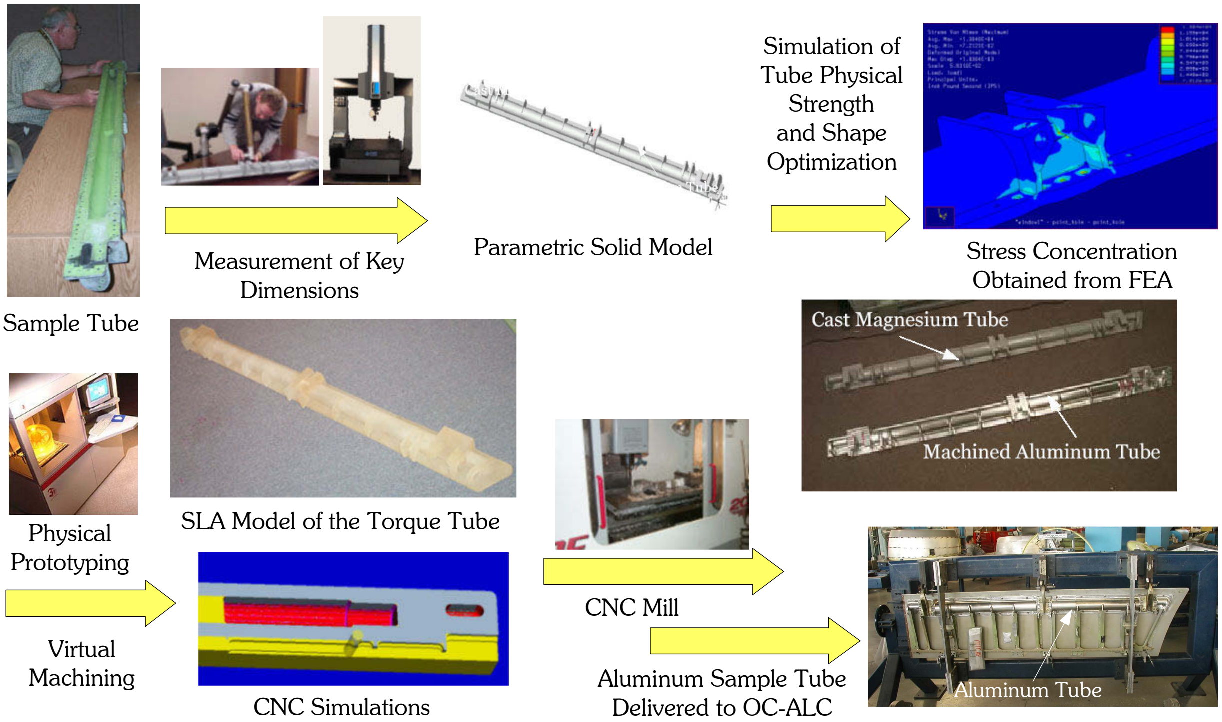


Fig. 1. Reverse engineering, re-engineering, and manufacturing of AWACS torque tubes.

The objective of this paper is to present an integrated testbed that incorporates technology for reverse engineering, re-engineering, as well as fast prototyping for aging systems using COTS software and tools. The overall RRF process will be discussed in Section 2. The reverse engineering, re-engineering, and fast prototyping technologies with application examples will be presented in Sections 3 to 5, respectively. Integration and capability for design collaboration are outlined in Section 6. Conclusions and future work are given in Section 7.

## 2. THE OVERALL PROCESS

The integrated RRF process, as illustrated in Figure 2, supports reverse engineering, re-engineering, and fast prototyping. The reverse engineering aims at not only reconstructing solid models from physical sample parts, but more importantly, constructing parametric solid models with geometric features and dimensions. Usually, the NURB (Non-Uniform Rational B-spline) surface models are sufficient for reverse engineering if not considering re-engineering. However, in order to support re-engineering, geometric features embedded in the NURB surface model must be recognized and properly parameterized.

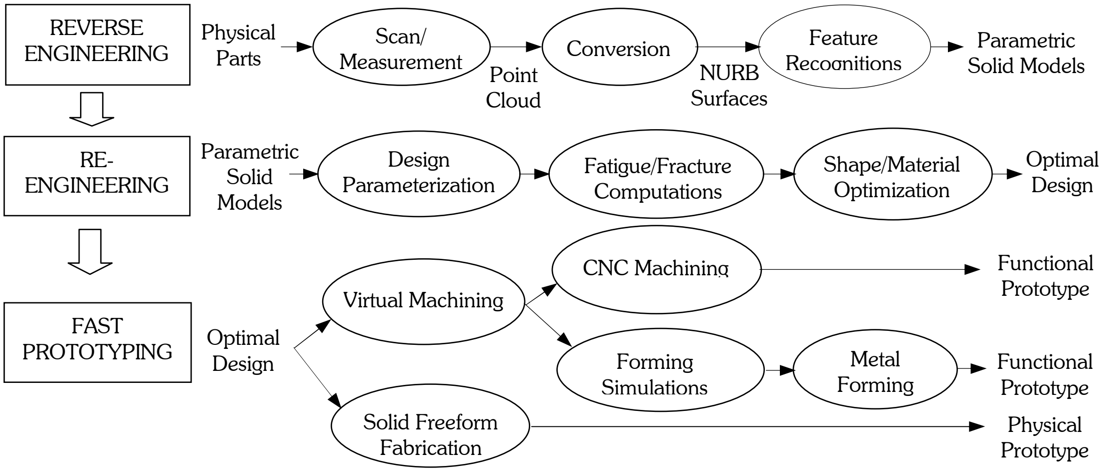


Fig. 2. The proposed RRF process.

The re-engineering focuses on incorporating fatigue and fracture computations as well as shape optimization for optimal or near-optimal component designs. Computer modeling and simulation tools, such as multibody dynamic simulations, finite element analysis (FEA), and fatigue and fracture prediction techniques have been employed to simulate the fatigue and fracture behavior of the failed parts. Based on the simulation results, material and part geometry can be optimized for required performance with a minimum cost (or minimum part weight in most cases).

In the fast prototyping, the solid freeform fabrication (SFF) technology (also called Rapid Prototyping) is employed to fabricate physical prototypes of the re-engineered parts for design verification. At the same time, virtual machining and metal forming simulations will support manufacturing process planning and simulation before fabricating the functional prototype or embarking parts manufacturing.

An integration framework has been developed using *Windchill* of Parametric Technology Co. to embrace the tools and technology involved, support design collaboration, and facilitate information sharing and project management. More details are explained in the following sections.

## 3. REVERSE ENGINEERING

One of the major steps in reverse engineering is recovering part geometry from the physical sample. The geometry recovering process consists of two steps, the scanning or measurement to capture the part geometry in discrete points, and converting points into useful surface forms.

There are many different kinds of scanning or measurement devices. Basically, they belong to contact or non-contact category. The probe at the tip of a contact measurement device, such as a coordinate measurement machine (CMM), must contact the part surface to record the location of the surface points. Both portable and fixed devices are available to meet different needs. The non-contact type devices usually employ laser beam or X-ray for scanning or measurement. Note that the non-contact devices, including optical, laser, CT (Computed Tomography), MRI (Magnetic

Resonance Imaging), etc., usually work very well with freeform surfaces, e.g., biological parts. Mechanical parts may contain regular entities, such as circular holes, or sharp edges, which sometimes present difficult for the scanning devices. In general the non-contact devices generate thousands to millions of points in minutes and provide high levels of accuracy in support of engineering tasks.

The scanned discrete points are called *point clouds*. In order to support engineering tasks, point clouds must be further processed to a more useful and manageable form. Very often, a point cloud is first fitted with a triangular mesh, from which curves and small patches are constructed; the patches are then converted into a surface model, usually in a NURB format. The mathematical conciseness of the NURB representation greatly simplifies data management and numerical computations, thereby allowing excellent geometric visualizations and relatively good manufacturing support. However, the surface models are not equipped for support of engineering designs because they are not parametric. Without parameterization, they cannot be changed or documented in engineering drawings with proper dimensions. In addition, the NURB surface representation hinders geometric feature recognition due to the fact that NURB patches (small surface pieces) tend to capture intrinsic details of the unintended geometric features (such as welds) and the NURB patches are not mathematically compatible with regular surface representations found in CAD, such as cylindrical surfaces, revolved surfaces, etc.

The reverse engineering of this research focuses on developing a process for creating parametric solid models from digital point clouds using commercial off-the-shelf (COTS) software tools. The modeling approach employs both surface construction and feature recognition techniques. These parametric solid models are critically important for logistics support, primarily re-engineering failed parts found on aging systems. An ideal scenario that requires minimal effort from users, while still provides accurate enough parametric solid models with design intents recovered is proposed (Figure 3). Up-to-date technologies, both in the form of research literatures and COTS tools, including *Imageware*, *ICEM, Paraform, GeoMagic, CATIA*, and *FeatureWorks* have been investigated and found insufficient in completely realizing the ideal scenario. Three major issues were identified. First, the surface construction has not been fully automated. All COTS tools demand users have significant geometric modeling knowledge, advanced computer skills, and lots of patience. Moreover, they all have steep learning curves, often requiring extensive training for just the most basic tasks. Even average applications can be labor intensive, because users must deal with points, curve segments, and many small surface patches, instead of simpler solid features commonly offered in CAD. Second, the existing feature recognition tools only recognizes limited types of features in a very rigid way; that is, only one option among other possible feature forms is determined and given to the users. Third, the NURB surface models constructed are not suitable for feature recognition. The surface model consists of a network of $G^1$ NURB patches are often too irregular for feature recognition.

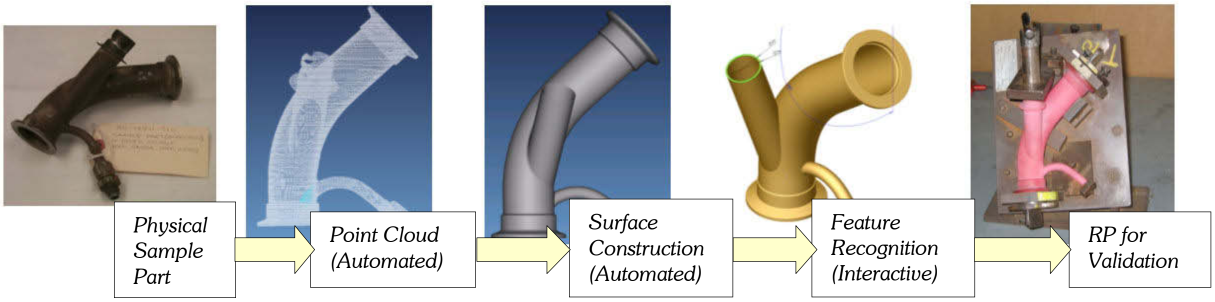


Fig. 3. The proposed ideal process for feature capturing.

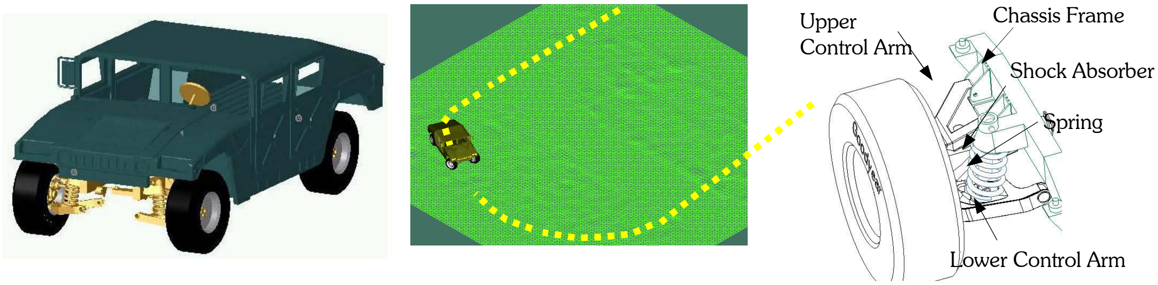
Therefore, the best possible practice for creating parametric solid models using existing COTS tools is probably still the direct solid modeling approach, where completely new, fully parametric sketches are created directly in CAD, using the imported point data as a tracing guide for the sketches. Creation of this type of model requires first determining what features would be best suited to a particular part. Then, the dimension information of these features must be determined from the original point data. An anti-icing tubing (Figure 3) commonly found on airplanes is employed for support of the study. Parametric solid models of the tubing are constructed, from which a physical prototype is fabricated using a StereoLithography Apparatus (SLA) and is then mounted on production fixtures to validate its accuracy in geometry [3].

A number of critical capabilities to be developed by both commercial and research sectors, required for realizing the ideal parametric solid modeling scenario have been recommended [3]. Among which, Hoppe-Eck's algorithms [6] are found promising in fully automating the surface construction process, and Venkataraman's algorithms [10] for feature recognition must be further improved to support more feature types as well as engineers' effort to recover design intents interactively. Furthermore, the incompatibility of NURB surfaces generated from surface construction software and the regular CAD-like surfaces, such as extruded cylindrical surfaces, must be resolved in order to support the ideal scenario.

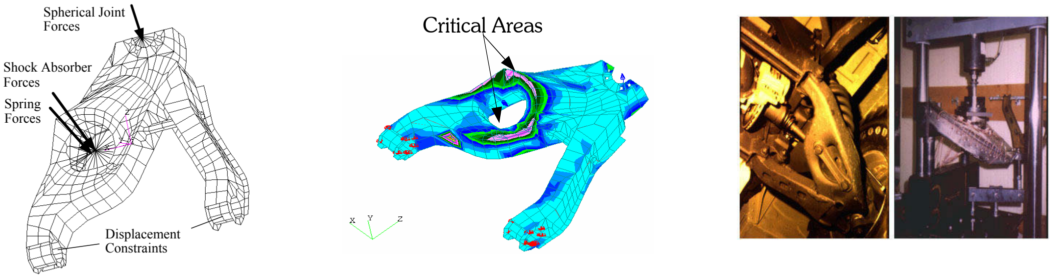
## 4. RE ENGINEERING

While re-engineering old parts, it is often necessary to modify the design or to optimize existing design in terms of performance, material, or total cost. The designers must ascertain that the new or modified design is capable of withstanding working loads, has a desired service life, is manufacturable, and is cost-effective. Such requirements mandate structural and reliability analyses, topology or shape optimization, and manufacturing process simulations.

As mentioned in Section 1, fatigue and fracture under the effect of dynamic loads are the most common causes of failure in mechanical components. Considering that the testbed is being developed specifically for re-engineering parts of aging systems, it is imperative to conduct fatigue and fracture analyses to predict service life of components. The fatigue life of a component can be divided into three main stages: crack initiation, crack propagation, and fracture failure. The *crack initiation life* computation (Stage I crack) predicts where and when the crack will start due to cyclic loads. The *crack propagation life* computation (Stage II crack) predicts direction and rate of crack growth. And the *fracture mechanics* (Stage III crack) predicts, under a given load, the size of the crack that leads to an unstable crack growth and ultimately a catastrophic failure. The crack propagation and fracture mechanics are particularly useful in obtaining safety assessment of parts in aging systems. There are two major classes of dynamics fracture problems: (1) fracture initiation as a result of dynamic loading, and (2) rapid propagation of a crack [11]. In the latter case the crack propagation may be initiated either by quasi-static or rapid application of a load and may get arrested after some amount of unstable propagation. The quasi-static crack initiation and propagation theory has been well developed. The strain-based approach, which is based on this theory, is widely employed for crack initiation life prediction subject to external and inertia loads with variable amplitudes. The strain-based approach is demonstrated using a lower control arm of the High Mobility Multipurpose Wheeled Vehicle (HMMWV) (Figure 4) with experimental validation [5].



(a) HMMWV CAD Model (b) Dynamic Simulation (c) HMMWV Suspension Subsystem

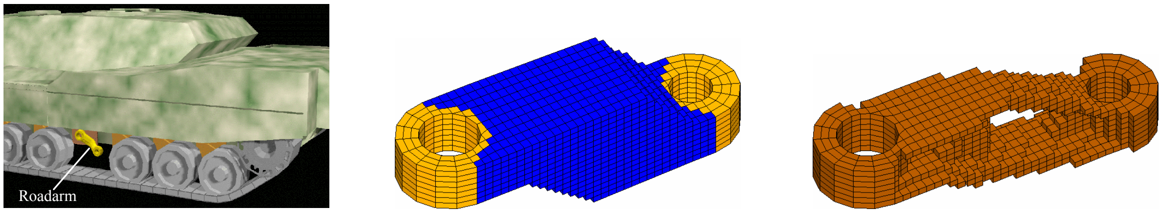


(d) FEA Model (e) Fatigue Life Prediction (f) Fatigue Test Using MT

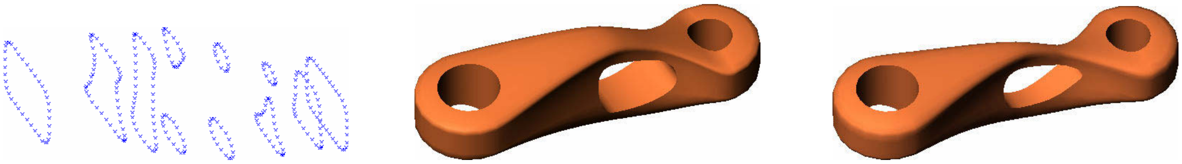
Fig. 4. Fatigue life predictions and MTS experiments.

As shown in Figure 4, the finite element model of the lower control arm is constructed first. Then, dynamic simulations are conducted using COTS tools such as DADS or ADAMS, for the entire vehicle. The load history data collected from dynamic simulations and the FEA results can be transferred to the fatigue life prediction software, such as *MSC/Fatigue*, where the computational codes are developed by *nCode International Ltd*. Since the nature of the loading is random, rainflow cycle counting technique is used to count number of stress cycles. The time-history of the loads is associated with the stresses obtained from the FEA results using a dynamic stress computation module in *MSC/Fatigue*. A plasticity correction method, such as Neuber or Seeger-Beste method is applied to account for the plastic strains during the crack initiation analysis. Based on all this information, *MSC/Fatigue* carries out the crack initiation analysis and computes fatigue life of the component. Looking at the plot of fatigue life, as shown in Figure 4e, it is clear that the crack is most likely to initiate from the area near the shock absorber mounts.

Stage II crack growth is governed not by the local shearing stress but by the maximum principal stress in the neighborhood of the crack tip. Thus the crack tip deviates from its slip path and propagate in a direction roughly perpendicular to the direction of the maximum normal stress. When the crack length reaches a critical size, one additional cycle causes complete failure, i.e., the Stage III crack. The linear elastic fracture mechanics (LEFM) [11] is usually employed to quantify the material fracture behavior. If the strain is not significant (<2%), LEFM works well for most of the problems. For impact-induced fatigue and fracture, the structural responses usually extend into non-linear and plastic ranges. In addition, dynamic fracture mechanics contains three complicating features that are not present in LEFM and elastic-plastic fracture mechanics: inertia forces, rate-dependent material behavior, and reflected stress waves. In certain problems, one or more of the above effects can be ignored. If all three effects are neglected, the problem reduces to the quasistatic case. The theoretical framework of *elastodynamic fracture mechanics* is fairly well established. Most of the commercial software tools are able to solve quasistatic and elastodynamic fracture problems for classical 2-D models or regular 3-D geometries based on LEFM theory. However, propagation of a crack in an arbitrary 3-D solid under the influence of dynamic or impact load remains a challenge. The combination of the Extended Finite Element Method (X-FEM), which is used for modeling voids in a structure, and the Level Sets Method (LSM), which is used to model moving interfaces, was recently employed for modeling crack growth in an arbitrary 3-D solid [8]. The integration of the X-FEM and LSM method into the testbed is being investigated.



(a) Tracked Vehicle Roadarm (b) Before Topology Optimization (c) After Topology Optimization



(d) Geometric Points on Cross Sections (e) Reconstructed CAD Model (f) After Shape Optimization

Fig. 5. Topology and shape optimization process applied to a tracked vehicle roadarm.

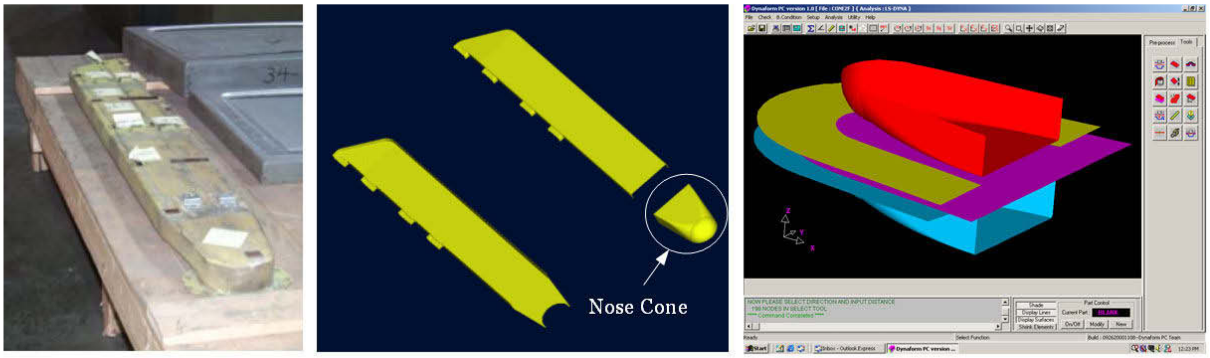
Integrated topology and shape optimization capabilities have been developed and incorporated into this testbed. After topology optimization, the boundary of the structure is not smooth. Therefore, boundary smoothing and geometry reconstruction operations are performed. Then, shape optimization is conducted to ensure that the components contain minimum material and yet meet all the performance requirements. A tracked vehicle roadarm example shown in Figure 5 demonstrates the integrated topology and shape optimization process [4]. Significant material saving is realized using the integrated design process. Also, virtual manufacturing is integrated into this design process to assess manufacturability and to estimate total manufacturing cost for the roadarm [4]. In addition, an optimization problem with manufacturing cost as an objective function and structural performance measures as constraints has been successfully demonstrated using the torque tube example [7].

As discussed above, the testbed is well capable of designing heavy load carrying components that consume minimum material and meet structural performance and reliability requirements. Fast prototyping of these components using advanced manufacturing techniques is discussed next.

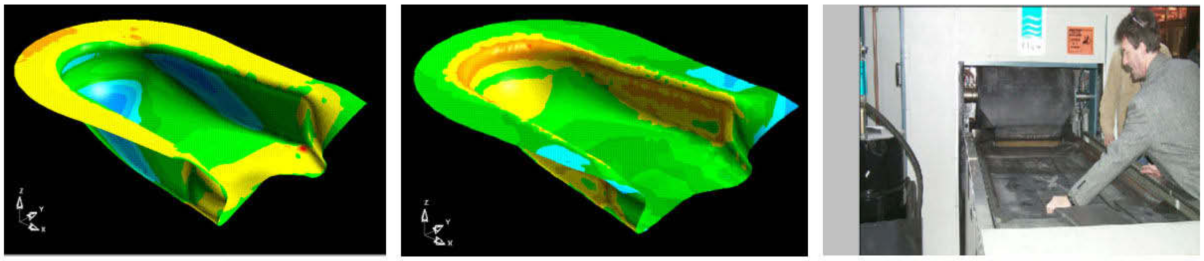
## 5. FAST PROTOTYPING

The objective of the fast prototyping capability is to support the logistics centers to produce physical samples and functional replacement parts of small quantity in a short turnaround time. There are three prototyping capabilities included in the testbed, the rapid prototyping, CNC machining, and metal forming simulation. The RP technology supports fabrication of physical sample parts directly from CAD solid models without tooling or fixtures. Currently, the *ModelMaker II* from Solidscape, Inc. is included in the testbed. In addition, other RP technologies and machines, such as SLA and Selective Laser Sintering (SLS) are available commercially, for example American Precision (www.approto.com). The RP machines support fabricating physical prototypes of the redesigned parts, which can then be mounted to fixtures to validate their geometry. In addition, the physical samples can serve as plastic or wax patterns to produce functional parts in a small quantities using, for example, investment casting.

Machining and forming are two primary manufacturing processes for fabricating a broad range of mechanical parts and subsystems in logistics centers. In air logistics centers, forming is often employed to fabricate shell structures (aircraft skin panels), and machining is employed either to directly cut the mechanical parts or to fabricate dies or molds for parts manufacturing. Virtual machining technology and tool set are incorporated into the testbed. Virtual manufacturing is a simulation-based method that supports engineers to define, simulate, and visualize the manufacturing process in a virtual environment. By using virtual manufacturing, the manufacturing process can be defined and validated before cutting materials. Virtual manufacturing capabilities, including CNC machining simulation and forming simulation, have been incorporated into the testbed.



(a) Physical Sample (b) Parts to be Formed in Three Pieces (c) Forming Simulation in *DynaForm*



(d) Forming Simulation: Thickness (e) Forming Simulation: Stresses (f) Hydro-Forming Press

Fig. 6. Metal forming for the nose cone of the air duct.

For CNC machining simulation, *MasterCAM*, *Pro/MFG*, and *CATIA* are employed. The machining process of the AWACS torque tubes was simulated using both *Pro/MFG* and *CATIA* (Figure 1) [2]. There are total 5 operations involved. Each operation consists of 2-4 NC sequences, usually a rough volume milling to remove material using a larger cutter, followed by local milling to clean up remaining material using a smaller cutter, and surface milling to polish the machined surface to meet the surface finish requirement, usually characterized as scallop height. The machining sequences can be simulated in computer for verification and the toolpath created can be loaded to CNC machines for machining work. In addition to virtual machining, there are two HAAS CNC mills and one CNC lathe together with other traditional machines available for the testbed.

For the forming simulations, three tools have been investigated. They are *Optris*, *FastForm 3-D*, and *Dynaform*. All three of these software packages provide excellent modeling and simulation capabilities that would greatly speed up the design and manufacture process by reduction in trial and error to produce molds and templates, reduction of finishing operations such as trimming, and also by eliminating much of the manual labor. An air conditioning duct shown in Figure 6 from an Air-to-Air Refueling Airplane was employed for the study. This part is to be made using 0.080 inch thick stainless steel, and will be formed in three pieces. Through the completion of this study it has been proven that, given a part, mold or die designs and template designs can be generated by applying forming software packages. In addition, using the computer generated die and template designs, and by comparison between packages, it can be said that reasonably accurate forming simulations can be performed. From these simulations, the areas of wrinkling and tearing can be identified and corrected before any actual production of parts is carried out. This comes with many benefits, the most important of which is reduced cost. This is due to a substantial decrease in trial and error, which in turn also reduces material waste. By reducing trial and error, there is an associated decrease in time spent testing actual template and die designs. It allows rapid changes in variables such as die shape and movement, stamping forces and speeds, and then allows a simulation of the changes to be generated immediately.

## 6. SYSTEM INTEGRATION

The proposed RRF processes involve using different techniques, technologies and software. To efficiently accomplish the design tasks in each RRF step, advanced computer based tools are required. These heterogeneous tools usually use different file format, work on different platform and thus difficult to be integrated in one design environment. In this research, the focus is not on converting file formats or interoperability of CAD/CAM/CAE software. Our integration concern is to select proper available commercial software and allow the built-in compatibility of the software to meet the integration needs in reverse engineering.

Most reverse engineering solutions involve multidisciplinary design activities. Consequently, design collaboration is essential for a typical reverse engineering project to let multiple designers in different disciplines perform their roles. In the integration system, the design collaboration is based on two kinds of designers' interactions: asynchronous and synchronous. Asynchronous interactions involve email, notification, forums as well as sharing documents where the designer is not required to respond in real-time. During synchronous interactions, the designer is required to response at real-time. These synchronous interactions include white board, chat room, model viewer, video and audio communication and so on. To meet these requirements the integrated environment supports:

- Appropriate distribution of activities to members of the team;
- Tools that can support real-time collaboration among team members with engineering information;
- An environment that organizes and provides easy access to engineering and other information related to the project for the team;
- A knowledge base that includes information related to different reverse engineering processes, tools and techniques;
- A reverse engineering template that can be modified to support different reverse engineering processes and reduce the initial effort to setup products.

The RRF testbed is intended to provide an environment that is software independent and can support multiple geographically dispersed designers. This principle extends to all reverse engineering activities, data, and collaborative activities, as well as to the infrastructure design. The testbed is setup using simple client-server architecture. The *Windchill* and communication module is housed in the server and is connected to the Internet. Multiple clients (users) access product and reverse engineering information from the servers using a web browser environment. Some product management functions supported by the servers are: (1) managing the product data and model in a structure through which a designer can easily locate the product data; (2) keeping the data secure and restrict illegal operations through basic file access controls; (3) providing functions to manage the file operation privileges based on designers' roles in the team; and (4) supporting file status control to prevent the file inconsistency which may occur when two users modify the same file simultaneously.

In order to support real-time collaboration, a web-based tool has been developed (Figure 7). This collaborative tool supports text messaging, audio, video, sketching, and viewing of 3D models in real-time to facilitate activities required for meetings. To enhance collaboration among different members of the team, the collaborative 3D model viewer allows users to have real-time synchronous view of the model, add notes to the 3D model, and exchange text and audio information in real-time. Collaborative meetings, if needed, can be scheduled in an ad-hoc manner. When a meeting is scheduled, appropriate group members are sent an email that has the web-link to the collaborative tool and the scheduled meeting time. During the scheduled time all group members can log into the collaborative tool to discuss issues related to the project using the environment.

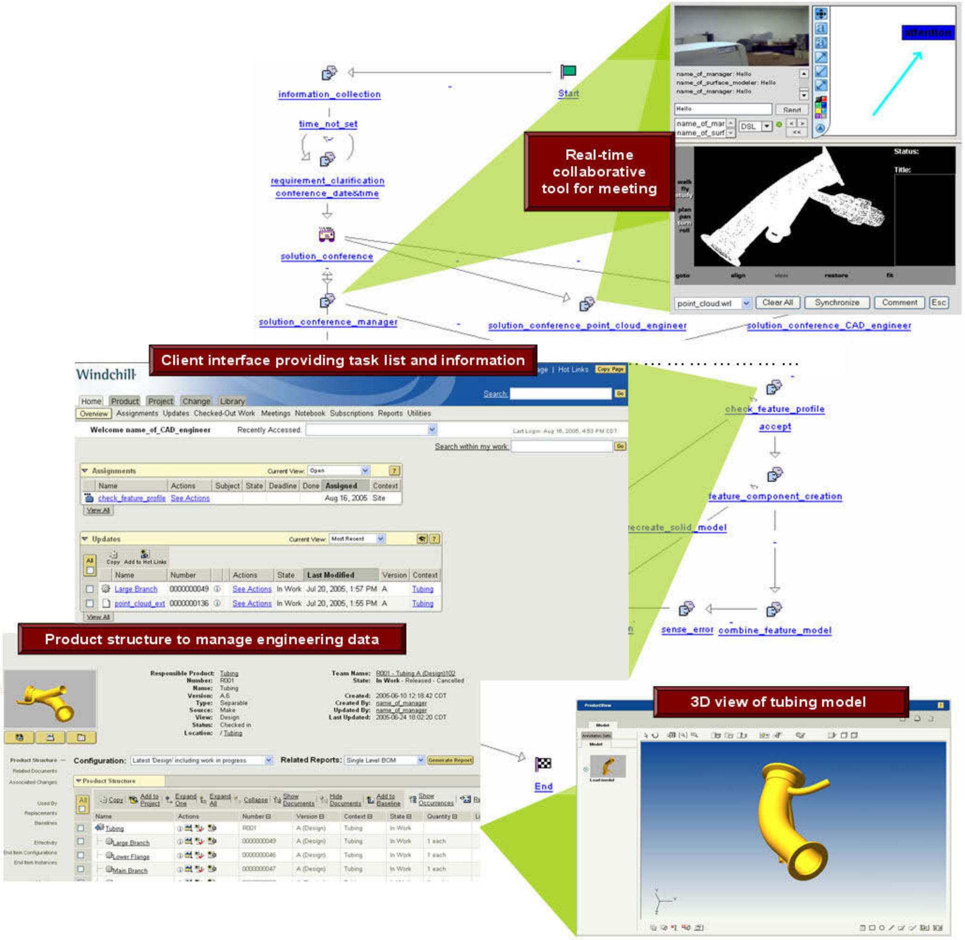


Fig. 7. Reverse engineering template and activities in the integration environment.

In order to evaluate the testbed, a case scenario was created. The reverse and re-engineering scenario highlights (1) a systematic reverse engineering approach, (2) an enhanced ability of team members collaboration, and (3) a customized *Windchill* product management system. The reverse engineering of the B-52 anti-icing tubing scenario involves an engineering team consisting of four members, who are geographically distributed: Manager, CAD Engineer, and two Point Cloud Engineers. A template with a flow of activities (see Figure 7), along with appropriate instructions, has been setup in the *Windchill* environment. This template is the start point for the manager to initiate a reverse engineering project. The initial steps for the manager involve gathering information, design constraints and point-cloud information for the product. Once the information has been gathered, the manager creates the team and calls a meeting in the integration framework using the real-time collaborative tools (Figure 7) to discuss details of the project. After the meeting appropriate reverse engineering process can be selected and modified according to the requirement and need of the project. The integration framework then supports accomplishing these tasks by appropriate users. Information and instruction on how to complete the different tasks are also available to the users from the environment. Information created from each activity is uploaded in the environment for other members of the team to view, access, evaluate and use. These data are organized in a set of defined folders that follow the product structure to reduce the effort of finding the files (Figure 7). The progress of the project can be monitored by any member of the team at any given time. After each task is completed the environment sends appropriate notification to relevant team members to proceed to the next steps.

## 7. CONCLUSIONS

In this paper, an integrated testbed that supports logistics centers to conduct reverse engineering, re-engineering, and fast prototyping of aging systems and components has been presented. A number of examples obtained from logistics centers have been employed to illustrate and demonstrate the feasibility of the proposed RRF process using the testbed. The COTS tools and equipment have been investigated extensively for constructing the testbed. The major issues identified in the reverse engineering process include the labor-intensive surface modeling, inflexible feature recognition capability, and incompatibility between NURB surfaces and geometric representation of CAD solid features. A number of development and research tasks have been formulated, including fully automating the surface construction from discrete point clouds using advanced algorithms. In re-engineering, existing crack propagation capability supports classical 2-D and very limited 3-D applications. Extended FEM and LSM hold potential for extending the crack propagation calculations to support general 3-D applications. For fast prototyping, more virtual manufacturing simulations, such as casting and welding, can be added to incorporate a broader range of manufacturing process into the testbed.

## 8. ACKNOWLEDGEMENT

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