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Review on Reverse Engineering Practices

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ABSTRACT
The application of Reverse Engineering (RE) is the need of various segments of industries when advanced or mathematical models of existing products are inaccessible. Replicating an existing product by reverse engineering and capturing all information and data to generate a detailed product knowledge bank for engineering design. RE is refined in different stages, scanning, part digitization and 3d modeling (CAD). This current paper introduces the RE process, portrays the recent trends in digitization field and furthermore interfaces with other manufacturing processes.
Keywords – CAD, Engineering design, Part digitization, Reverse Engineering.

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I. INTRODUCTION

Reverse engineering (RE) targets replicating a current product (part or component) by studying its physical measurements, structure and properties [1]. The objective of reverse engineering is to gather all the information of the product by aggregating the know-how of product function. RE can be applied in various segments of industry including restoration products, clinical products, software (programming), farming, aerospace, biomedicine etc., for current paper, focus is on geometric models from mechanical products. Generating CAD data is tedious in conventional manufacturing [2], whereas RE process start from an actual part to obtain the geometric model, shown in Figure 1 [3]. Mesh of geometries, material types, dimensions and tolerances need to reverse engineered by different RE frameworks. Especially, turbine manufacturing industry [4,5], aerospace field [6], biomedicine area [7,8], culture heritage [9], farming [10], also membrane module manufacturing for desalination and water treatment technologies [11], the CAD files doesn't exist. The need of Reverse engineering, within the product and manufacturing engineering, regularly emerges when:

- There is no availability of 2d or 3d CAD data of the component and original equipment manufacturer (OEM) does not exist anymore or produces that component [12-14];
- 2d or 3d CAD generated during initial phase of development and component is modified over the life cycle (from design, testing to field failures), therefore, the 2d or 3d is no longer relevant [14];
- Comparing a physical part to its 2d or 3d CAD or to a standard item for assessment or quality affirmation purposes [14];

A few design procedures such as the Systematic Approach [15], Axiomatic Design [16], and the Theory of Inventive Problem Solving [17], and Value Engineering helps engineers to propose a reliable design. RE is remarkable benchmarking technique to regenerate parametric design or for a new product concept [15,18]. 3D CAD generation by scanning an actual part is not RE, it is a basic structure of RE process and can be termed as reverse geometric (surface) modeling. Many advancements in scanning and digitization procedures have prompted productive part-to-CAD model outputs [1,12, 19-23]. Many RE tools are programmed such a way they generate free form shapes from scanned data [14-20].

Subject matter specialists are concerned about mesh construction [24,31-34], surface (geometric) continuity [27,31], sharp edge detection [35], and reducing measurement and registration noise [36-39].

Generating a 3D CAD model from an actual component is part digitization, basically data collection on its shape from actual component surfaces, resulting a cloud of 2-D or 3-D data points. To construct the component surface, the surface

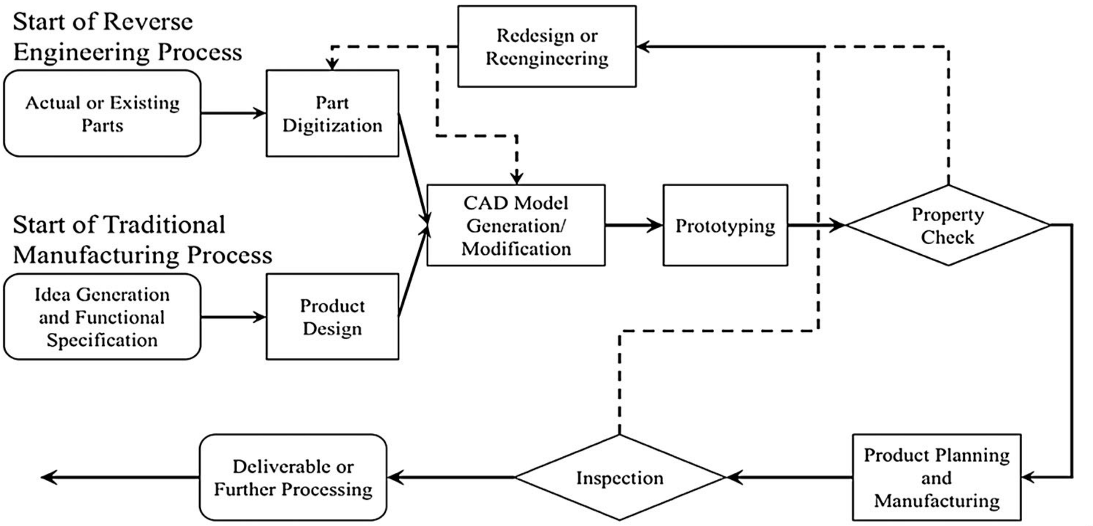

Fig. 1 Traditional vs. RE manufacturing process.

features (boundaries and surface segments) are identified from the cloud of data points. Variety of surfaces are used to model CAD segments;

- Polynomial functions are utilized to model barrel, cones, frustum etc. surfaces.
- Free form surfaces are modelled using parametric surfaces such as B-Splines, and Bezier surfaces [40].

There may be no significance of free form shapes or they may not be continuous and it may also be challenging to optimize them for certain iterations. The priority is always the engineered shapes or optimized geometries rather than free form shapes. Despite the fact, optimized geometries have free-form shapes, having specific product prerequisites [41]. In current paper, primarily RE process is introduced then, the recent digitization techniques and their classification will be discussed and next the strategies to interface RE with other manufacturing processes.

II. REVERSE ENGINEERING PROCESS

In RE process the existing component / product consists of product critical information, sub assembly / child part information and specific geometrical information. This is illustrated in Fig. 2 [1].

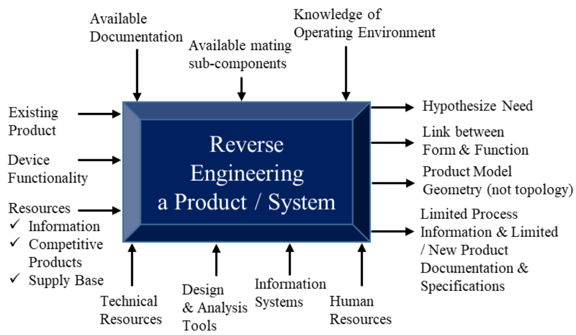

Fig. 2 Reverse Engineering

As discussed, reverse engineering process starts from an actual part to obtain the geometric model when compared to traditional manufacturing process (forward engineering) Both forward and reverse engineering cannot be fully automated, different CAD software and hardware assist to complete the process. RE process sub divided into certain activities, requiring the designer's skill and experience, with data for legitimate translation, physical and virtual analysis procedures required to analyze the product and for generating the know-how and new ideas for the manufacturing processes.

RE process is more than capturing the geometric model. Apart from the geometric model, the following critical elements should be dealt [1]:

- functional, form and fabrication features [1],
- interface, and assembly features [1],
- material and tolerance characteristics [1].

A functional feature helps to meet product prerequisites, Form features comprises of real shape and topography, and utilized to meet product specification. Fabrication features aids in manufacturing. These elements would not be required in the event of alternative manufacturing process [1].

In the event of meeting of independent and unrelated systems, Interface features comes into scenario. Inter related structures to be combine in Assembly features. An intensive analysis of product will lead for better understanding of the complete product prerequisites, and to bring clear development objectives [1].

The generated know-how can be used for value engineering and manufacturing purposes. Here, know-how is defined as data with context, capturing all the details when reverse engineering. The know-how to be fully implemented in detailed (tolerances, critical specifications etc.) manner while manufacturing the designed product, to avoid any malfunctions, warranty or field failures. Detailed comparison of forward and reverse engineering is illustrated in Table 1 [1].

III. DIGITIZATION TECHNIQUES

Digitization may be termed as process of information (data, geometric model) collection and then transforming the data to digital form. There are many challenges in digitization;

- Data accuracy,
- Slow speed than to the steps after digitization.

Data accuracy and fast speed, can led effective digitization by introducing various techniques. Classification of digitization techniques based on physical contact is as follows and also illustrated in Figure 3 [3].

- Contact method
- Non-contact method
- Hybrid method

Table 1 Comparison of Forward Engineering and Reverse Engineering

Description	Forward Engineering	Reverse Engineering
Functional Features	Product is optimized (optimum to meet specifications and functional requirements.	Functional features are indirectly derived.
Form Features	Form features comprises of real shape and topography, and utilized to meet product specification.	As geometric model is derived from actual component, a lot of variation get introduced into the model. To address this issue errors are removed from the model.
Interface Features	Modularity or Commonisation approach is used. In the event of meeting of independent and unrelated systems, Interface features comes into scenario.	Interface features are indirectly derived considering the availability of sub component or any product information.
Nominal Values	The product engineer specifically defines the nominal dimensions considering cost, design for manufacturing, design for assembly, fit and function of the product.	The nominal values can be having variations due to errors. This can be resolved by visiting the model again.
Tolerances	Product Engineer defines the tolerances to meet fit and function of product quality.	The GD&T are defined based on similar product experience & functionality.
Manufacturing Process	Based on product design, manufacturing / process engineer defines the manufacturing process following concurrent engineering methodology [92–95]	There may be some changes or complete change in the manufacturing process selection criteria. This decision depends on manufacturing volumes, cost and other constraints.
Process Capability	Process Engineer defines the process capability requirements based on product specific or customer specific requirements.	Process capability information can't be derived.
Overall	Shape – as defined in design (as per final CAD data), dimensions, tolerances (as per final drawings), and specifications (as per standards or agreed norms).	Most accurate geometric model / information is derived from the available resources.

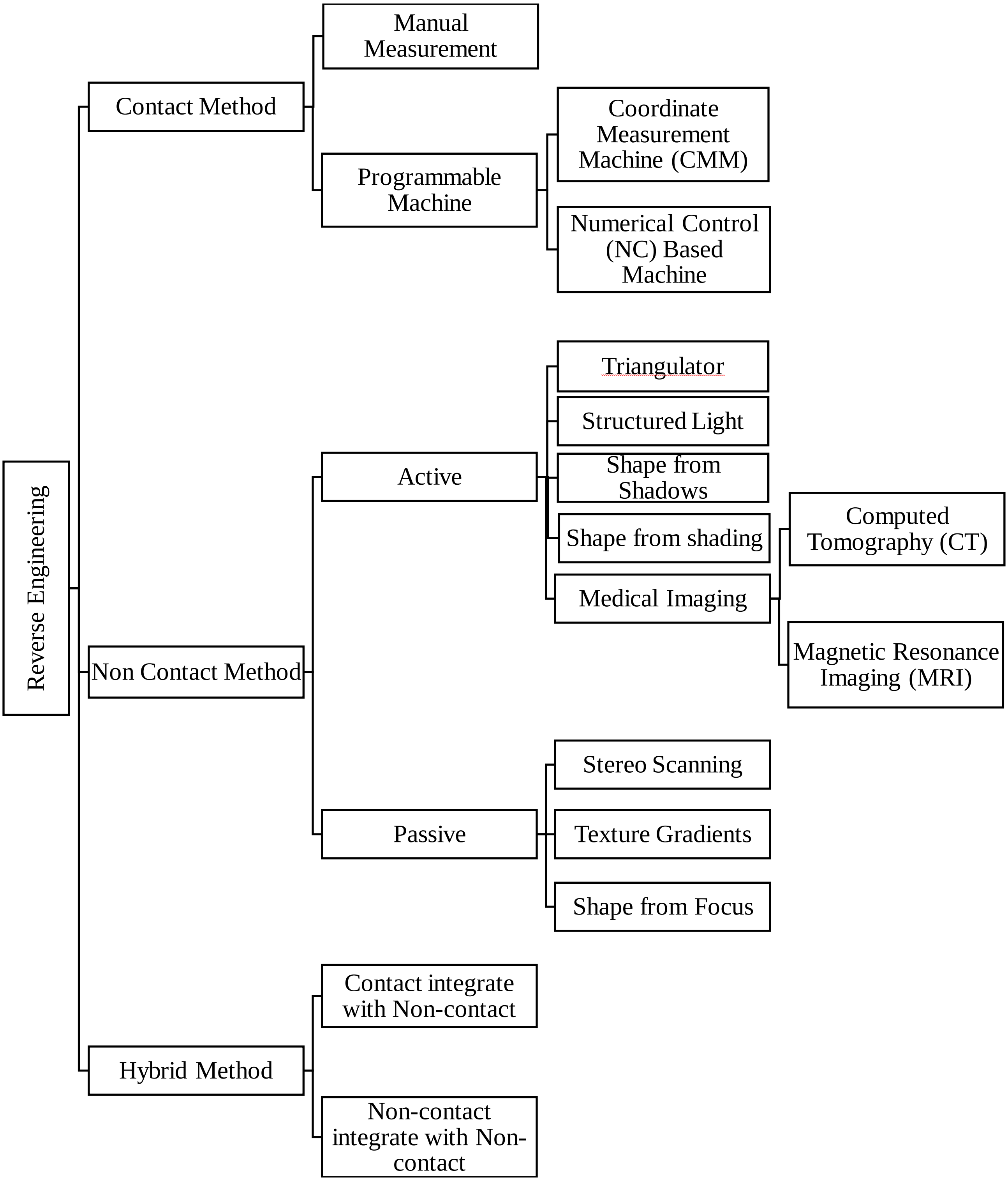

Fig. 3 Classification of Reverse Engineering Technologies

Contact methods
Most utilized, accurate but tedious conventional method, requires physical contact; contact probe or stylus between the component surface and a measuring device [3].

Manual measurement

Experienced product designers, identify important dimensions of component, that are used for preparing preliminary drawings. Measuring instruments include calipers, height, slip and radius gages etc. Identified important measurement of a surface can be directly entered into a CAD system. This methodology is rarely used for RE but flexible, having inconsistency in accuracy, the limitation of the form of surface or object, and tedious [3].

Coordinate measuring machine (CMM)

Since early 1960s, the CMM is the most mainstream hardware of RE. It interprets the spatial points on component surface through stylus attached to probe into a 3D Cartesian coordinate framework. The stylus gets triggered and a signal is generated on having the contact with component surface and that enables a measurement to be recorded. CMM performance is determined by three key major factors are [3]:

- types of configuration [3],
- control types [3], and
- fixture design [3]

Researchers are working continuously to improve CMM performance. Albuquerque et al., 2000, Lin and Chen, 2001 [42,43] Few scientists are working on CMM software calculations to avoid collision of CMM probes. ElKott and Veldhuis, 2005 [44] and Yu et al.,2013 [45] proposed that CMM can be utilized to scan free form surfaces but the assessment is mostly CAD correlated technique. A pattern of without cad, mechanization assessment way arranging of CMM has arisen, and originally shown in the area of free-form surface inspection. Chiang and Chen, 1999 [46] postulated a surface skinning methodology, consolidating a product iterative strategy for RE of formed surfaces. Li et al.,2013 [47] and Li and Nomula,2015 [48] proposed techniques of increasing the accuracy of CMM in measuring external geometry of porous objects for both CAD- and non-CAD directed methods.

Numerical control (NC)-based machine

Due to high capital investment on CMM, researchers started looking for alternate scanning equipment. Since early 1940s, NC-based machine can be easily programmed was introduced and utilized in the industries for automated manufacturing. Shen et al., 2000 and Cheng et al.,2007 [49,50] In spite of this, NC-based machine transformed with current state of- the-art scanning techniques and Milroy et al.,1995 [51] up-to-date path planning algorithms (software).

Non-contact methods

Non-contact methods take less time for scanning and derive component surface information by utilizing a medium; light, laser, sound, magnetic fields, or X-rays with measurement limitations on hollow structures on the surface of transparent materials and are further classified into:

- active and
- passive techniques.

Active System
Triangulation

The energy is projected on the component and transformed into geometric output by recording the reflected energy from the component. The principle of Triangulation for single light triangulators and laser strip is triangulating a measurement point on the component from precisely designed system that consists of energy source and a detector. This technology is having seamless accuracy. Scanning can be done from either bottom to top or right to left with user defined intervals. The output is the collection of location of points organized with equal interval cross-sectional layers, utilized for further processing. Creehan and Bidanda 2006b [52] established the accuracy and repeatability of laser scanning technologies ~0.001 inch. Gálvez et al., 2012, Lu and Wang 2015 [53,54] observed that laser scanners are fast and are commonly used in RE.

Structured light

In This system, Patterns of light is projected on to component surface and transformed into geometric output by recording the reflected projections from the component. The accuracy and speed of projection of different patterns is studied in details. Le Moigne and Waxman 1984, 1985 [55,56] used multi-resolution grid pattern light projected on the component for robot vision. Morita et al.,1988 [57] proposed a pattern made from M-array, basically a 2D extension of M-sequence, to amend pattern disorders. Maruyama and Abe,1993 [58] portrayed a range data acquisition method by projecting multiple slits with random cuts. Srinivasan et al.,1984 [59], Tang and Hung,1990 [60] have explored the projection of fringe patterns, explicitly for high measurement resolution with swift speed.

Shape-from-shadows

Rarely utilized in RE process, low cost, simple but less accurate, shape from shadows is a variant of structured light methodology. Fanany and Kumazawa,2004 [61] and Yu and Chang,2005 [62] proposed that modeling is conducted by capturing and analyzing the shadow of a component projected onto the target with moving light.

Shape-from-shading

In this technique the light is directly projected on the component resulting shadow in the background. The shading on the target surface will change according to the varying of the position of the light source. Horn and Brooks,1989 [63] reviewed algorithms to extract the shape information. Wöhler and Hafezi,2005 [64] found accuracy concerns, for a small scale of target and external factors influencing surface reflection.

Medical imaging (CT and MRI)
Computed Tomology (CT)

CT and MRI is primarily used for biomedical purposes. In CT scan, X-ray radiation is projected at the object from various points, estimating the fluctuating measures of X-ray radiations subsequently constricting by various densities from the other side. Liu et al.,2016 [65] CT scanner is utilized for viewing the internal structure of the human body that does have the ability to scan metallic subjects.

Magnetic resonance imaging (MRI)

This imaging technology utilized for disease detection and treatment monitoring and works on the principle of nuclear magnetic resonance. Image quality is dependent on the strength of the magnetic field. Because of strong magnetic field, the metallic objects are prohibited for scanning in MRI [3].

Passive systems
Stereo scanning

In this passive system, the geometric model is created by combining the photographs captured in different angle by at least two cameras. To generate geometric model design and calculation efforts are required, it is simple and low cost method. Tippetts et al.,2016 [66] published significant amount of research in the area of stereo scanning. Advance development is going on in the existing algorithms to achieve high accuracy and performance. The geometric model quality is dependent on sharpness of the surface texture and used in low precision jobs, and plays an important role in collision avoidance or motion planning [3].

Texture gradients

This is low cost, simple but less accurate technique. Szeliski,2010 [67] proposed that in texture gradients technique, the geometric model creation involves two facts, (1) the far the component / object, the smoother the surface seems and (2) A few texture elements (texels) image portrays surface orientation, therefore, the distance of certain texels from a known viewpoint can be estimated by inspecting the perceived texture at that distance.

Shape-from-focus

It's Low accuracy and non-uniform spatial resolution makes it unsuitable for RE process. Nayar and Nakagawa,1994 [68] studied that the target's depth and range information can be determined through the focal properties of a lens, therefore, a lens can be used for the purpose.

Hybrid methods

Hybrid method incorporate two or more digitization methods that provides and satisfies the expanding demands of digitization process with high accuracy, fast scanning speed, flexibility in RE process. In this paper hybrid methods primarily focusses on sensor selection, scanning path planning, and coordinate system unification. Bradley and Chan,2001, Carbone et al.,2001, Sładek et al.,2011, and Li and Wei,2016 [69,70,71,72] proposed to unification of non-contact and contact (CMM) scanning techniques; the non-contact methods are used for path planning and CMM for precise data collection. Chan et al.,2001 [73] introduced a multi-sensor approach for rapid digitization by integrating a CCD camera for path planning and a laser scanner for accurate data collection. Li et al.,2014 [74] present a tactile-optical system where a tactile probe was used to compensate the data from a laser line scanner. Lu and Wang,2015 [75] mount the point laser probe next to CMM to scan next path and provide path planning for the contact scanning probe.

IV. INTERFACING RE WITH OTHER MANUFACTURING PROCESS

The genuine characteristics and adaptability of RE frameworks is the capability to interface with other manufacturing processes to develop the components through CAD/CAM stages. Bidanda et al.,1991 [76] The digitized raw cloud point data is filtered, smoothened and then translated into specific CAD format for computer platforms. Xu,2009 [77] described, three major modelling techniques; wire-frame, surface and solid modeling. Motavalli and Bidanda,1991 [78] observed that Wire-frame modeling is earliest, fundamental and used as data reduction technique for RE process, as the data is stored as a collection of points, lines, and various curves. The wire-frame modeling partially meets critical design intricacies and free-form objects. Surface modeling techniques are more flexible and has the ability to model edges and surfaces, there are multiple surface modeling technique, Polygonal meshes and Curve and surface fitting. In Polygonal meshes the discrete data clouds are modeled connecting through small patches and converted into smooth surfaces. Krishnamurthy and Levoy 1996, et al.,2016 [79] Simplicity and flexibility for free-form surfaces provides Polygonal meshes a cutting edge in computer graphics and animations with some limitations of small gaps between surface patches due to scanning concerns. Curless and Levoy,1996, Chui and Lai,2000, Liepa,2003, Jun,2005 [80,81,82,83] different commands are developed for patch filling and can be found in archival journals. Curve and surface fitting of cloud point data is extensively used technique for surface modeling. Chivate and Jablokow,1995 [84] provided a comprehensive but not updated overview of surface representations and fitting mechanisms.

Table 2 Comparison between surface modeling techniques in RE.

Surface Modeling techniques	Surface Representation	Advantages	Disadvantages
Polygonal meshes		Simple Mathematical Model	Bulky Storage
			Difficulties for redesign or reengineering
			Pore existence
Curve and Surface fitting	Algebraic Forms	Efficient Computation	Any modification of data implies refitting the whole surface
		Closure Properties	
	Parametric Forms	Easy to modification	Extensive Computation
		Robust to outliers	

surface representations are classified as: algebraic forms and parametric forms. Boender,1991 [85] studied that target surface assumption in Algebraic forms can be represented by an implicit equation f (x, y, z) = 0 in three-space or by a homogeneous polynomial equation f (x, y, z, w) = 0 in a four-space. In algebraic forms, least squares fitting methodology computes the coefficients of the equation. In case of data modification, the data set would cause refitting of the whole surface. In Parametric form the surfaces or curves are represented in terms of two parameters, u and v and it includes Bezier’s surface/curve, Bspline surface/curve, and non-uniform rational basis spline (NURBS) surface/curve. All the above mentioned three representations are different in their basic functions. Specifically, Bezier’s surface/curve utilize Bernstein polynomials as its basis function; B-spline surface/curve uses polynomials as its basis function defined over a knot vector; and NURBS surface/curve employ rational polynomials as its basis function. Ma and Kruth,1998, Sarfraz,2006, Gálvez et al.,2007, 2012, Ülker and İşler,2007, Gálvez and Iglesias,2016 [86,87,88,89,90,91] Fitting data cloud into these three surface representations has attracted a great deal of interest.

With the evolution of surface fitting processes, surface models are generated and can be rendered into a solid model inside CAD platforms. And further used for finite-element analysis, fluid flow analysis, and NC part programming for CAM.

V. CONCLUSION

From the review of literature, different findings are concluded. A broad range of technologies that can be used to develop RE for manufacturing purposes has been described. Two main parts of state-of-the-art RE are discussed: scanning/digitization techniques and interfacing techniques with other manufacturing processes. Because both of the components are equally important to the performance of a final CAD model generation, integrated systems of different combinations should be chosen based on specific circumstances. Also, these integrated systems make it possible to reduce the product design throughput time by going from a physical part to a final deliverable. However, some bottlenecks, including the inaccessibility of the bottom side, internal structure, or blind hole, still need further work in order to coping with gaps in applicability and level of automation for RE.

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