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STEP-based product modeling system for remote collaborative reverse engineering

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Abstract

Production of high-quality products with lower cost and shorter time-to-market is an important challenge in the face of increased global competition, and reverse engineering plays an important role in accelerating product and process development. With the advent of new technologies such as network, multimedia and product data exchange standard STEP (STandard for Exchange of Product model data), there are many advantages to adopt these technologies to enhance the competitiveness of an enterprise. In this paper, a product information recording module for reverse engineering is developed to enhance the performance of product development. A STEP development tool, ST-Developer, and Visual C++ were used to develop this module, which can be used to record key information expeditiously during a collaborative process, and can also be used for further exchange of information, or as the basis for manufacturability evaluation. In this paper, the developed STEP-based information recording system is further integrated with the conventional Computer Supported Cooperative Work (CSCW) methods such as videoconferencing and application-sharing to form a remote collaborative reverse engineering system, which can provides a new strategy for an enterprise to speed up the product development cycle, reducing production cost, as well as sharing knowledge and experience.

Keywords: STandard for Exchange of Product model data; Collaborative engineering; Reverse engineering

1. Introduction

Product and process development is a very complicated engineering process with strong interactions among its development tasks, and requires iterative discussion to communicate and coordinate the re-design process. Recently, the concept of concurrent engineering together with integrated product and process development has been frequently discussed. The essence of this concurrent product and process development is an integrated and collaborative process, where people in different disciplines cooperate to specify and design products and their processes, for which coordination, communication, and negotiation are required. To achieve this, Lee et al. [1] integrated knowledge, geometry and data to develop a concurrent mold design system. Since new product and process developments require simultaneous incorporation of a wide variety of design and manufacturing expertise, concurrent engineering using new multimedia and network techniques will be a feasible solution to integrate experts who work at locations worldwide.

In recent years, reverse engineering has played an important role in accelerating product and process development; and there have been many studies on this topic [2–5]. Although most of them have focused on the technology of surface reconstruction and scanned data reduction, it is necessary to develop a STandard for Exchange of Product model data (STEP)-based information recording module to store and transform the knowledge during the reverse engineering processes. This paper combines product data modeling, the concept of concurrent engineering and Computer Supported Cooperative Work (CSCW) technologies to

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develop a rational, extensive and rapid collaborative reverse engineering system to speed up and to improve product and process development.

Recently, there have been numerous efforts on STEP research, such as surface data definition, metrology planning for contact coordinate measure machine (CMM), engineering data management (EDM), etc. Vergesst [6] studied the geometrical aspects of STEP, especially on B-spline curve and surface. Lin and Chow [7] researched the resources and constraints of contacted CMM and defined their EXPRESS data. Peng and Trappey [8] developed an integrated product database for EDM based on Parts 41–44 of their integrated resource model. As reverse engineering has become more important in speeding product and process development, it is necessary to research STEP-based reverse engineering information. In this paper, a STEP-based product modeling system for remote collaborative reverse engineering has been developed. This system focuses on non-contact CMM (scanner), and the related product and process information is systematically studied.

A series of research efforts has been focused on CSCW since the 1980s and has been shown to be able to support collaborative work effectively. Most of these researches focused on resolving the collaboration issues arisen from time and place differences through the assistance of videoconference, application-sharing systems and some other multimedia tools to ease the collaborative work. However, it seems that the history information on the product data during the collaborative reverse engineering session has not been tackled through the application of STEP yet. Generally, there are four categories [9], as shown in Table 1, in the CSCW issues: (1) same time and same place, (2) different time and same place, (3) same time and different place, and (4) different time and different place. This paper has been focused on the third category "same time and different place". The objective of this paper is to develop STEP-based information recording system integrating conventional CSCW tools, such as videoconferencing and application-sharing, to form a remote collaborative reverse engineering system.

Table 1
Research focus on CSCW methods in this paper (2×2 Johansen's time–place matrix [9])

Place	Time	
	Same	Different
Same	Meeting environments	Team work Work shifts
Different	Tele-, Video-, Desktop-Conferencing	Electronic mail Computer conferences Collaborative writing Workflow management

2. System analysis

The conventional reverse engineering process involving many iterative activities for design change is shown in Fig. 1. In contrast, this paper proposes a new methodology to integrate expertise in order to collaboratively discuss and provide timely decision-making to shorten the process cycle. Fig. 2 shows the IDEF0 system analysis model, which is based on remote collaborative reverse engineering metrology. Using the synergy of the IDEF0 structural analysis model and the CSCW strategy, the concept and objectives of a remote collaborative reverse engineering system can be clearly seen. The characteristics of product and process development with remote collaborative reverse engineering, including the activities and tasks involved, their constraints, and supporting resources, as well as information flow in the process can be clearly described. The activities of product and process development with reverse engineering in this paper are divided into (1) metrology planning, (2) digitized data processing, and (3) surface reconstruction and modification.

To concisely describe the contents of cooperative work in this system of remote collaborative reverse engineering, Fig. 3 illustrates the engineering processes, communication methods, and the STEP-based product engineering information recording module, which can be used to record the key information in CSCW process such as videoconferencing or application-sharing. For instance, the maximum error or curvature of the fitting

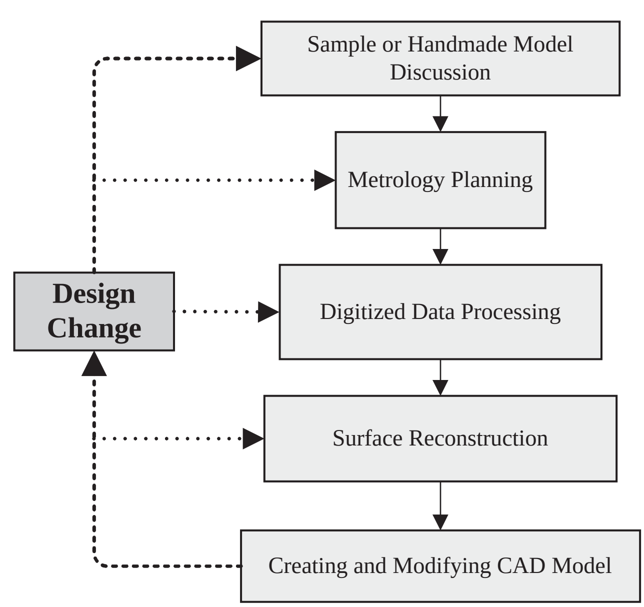

Fig. 1. Conventional reverse engineering system process.

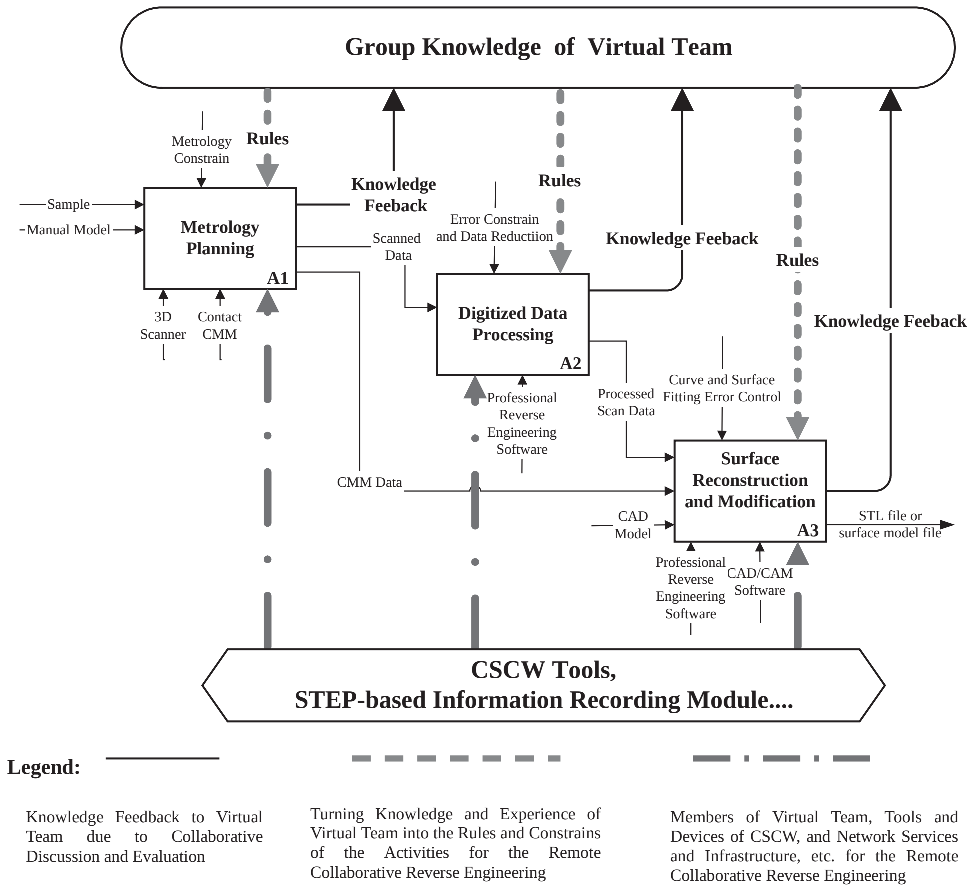

Fig. 2. IDEF0 system analysis for remote collaborative reverse engineering.

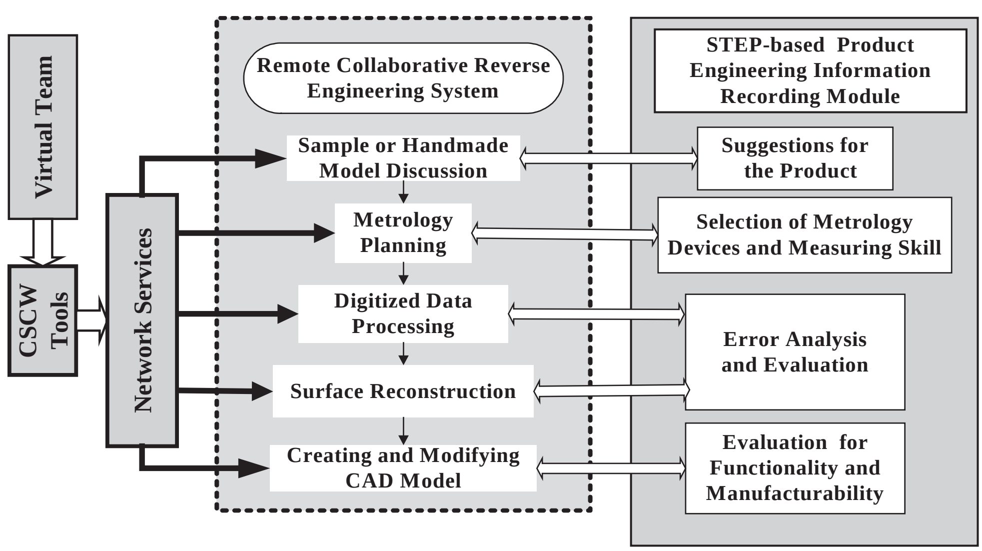

Fig. 3. Discussion issues in the remote collaborative reverse engineering system process.

surface is important information in collaborative surface reconstruction. The communication and coordination of the virtual team may be assisted by means of CSCW tools through various network services. The CSCW tools include videoconferencing, electronic whiteboard, application-sharing, text chat board, and file transfer. The demand for broader bandwidth is increasing for digital audio and video data transmission, at the cost of huge data networking. However, the exploitation of new technologies, along with the enhancement of the network infrastructure, has improved transmission quality by adopting Quality of Service (QoS) for the network.

There are various stages in different sessions of the remote collaborative reverse engineering system, as shown in Fig. 3: (1) suggestions for the product; (2) selection of metrology devices and measuring methods; (3) error analysis and evaluation; (4) evaluation for functionality and manufacturability, etc. For example, in the first stage of remote collaborative reverse engineering processes (suggestions for the product), a videoconferencing session is used for discussions regarding the part under design. The issues in this session may be suggestions submitted by members in design, manufacturing, assembly or service departments. Suggestions on the shape, function, material, etc. of the product are key subjects, in order that conflicting viewpoints among different departments may be co-ordinated in advance. This preventive manufacturing strategy will minimize re-design, thus reducing the cost and time required for product development.

3. Data modeling for reverse engineering

In order to build a complete product life-cycle data representation into an engineering design, an international standard, STEP [10], has been developed to fully define the product-cycle information, and its initial release (ISO 10303) was approved in March 1994. STEP is divided into a number of separate standards, called Parts, which are organized into the seven groups of description methods (Parts 11–19), implementation methods (Parts 21–29), conformance testing methodologies and framework (Parts 31–39), integrated generic resources (Parts 41–99), integrated application resources (Parts 101–199), application protocols (Parts 201–1199) and abstract test suits (Parts 1201–2199). The application protocols support various applications such as automotive design process (Part 214), printed circuit board (Part 210) [11] and ship building (Part 218), and they are continuously being extended. However, there is currently no application protocol for reverse engineering, so it is necessary to develop a STEP-based product data model for reverse engineering.

An application protocol is first written independently of STEP using the terminology of application area. The STEP architecture employs both IDEF0 and IDEF1x for describing an Application Activity Model (AAM) and Application Reference Model (ARM). This model is then implemented using both the integrated resources and the extensions defined in the application protocol itself. The result is an Application Interpreted Model (AIM), which is the actual data model of the application protocol in STEP. The data model of STEP is defined in the EXPRESS language [12], which is Part 11 of the standard. This language has both textual and graphical notations; the latter of which is called EXPRESS-G. In this paper, the EXPRESS entities for the reverse engineering data model include (1) a newly defined entity, (2) a hybrid defined entity formed by new definition and integrated generic resources, and (3) an entity extracted from integrated generic resources.

3.1. Data model for sample discussion and metrology plan

Table 2 shows the EXPRESS data for sample discussion and metrology plan. The entities such as part, non-contact CMM (scanner), and parameter setting for scanning are new defined entities, while the tolerance entity is extracted from Part 47 of ISO-10303. The Part 47-Integrated generic resource: shape variation tolerances is a part of ISO10303 which specifies the resource constructs for representing dimensions and tolerances of product shapes. The dimensions specify the sizes of a shape and locations of identifiable portions of a shape. The tolerances specify the allowable deviation of a product from its defined shape and dimensions. The EXPRESS format of some entities in Table 2 is shown in Fig. 4, and the EXPRESS-G diagram of the part entity in Fig. 4 is shown in Fig. 5. Until now, there is no application protocol for reverse engineering, so in this paper we propose suggestions on the definition of some entities during reverse engineering process. In Table 2, the entities such as sample, scanner specification, and parameter setting of scanning are newly defined, but the scanning tolerance entity can be adopted in the definition in ISO10303 Part 47.

3.2. Data model for pre-processing of point cloud data

The EXPRESS data for pre-processing of cloud point data is shown in Table 3. Here, entities such as scanned point cloud data, parameter setting of engineering software and pre-processing point data are newly defined entities, whereas the coordinate transformation entity is a mixed entity formed by new definition and integrated generic resources Parts 42, and the geometric

Table 2
EXPRESS data for sample discussion and metrology plan

ARM data	STEP entity	Reference source
Sample	Part	New
Non-contact CMM (scanner)	Scanner	New
Parameter setting for scanning	Parameter_setting	New
Tolerance	Tolerance	(ISO-10303 Part 47)

```
ENTITY part;
                    dimension:dim;
                    material:STRING;
                    color: part_color;
                    paint: BOOLEAN;
                    shape_visibility: surface_visibility;
                    need_to_multi_scan:BOOLEAN;
                    shape_is_hollow:BOOLEAN;
                    fixability: BOOLEAN;
                    surface_roughness:STRING;
                    surface_detalied_description: LIST[1:?] OF STRING;
END_ENTITY;
```

```
ENTITY scanner;
     original_company:STRING;
     model_type:STRING;
     tranlation_range:dim;
     rotation_range: REAL;
    description: LIST[1:?] OF STRING;
END_ENTITY;
```

```
ENTITY parameter_setting;
    coordinate: coordinate_setting;
    first_translation_scan:
scan_setting;
    second_translation_scan:
scan_setting;
    rotation_scan:  scan_setting;
    description: LIST[1:?] OF STRING;
END_ENTITY;

ENTITY coordinate_setting;
    coordinate_no:INTEGER;
    coordinate_position: dim;
    coordinate_orientation: orientation;
END_ENTITY;

ENTITY scan_setting;
    scan_start: real;
    scan_end: real;
    scan_step: real;
END_ENTITY;
```

Fig. 4. EXPRESS format of some entities for metrology plan.

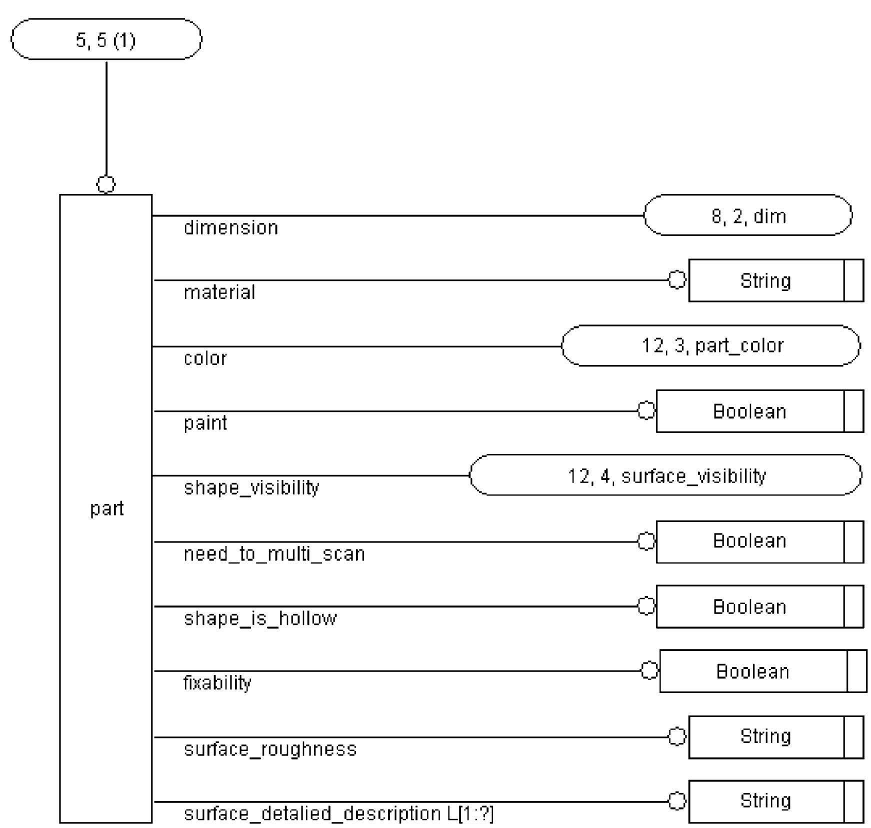

Fig. 5. EXPRESS-G graphical representation for a part entity.

Table 3
EXPRESS data for pre-processing of point cloud data

ARM data	STEP entity	Reference source
Scanned cloud points data	cloud_points_data	New
Coordinate transformation	coordinate_transformation	New + geometry_schema (ISO-10303 Part 42)
Engineering software	parameter_setting	New
Preprocessed points data	pre_processed_data	New
Geometry data	Point, curve....	(ISO-10303 Part 42)

data such as point, curve, etc. are extracted from Part 42 of ISO-10303. Part 42-Integrated generic resource: Geometric and topological representation is the portion of ISO10303 which specifies the resource constructs for the explicit geometric and topological representation of an ideal product model. This part is sub-divided into three parts: (1) geometry, (2) topology and (3) geometric shape models. The EXPRESS format for some entities in Table 3 is shown in Fig. 6.

3.3. Data model for surface reconstruction and modification

Table 4 shows the EXPRESS data for surface reconstruction and modification. The entities of the analysis of maximum curvature and maximum fitting error for reconstructed surface part are newly defined entities, whereas the entity of the tolerance is extracted from Part 47 of ISO-10303. The entities of the reconstructed data are formed from new definition and integrated generic resources Parts 42. The EXPRESS format of some entities in Table 4 is shown in Fig. 7.

4. Implementation

4.1. System configuration

Fig. 8 illustrates the system configuration of the implemented remote collaborative reverse engineering system used by the Metal Forming Laboratory (MFL) at the National Cheng Kung University (NCKU), the Computer-based Virtual Design Center (CVDC) at Far

```
ENTITY cloud_point_data;
     file_name: STRING;
     file_type:STRING;
     file_size_in_mega: REAL;
     point_no: INTEGER;
END_ENTITY;
```

```
ENTITY coordinate_transformation;
          datum_coordinate:coordinate_setting;
          input_data:  cloud_points_data;
          operator:cartesian_transformation_operator_3d;
          output_data: cloud_points_data;
END_ENTITY;
```

```
ENTITY software;
    version: STRING;
    name:STRING;
    usage:LIST[1:?] OF STRING;
    description: LIST[1:?] OF
STRING;
END_ENTITY;
```

```
ENTITY pre_processed_data;
     file_name: STRING;
     file_type:STRING;
     file_size_in_mega: REAL;
     point_no: INTEGER;
     description:STRING;
END_ENTITY;
```

Fig. 6. EXPRESS format of some entities for pre-processing of point cloud data.

Table 4
EXPRESS data for surface reconstruction and modification

ARM data	STEP entity	Reference source
Analysis of maximum curvature for reconstructed surface	analyze_max_curvature	New
Analysis of maximum fitting error for reconstructed surface	analyze_max_surface_reconstructed_error	New
Reconstructed surface data	surface_reconstructed_data	New + geometry_schema (ISO-10303 Part 42)
Tolerance	Tolerance	(ISO-10303 Part 47)
Geometry data	Point, curve, surface...	(ISO-10303 Part 42)

```
ENTITY analyze_max_curvature;
     plus_max__positive_curvature: REAL;
     minus_max__negative_curvature:
REAL;
END_ENTITY;
```

```
ENTITY  analyze_max_surface_reconstructed_error
      plus_max_positive_fitting_error: REAL;
      minus_max_negative_fitting_error: REAL;
END_ENTITY;
```

```
ENTITY  surface_reconstructed_data;
       surface_information: bounded_surface;
       file_name: STRING;
       file_size_in_mega: REAL;
       file_type: filetype;
       description: STRING;
END_ENTITY;

TYPE filetype=ENUMERATION OF
         (STL, IGES, DXF, STEP, other);
END_TYPE;
```

```
  ENTITY bounded_surface
        SUPERTYPE OF (ONEOF(b_spline_surface,
              rectangular_trimmed_surface, curve_bounded_surface,
              rectangular_composite_surface));
  END_ENTITY;
```

```
ENTITY b_spline_surface
   SUPERTYPE OF (ONEOF(b_spline_surface_with_knots, uniform_surface,
                quasi_uniform_surface, bezier_surface)
                ANDOR rational_b_spline_surface)
   SUBTYPE OF (bounded_surface);
     u_degree          : INTEGER;
     v_degree          : INTEGER;
       control_points_list   LIST [2:?] OF LIST [2:?] OF cartesian_point;
     surface_form       :b_spline_surface_form;
     u_closed          :LOGICAL;
     v_closed          :LOGICAL;
     self_intersect       : LOGICAL;
   DERIVE
       u_upper  INTEGER := SIZEOF(control_points_list) - 1;
…
```

Fig. 7. EXPRESS format of some entities for surface reconstruction and modification.

East College (FEC) and the Precision Metrology Laboratory (PML) at the National Taiwan University (NTU), all in Taiwan, as well as the Center for Advanced Manufacturing Research (CAMR) at the University of South Australia (UniSA), Australia. Hybrid network services (ISDN and Internet) are used to consider extensibility (Internet) and feasibility (ISDN). The reason to use ISDN for videoconferencing is its popularity and economy, since only a few network services presently can provide the QoS of constant bandwidth. The devices and software used for ISDN videoconferencing include PC, high-resolution camera, high performance microphone, PC-based Codec (compress/decompress) card, ISDN network card, and videoconferencing software developed by Visual C++ under NT operation system environment. The distance between NCKU and NTU is about 300 km and about 15 km between NCKU and FEC. ISDN network service was provided by Chunghwa Telecom Company, and the Internet network service provider was Taiwan Academic Network (TANet). The bandwidth of ISDN videoconferencing adopted in this paper has a constant 128 kbps (kilobits per second) bandwidth for per ISDN/BRI (Basic Rate Interface) line. The performance of the Internet from NCKU to various testing points has previously been analyzed and evaluated in a previous work [13].

4.2. STEP program development

The system development flowchart of the STEP-based information recording module is illustrated in Fig. 9. The first step is to implement the system analysis using

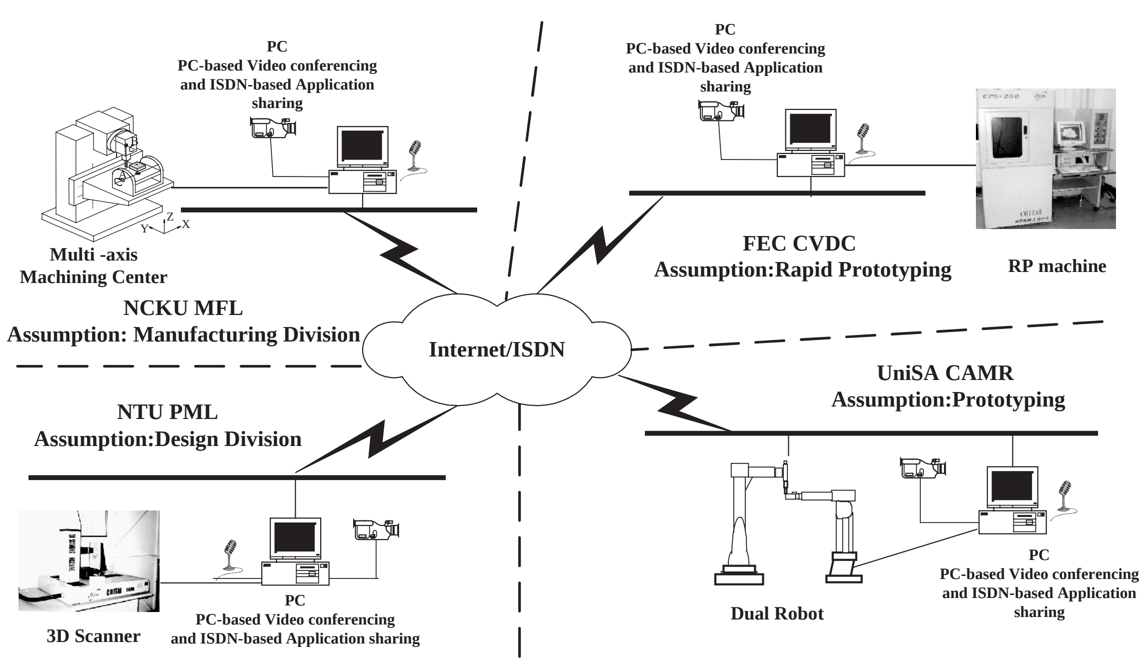

Fig. 8. System configuration.

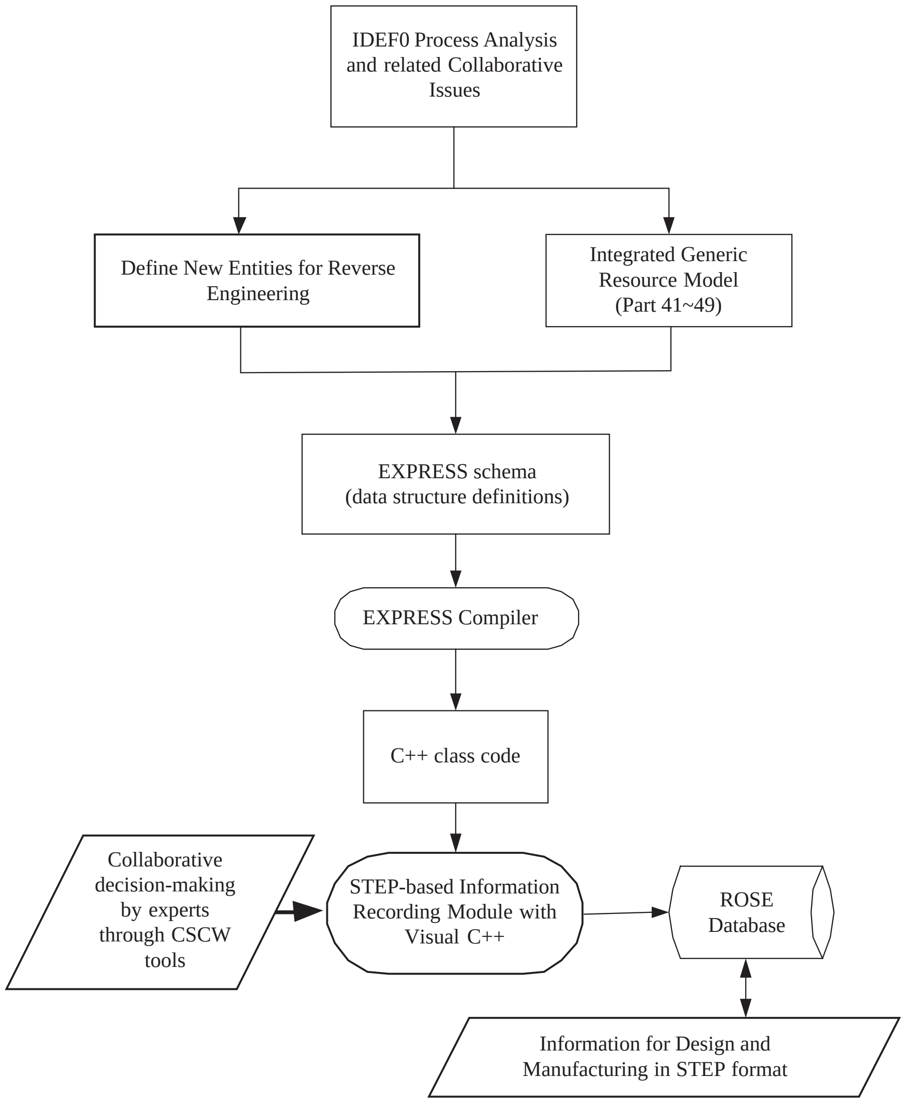

Fig. 9. System development flowchart of the STEP-based information recording module.

the IDEF0 method, as in Fig. 2, and to investigate which discussion issues are significant in the collaborative processes for reverse engineering. Then, the data modeling is implemented including defining new entities, as well as integrating or extracting entities from integrated generic resources to construct the EXPRESS information model. A STEP development tool, ST-developer [14], and Visual C++ were employed as the development medium to support the development of this product model in EXPRESS format for remote collaborative reverse engineering system. ST-Developer is a set of software tools for working with EXPRESS information models and EXPRESS-defined data sets in a variety of databases and programming environments. The EXPRESS compiler takes information models defined in the EXPRESS language as input, and compiles this information into C++ code which can be used with ROSE C++ application programs. An application program developed with Visual C++ is used as information input for the collaborative process and as the control mechanism for the ROSE database. Finally, the ROSE file [15] can be transformed to the STEP file defined in Part 21 of ISO-10303. Therefore, the decision-making by the experts through collaborative coordination can be stored in a neural file format of the international standard, STEP, and it can be further transformed to the suggestions for manufacturing through the manufacturability evaluation.

4.3. Example

The key information during reverse engineering processes—including the suggestions for product preliminary design, pre-processing of cloud point data or surface reconstruction—can be collaboratively decided and expeditiously recorded by the design and manufacturing divisions through videoconferencing or application-sharing, along with STEP-based information recording module developed in this paper. This strategy can overcome the shortcomings of conventional videoconferencing, which is not supported by automatic information recording. Furthermore, the data structure of the recorded information is in an international standard, STEP, which supplies complete life-cycle information for a product, and whose neutral format can be exchanged among heterogeneous systems. Fig. 10(a) shows a snapshot of videoconferencing with the aid of STEP-based product engineering information recording module to collaboratively decide the key engineering information of a telephone part for manufacturing by engineers in NTU and in NCKU. Fig. 10(b) shows a snapshot of the discussion on the fitting errors of constructed surface with application-sharing, along with the STEP-based product engineering information recording module. Fig. 10(c) shows a snapshot of the collaborative tool path simulation and verification; the information about the machine selection and tool diameter setting in the collaborative session is also recorded in STEP format. Fig. 10(d) shows a snapshot of the information resulted from the aforementioned collaborative session; this information can be used to assist the making of manufacturing decision. A portion of the physical file and the ROSE file produced in the metrology planning stage are shown in Fig. 11.

5. Discussion

Using the STEP-based product engineering information recording module in the CSCW process, manufacturing information such as product tolerance or machining method can be recorded as references for manufacturability evaluation better than in a conventional CSCW method. The recorded information is consistently in neutral format, and it possesses overall life-cycle information to be shared among distributed engineers worldwide.

The comparison between the proposed methodology and the conventional CSCW methodology is shown in Table 5. The advantages of the proposed methodology over the conventional CSCW methodology are that the developed system is an integrated system not only on the assisting tools but also on the product information data during the collaborative reverse engineering processes.

The framework of the remote collaborative engineering system proposed in this paper provides a new viewpoint to accelerate product and process development; and it possesses scalability, flexibility and integrity for other cooperative engineering activities. It supports a practical and economical method to share hardware,

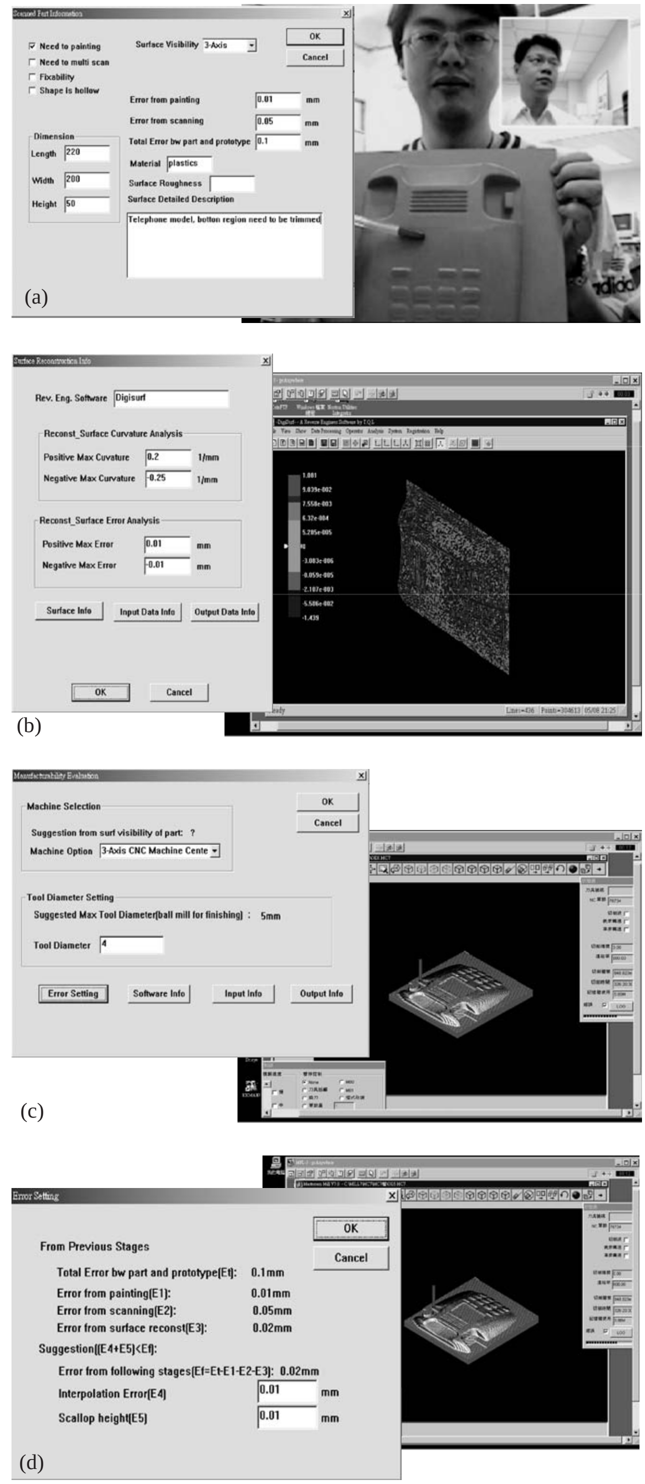

Fig. 10. Snapshots in the processes of the remote collaborative reverse engineering system developed in this paper through conventional CSCW methods (videoconferencing or application-sharing), along with the STEP-based product engineering information recording module. (a) Discussion regarding a telephone part, (b) discussion on the fitting error of the constructed surface, (c) discussion on the simulation and verification of the cutting path, and (d) information recorded from the previous stages and the suggestions for cutting parameters derived from the collaborative design information.

```
Physical file
FILE_DESCRIPTION(
/* description */ (''),
/* implementation_level */ '2;1');
FILE_NAME(
/* name */ 'metrology_plan',
/* time_stamp */ '2001-06-
12T16:58:07+08:00',
/* author */ (''),
/* organization */ (''),
/* preprocessor_version */ 'ST-
DEVELOPER 1.6',
/* originating_system */ '',
/* authorisation */ '');
FILE_SCHEMA (());
  ENDSEC;
```

```
ROSE file
DATA;
#10=ROSEDOMAIN('metro_plan',(#119),(#12,#13,#14,
#15,#16,#17,#18));
#11=ROSEDOMAIN('SetOfcloud_points_data',($),(#19));
#12=ROSEATTRIBUTE('scanned_sample',#123);
#13=ROSEATTRIBUTE('scan_machine',#125);
#14=ROSEATTRIBUTE('tool_to_fixed_sample',#126);
#15=ROSEATTRIBUTE('error_from_painting',$);
#16=ROSEATTRIBUTE('error_from_scanning',$);
#17=ROSEATTRIBUTE('scan_parameter_setting',#128);
#18=ROSEATTRIBUTE('scanned_data',#11);
#19=ROSEATTRIBUTE('cloud_points_data',#127);

...
```

Fig. 11. Example of a ROSE file and a physical file in the metrology plan stage.

software and knowledge for engineers in dispersed geographical locations.

The evaluation of samples or prototypes requires a videoconferencing system with high resolution and stable video and audio transmission quality, so ISDN is adopted in this paper for the networking to provide a constant 256 kbps bandwidth. Since the Internet is the most economical choice for scholars and business to do CSCW work and to share global resources, it is used to bridge the CSCW work, providing an environment to collaboratively evaluate computer-aided engineering activities. Therefore, the system configuration and framework proposed in this paper employ a hybrid networking system including both ISDN and Internet. Due to the unreliability of the Internet, its performance must be analyzed and evaluated before practical application. Therefore, adoption of better QoS by the Internet Service Provider and the net-provider will strengthen the research results.

6. Conclusions

This paper presents a systematic approach towards the development of a remote collaborative reverse engineering system for a concurrent product and process development environment. As a synergy of multimedia and network techniques, this study uses CSCW methodology, concurrent engineering concept, and reverse

Table 5
Merits of the developed system compared with conventional CSCW methods

Stages during reverse engineering sessions	Collaborative methods				
	A	B	C	A + B + C	Remarks
	Conventional CSCW tools		STEP-based information recording module developed in this paper	Remote collaboration engineering system developed in this paper	Snapshots to illustrate the developed system in this paper
	Videoconferencing system	Software application-sharing			
Discussion regarding a telephone part	∨		∨	∨	Fig. 10(a)
Discussion on the fitting error of the constructed surface		∨	∨	∨	Fig. 10(b)
Error analysis and evaluation		∨	∨	∨	Fig. 10(c)
Suggestion information for cutting parameters derived from the collaborative design information		∨	∨	∨	Fig. 10(d)

Note: The symbol " ∨ " denotes that the collaborative methods does enhance the performance of the sessions during reverse engineering.

engineering activities in order to develop a rational, extensive, practical and timely collaborative system for accelerating product and process development. An economic, practical, and efficient method has been proposed to construct an environment for remote collaborative reverse engineering and resource sharing using a hybrid network of Internet and ISDN. Key information in remote collaborative reverse engineering system can be recorded in the international standard, STEP, with a product engineering information recording module. This information can be used as a formal and neutral data exchange for heterogeneous systems, or as a decision-making support for manufacturability evaluation. It also can provide a reference for further development for the application protocol of reverse engineering. The proposed approach, methodology, and system framework are generic for other applications. The results of this research will facilitate rational decision-making, as well as synchronization of new product and process development, thus improving the efficiency and quality of product development, while reducing its cost.

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