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Reverse engineering modeling methods and tools: a survey

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ABSTRACT
Reverse Engineering (RE) is a long-term goal of engineering and computer science; it aims at the reconstruction of CAD models from measured data by means of 3D mathematical surfaces and geometrical features representing the geometry of a physical part. In the last two decades, reviews and surveys have occasionally covered this topic, but a systematic dissertation of modeling methods from a mechanical engineering point of view is still missing. The purpose of this paper is to fill this gap; starting from a general description of the overall RE framework (acquisition, segmentation, classification, fitting), both an up-to-date survey and a categorization of available modeling techniques and tools working on 3D data are provided. The main aspects of various strategies are discussed as well, in order to highlight strengths and weaknesses characterizing different approaches. Moreover, an overview of commercial software for RE is presented, considering both dedicated solutions and packages supplied as add-on with 'traditional' CAD systems. Finally, possible improvements to be addressed by the research in the RE field are discussed, outlining potential future trends that are still to be investigated.

KEYWORDS
Reverse engineering; CAD reconstruction; constrained fitting; 3D modeling; reverse engineering software

1. Introduction

Widely employed in almost all engineering fields, 3D Computer Aided Design (CAD) models are among the most common medium to convey dimensional and geometrical information on designed parts, machines, plants and so on. The increasing efficiency of the product development cycle, the reduction of costs of the whole design process and the possibility of designing and fabricating complex components (e.g. taking advantage from Computer Aided Engineering and Manufacturing tools - CAE/CAM) are some well-known examples of the key-benefits achieved by using CAD models in engineering practice.

In several situations, unfortunately, the CAD model of an 'object' is not available to the designer, does not even exist, or no longer corresponds to the real geometry of the manufactured object itself. This may be due to various circumstances spanning from manufacturing related issues (e.g. hand-made objects or post-production changes), to wear occurring during a part working life (e.g. in case of repairing worn-out parts), or even to the unavailability of digital data (e.g. in the case of the re-design of obsolete parts manufactured in pre-digital era, legal restriction, or trade secrecy). A strategy to retrieve an object's digital model when this is not available is, therefore, beneficial to several situations.

In case 2D drawings are available, the orthogonal projections of the part can be processed to extract useful geometric data, as described in [38,42,64]; a comprehensive review of these techniques is provided in [31]. Whenever 2D representations are not available, the common strategy is 1) to 'measure' 3D data directly on the object and 2) to use the obtained information to build a digital representation. The present paper focuses on the description of approaches dealing with the processing of acquired 3D data to retrieve a geometric model.

The reconstruction of digital models from measured data has been a long-term goal of engineering and computer science in general; this process, usually called 'Reverse Engineering (RE)' or 'CAD reconstruction', aims at the generation of 3D mathematical surfaces and geometrical features representing the geometry of a physical part. This is a key problem that finds multiple applications in engineering, such as quality control, re-engineering of parts and design of custom-fit parts. Not by chance, these techniques have proved to be particularly useful in, among others, automotive and medical fields, where the digitalization of clay models and

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human body parts, respectively, are commonly carried out. Most of the tools commonly used by designers are implemented within commercial RE software packages, which combine typical CAD modeling functionalities with a set of dedicated functions to interact with 3D scanned data (i.e. point clouds/mesh). In this case, the reconstruction is generally achieved by carrying out a time-consuming process, which requires a skilled operator to guarantee a ready-to-be-used result in downstream applications.

2. Related work

The problem of providing a consistent digital representation of a physical object geometry from scanned data is still open, especially considering the mechanical engineer perspective who generally needs methods capable of producing results that are: i) accurate and close to the original design of the part; ii) obtained in a limited timespan; iii) easily spendable for the designer's final need, which usually involves a step in a CAD/CAM/CAE software [80]. In the last 20 years, considerable efforts have been dedicated to achieve a satisfying RE strategy and a vast literature of various approaches and methods has been produced.

A first review of methods dealing with the fitting of analytical surfaces to scanned data is provided in [83]. The authors introduce the problem and the general framework adopted by early methods dealing with CAD reconstruction, focusing on the blending of adjoining surfaces. A similar approach is followed in [62], where the author enlists early techniques dealing with part digitization, segmentation, and modeling of the final CAD model. However, significant improvements have been lately proposed.

A valid software-oriented review of 3D *shape engineering* is presented by Chang & Chen in [21], providing a description of CAD reconstruction methods particularly concerned with feature-based parametric methods. Well-known RE software systems are also assessed by means of reconstruction examples to show their strengths and weaknesses dealing with feature-based modeling. Though offering only a partial perspective of the whole RE literature, their work highlights some practical problems and needs encountered by designers that are typically overlooked in several reviews.

Following the work and the concepts previously discussed in [21], a concise review of the technical advances achieved in the RE process is proposed in [4]. The author outlines the main phases of the typical RE framework but a limited number of methods are covered; a short review of two main commercial software systems (i.e. Geomagic Studio v11 and Rapidform XOR3) is also proposed by means of a case study involving a RE process of a sport car.

A recent and very accurate survey of surface reconstruction techniques from point clouds, analyzing more than 100 works, is provided by Berger et al. in [17]. The authors highlight advantages and limitations of different strategies, which are organized according to the hypotheses that different algorithms assume in order to reach the solution (e.g. quality of the data, smoothness of the surface, knowledge of the final shape, etc.). Berger's work, however, is generally concerned with free-form reconstruction and it's not particularly suitable to the reconstruction of engineering parts, even though there is also a limited number of references to techniques performing the fitting of pre-determined shapes. An interesting bird's eye view of evaluation methods for reconstructed surfaces is also provided, proposing tools to test and compare reconstruction algorithms and their results.

Most recent contributions to the description of the RE state of the art can be identified in [37,9]. A review covering the updated state of art of the entire reverse engineering framework, describing its application in manufacturing processes, is presented in [37]. The authors focus on the description of acquisition systems, covering practical aspects, and give an insight of current trends, such as the relation between RE and additive manufacturing. In [9], the authors present a description of the fundamental aspects of 'geometric' RE, providing interesting contributions on multiple aspects of the general RE framework (i.e. conceptual, geometric and computational); furthermore, a well-organized description of point clouds processing tools, oriented towards the recognition of geometric features, is presented. Both the mentioned studies, however, do not focus on the actual generation of surfaces and the modeling strategies that have been presented in the literature to achieve the reconstruction of a valid CAD model.

The works briefly sketched-out above demonstrate the considerable interest of both the scientific and the industrial communities towards the RE topic but, at the same time, show there is room and usefulness for a survey of CAD reconstruction methods from a practical engineering perspective, providing an up-to-date description of tools and methods available to designers; this gap is particularly wide considering the rather poor literature concerning the description of state-of-the-art reverse modeling strategies. According to these premises, this paper is meant to help filling this gap, describing existing RE methods and pinpointing weaknesses and advantages from the point of view of a designer dealing with real reconstruction problems. Since a significant part of improvements in RE tools have been introduced and made available to designers thanks to commercial software systems, they have also been included in the present analysis. The description of the software tools available to perform RE tasks and their development is an aspect typically overlooked by most techniques; moreover, the reports on this field are characterized by a fast obsolescence due to the rapid and continuous developments of software systems. As a result, an updated description of RE commercial software systems is missing in literature.

After presenting a general overview of the whole reconstruction framework and of its composing steps (Section 3), to provide the reader with a general comprehension of all the aspects of the problem, this work focuses on the modeling step (i.e. generation of CAD model), which in authors' opinion is the most interesting phase to discuss, being responsible of the creation of CAD surfaces and features. This is a crucial point [83], since RE techniques typically exhibit significant differences in the adopted algorithms and strategies. Accordingly, in Section 4, a classification of the main strategies for the generation of CAD models from pre-processed 3D data is proposed. An up-to-date overview of dedicated RE software packages and 'conventional' CAD platforms (equipped with RE functions) is outlined in Section 5. Finally, possible research trends and concluding remarks are addressed in Section 6.

3. RE general framework

The general RE framework can essentially be decomposed in steps that are common, with few exceptions, to the vast majority of techniques available in literature [86,4,52,85,54,56,70,82,15,90,32,89]. The main phases of the RE process, depicted in Fig. 1, consist of the following tasks: a) Data capture and pre-processing of the original data; b) segmentation of the point clouds/meshes; c) classification of the regions identified in the segmentation step; d) generation of analytical surfaces and features, usually fitted to the classified regions; e) finishing operations (e.g. stitching of adjoining surfaces) and CAD model reconstruction. This framework is also adopted by commercial software systems, where every step is carried out using a specific tool or function (e.g. segmentation tool, shape-fitting tool).

In the following paragraphs the above-mentioned steps are introduced to provide the reader a general comprehension of all the aspects of the problem; several references of works oriented to specific topics are also offered in order to guide the reader interested in an aspect that is hereby only marginally discussed to useful literature contributions.

3.1. Data capture and pre-processing

The 3D acquisition can be accomplished by using several devices. In the past decades, many 3D acquisition technologies (e.g. tomography, photogrammetry, CMMs, laser scanning) were developed and used in RE. Each of them has its strengths and limitations regarding accuracy, accessibility to the surface of the target, easiness of use, surface requirements, illumination, cost [12]. A common taxonomy of such devices is made with respect to the acquisition technique, classifying them in contact or

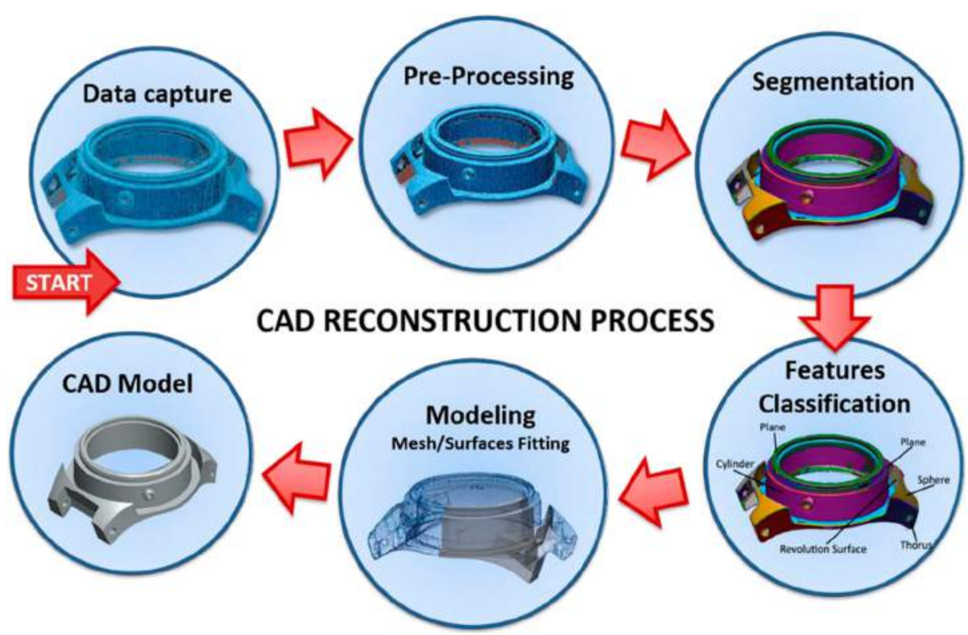

Figure 1. General RE framework: reconstruction of a watch-case.

non-contact methods. Contact methods rely on a probe that physically touches the object and is controlled by a coordinate measurement machines (CMMs) or robotic arms, in order to acquire the coordinates of a series of points. Non-contact methods, instead, observe the scene using sensors such as digital cameras. Albeit assuring a fast acquisition and being rather economic (with respect to contact methods), non-contact systems are usually less accurate and could be potentially affected by the surface properties of the object; nevertheless, optical systems (and laser-based scanners in particular) are arguably the most common devices [18], at least for mechanical applications.

Depending on the scenario and the application requirement, as well as some key factors (e.g. the work volume), different classes of technologies are usually employed. In civil engineering, as an example, time-of-flight systems [45] or phase-shift systems [40] are usually the most used techniques, as they allow the acquisition of very big volumes in a limited time. An up-to-date review of these systems is provided in [65] and in [37].

After the acquisition phase, a pre-processing step is necessary to prepare the obtained 3D data for the subsequent operations. This step is part of every RE process and often presents a straightforward implementation, sometimes performed directly by the acquisition software. Decimation of the number of acquired points, point clouds registration, and a smoothing process are only some of the typical processes carried out in order both to reduce the error and complexity of the acquired data and to obtain a usable 'starting point' for segmentation.

In the past decade, the development of CAD tools has moved towards the needs introduced by additive manufacturing. Accordingly, mesh processing techniques were developed and introduced even in traditional CAD modeling environments; such tools are now available in commercial software influencing the typical workflow of mechanical engineers; for instance, convergent modeling recently introduced in Siemens NX 11 [72] can directly use mesh in the CAD model. A survey of registration methods can be found in [76]; moreover, a review of 3D acquisition and data-processing tools is presented in [20], where several 3D acquisition technologies and devices are described together with the most used pre-processing methods.

3.2. Segmentation and feature classification

Segmentation is the process of subdividing the acquired tessellated model or point cloud into separate regions of triangle/points, under some geometrical criteria (e.g. curvature analysis). The goal of this step is to achieve a structure of regions which is as close as possible to the set of geometrical features and surfaces composing the model to be reconstructed.

It is important to distinguish between RE approaches that operate directly on point clouds versus those that require first retrieving triangulated meshes. The noisiness of point cloud data and the lack of combinatorial/topological structure introduce additional challenges that makes their segmentation and feature discovery harder w.r.t. mesh data. Such relevant aspects are not deeply discussed in this paper for sake of brevity; the interested reader can refer to [63] and [79].

The quality of the segmentation is a crucial factor [3] that needs to be taken into account when dealing with CAD reconstruction, since it represents an essential information for the following modeling steps and influences the overall workflow of the reconstruction process. Indeed, the ideal starting point for CAD reconstruction processes is a segmentation producing a region structure adherent to the original CAD model feature tree (which defines the CAD topology), where every identified region it is easily associable to a single feature or surface of the part. The segmentation process is usually controlled by a set of parameters that tunes the refinement of the region recognition procedure and influences type and dimensions of the resulting identified regions. For instance, the results obtained applying the same segmentation process with two different refinement threshold values in the region identification criterion are reported in Fig. 2. Specifically, Fig. 2a shows a segmentation not representative of the object topology, due to a high sensitivity of the procedure that generates scattered regions. Conversely, in Fig. 2b, a more coherent result, with respect to the geometry of the object, is shown.

An extensive overview of 3D mesh segmentation strategies is given in [79] and [3], where a range of algorithms are described. In [79], in particular, is presented an up-to-date survey of segmentation methodologies and performance evaluation tools; the authors present a thorough classification of segmentation techniques by subdividing them in 10 principal categories, based on the methodological approach followed and the type of surface-descriptors used (i.e. clustering, region growing, surface fitting, topology, spatial subdivision, spectral analysis, boundary detection, motion characteristics, probabilistic models, co-segmentation). Among these strategies, one of the most well-established one is represented by the *region growing* [84] technique, where each partition is generated starting from a seed element: the considered area is expanded checking its neighbourhood, according to a growing criterion. Another widely explored technique is the *edge-based* or *boundary detection* strategy, aiming at directly identifying

Figure 2. Comparison of results, obtained with different segmentation parameters (taken from [21]): a) low-quality segmentation result, obtained with a high sensitivity threshold; b) valid segmentation result obtained with a lower sensitivity threshold.

the boundaries of the regions, analysing discontinuities and monitoring various geometrical parameters. This approach generally assures a good identification of sharp edges; conversely, the recognition of smooth transitions proves to be challenging [8]. Successful results are also achieved by the *Watershed-based* method [57], where the process of a water flow filling a surface is used as analogy to perform the segmentation. In this hypothesis, different regions of a surface are considered as basins and filled by the water independently; accordingly, the points where two basins come in touch are considered as division lines between regions. Initially developed for image segmentation, this approach has been successfully extended to a 3D application in [57]. Another class of approaches widely investigated makes use of non-local surface descriptors, such as volume-based functions (e.g. Minimum Slice Perimeter, [44]) or the Medial Axis Transform [2]; these strategies generally aim at obtaining a more reliable 3D segmentation by escaping from local properties of the surface that may compromise the correct identification of a region.

One of the most recent and successful segmentation techniques entails the application of *Deep Learning* tools, such as *Convolutional Neural Networks* (CNN) [41,55], which results, if properly trained, as very effective for the labeling of class of objects characterized by a limited number of regions to be identified.

In general, the assessment of different segmentation techniques' effectiveness represents a non-trivial task and it is generally dependent on the type of the considered objects. As suggested in the benchmark proposed in [22], a large dataset of objects (namely, Princeton Segmentation Benchmark) can be independently segmented by humans and automatic algorithms; then, a rating is drawn by evaluating the similarity of the results of each algorithm with respect to those obtained by humans by considering different performance indexes.

Although the topic is of great relevance in RE [8,9], an in-depth analysis of segmentation is actually beyond the scope of the present work. In fact, recent approaches to CAD reconstruction do not typically focus on segmentation, rather proposing innovations in other areas. A noticeable exception is the work presented in [82], where the authors describe the state-of-art of segmentation methods and propose an automatic procedure to obtain a 'CAD-like' segmentation that reflects the original design intent of the part. Specifically, a segmentation based on combinatorial Morse theory leads the creation of a feature-skeleton on the mesh to identify i) most significant regions and ii) groups of triangles connecting the regions. An estimation of the mean curvature of the mesh computed locally is used as indicator function to determine primary regions.

The *feature classification* process is strictly related to segmentation, as it relies on the same information and interpretation of geometry coming from such a phase. Hence, both steps are tightly connected, so often it is not possible to distinguish one from the other [48]. Indeed, a number of algorithms and methods solving the segmentation problem propose solutions fulfilling also the classification needs. As an example, in [8], an algorithm that performs a point segmentation/classification controlled by a fuzzy logic analysis of geometrical differential properties is proposed. In [14], a 'direct segmentation' algorithm is presented, where different types of filters are applied to classify scanned object surfaces into features of increasing complexity (i.e. planes, cylinders, cones, linear extrusions, spheres, tori, revolution surfaces). A surface characterization algorithm, recognizing and extracting primitives from a 3D mesh and based on a curvature analysis that allows the identification of point areas associated to a determined geometrical feature, is discussed in [13].

3.3. Modeling: generation/fitting of analytical surfaces

Generation and fitting of surfaces are arguably the most important step of the whole presented framework, as the obtained results may differ significantly depending on the strategy chosen to perform this task. Various methods deal with this problem from a different perspective, providing results that differ in the type/format of the obtained CAD model, in the affinity of the result to the desired/original model and other relevant aspects (e.g. compliance of geometric constraints, time required to build the model and readiness of the obtained digital representation for downstream applications).

A survey addressing the state of the art of this step, i.e. an in-depth analysis of the different strategies adopted in literature to perform the generation/fitting of surfaces, is the main aim of the present work; accordingly, an exhaustive description is addressed in Section 4.

3.4. CAD Model generation – finishing operations

The final step of the RE framework, namely the actual generation and finishing of the CAD model, is typically accomplished by using very heterogeneous methods, depending on the whole reconstruction framework, as well as the kind of the desired result obtainable by using a given RE strategy (parametric or non-parametric). Typical operations that may be required are the stitching of adjoining surfaces [16], generation of fillets and chamfers [16] and imposition of geometric constraints (i.e. beautification step [54] described in Section 4.1.2). The CAD model generation step is, sometimes, directly carried out during the modeling/fitting of analytical surfaces procedure and they can be considered as a unique step.

4. CAD reconstruction strategies

A complete and exhaustive classification of CAD reconstruction strategies is really challenging due to the number of specific features that could be adopted as discriminating factors. In this section, an arrangement is provided in accordance to different points of view that are significant for a CAD designer. A basic distinction has been roughed out between feature-based methods and non-feature-based methods. Feature-based reconstruction aims at generating parametric CAD models and represents the essential trait shared among most of the analysed methods. Non feature-based methods, also known as surface-based methods [85] essentially focus on approaches relying on the freeform tools. An overview of the proposed subdivision, summarizing principal strengths and drawbacks, along with a list of relevant references, is reported in Tab. 1. It has to be

Table 1. Comparison of advantages and disadvantages of different CAD reconstruction strategies.

	CAD reconstruction strategy	Strengths	Drawbacks	References
Feature-based reconstruction strategies	Independent fitting of surfaces	Generation of independent surfaces tightly conformed to the 3D data; low computational burden and user interaction	Partial-to-none retrieval of design intent, such as geometric constraints and relations between features; effectiveness performance mainly limited by the segmentation process	[83][13]
	Constrained fitting (user-defined constraints set)	Improvement in the level of the retrieved design intent; exploitation of human expertise in constraints identification	Detection and validity checking of constraints demanded to the user; complex mathematical formulation to enforce constraints; high computational costs	[33][90][70][89]
	Constrained fitting (automatic detection of constraints set)	Improvement in the level of the retrieved design intent; low user skills and interaction required	Critical effectiveness in automatic constraints detection process and in the definition of a valid constraints set; complex mathematical formulation to enforce constraints; high computational costs, due also to constraints detection and identification phase	[54][85][52][50]
	2D sections and sketches	Processing of significant 2D sections or sketches instead of complete 3D objects; suitable for mechanical parts generated by specific operations (e.g., loft, sweep, extrusion)	Critical selection of meaningful sections (demanded to users or by means of automatic procedure); geometry-dependent effectiveness	[85][6][50][67][49][39]
	Knowledge-based	Improvement in the level of the retrieved design intent; exploitation of prior knowledge (e.g. feature recognition, constraints set) on the parts/objects to be reconstructed; reconstruction process oriented to parametric CAD models	Automatic detection of features and constraints on the acquired data currently limited to simple and application-specific features	[33][27][26][19][30][74]
Freeform strategy		Generation of models tightly conformed to the 3D data; shape-independent reconstruction effectiveness; low user interaction;	No CAD features identification by using plain freeform strategies	[17][13][81][28][51]

pointed out that multiple strategies might be generally suitable for different parts of the same object depending on their shapes and characteristics. Hence, in practical applications the adoption of multiple techniques within a single RE process usually represents the most convenient choice; this is also proven by the development of reconstruction approaches offering different kind of tools within the same framework (e.g. [6]).

4.1. Feature-based reconstruction strategies

4.1.1. Independent fitting of surfaces

Independent fitting of surfaces represents the early strategy to confront with the problem of reconstructing a CAD model of an object starting from 3D data. In this approach, every identified group of triangles/points is considered as a separate entity and a straightforward fitting of a mathematical surface to the considered region is accomplished; in other terms, the distance between the surface (expressed using a set of parameters) and the group of triangles/points is minimized using an appositely devised objective function. Accordingly, no additional information besides distances is extracted, generating CAD models tightly conformed to the 3D data. This framework partially overlooks at important factors that could increase the level of design intent retrieved and the overall reconstruction quality, such as the recognition of geometric constraints or relations between surfaces and features to be enforced in the generated model.

Considering the direct fitting of 3D surfaces by means of a parametric approach, the groundwork is laid by Taubin in [78], where the minimization process is solved as an eigenvalue search problem; the author introduces also an error metric to map the surface/point distance (by means of a first-order approximation) that has been widely applied in subsequent work; with this respect, an updated overview of quadric fitting techniques is presented in [7].

Noticeable examples of independent fitting of surfaces are presented in [83], where a general description of this approach is provided, and in [13], where a framework to reconstruct B-REP models starting from 3D meshes is proposed. The method initially identifies point regions and corresponding primitives (e.g. planes, spheres, cones and cylinders), computing the surface parameters that best approximate the point area. Subsequently, adjacent regions and intersecting edges are evaluated and a valid wire structure, which constitutes the basic information of the B-REP model, is created. The primitive recognition step is carried out firstly by performing a curvature analysis and then by testing the correspondence of a series of geometrical properties of each primitive to the analytical surfaces to be identified (e.g. for a sphere, all the evaluated points need to have the same curvature, equal to the inverse of the sphere's radius). Furthermore, the framework presented in [13] entails that every identified CAD surface is generated using only the information obtained from the single associated mesh region. Thus, the B-REP model generated at the end of the process does not consider possible relations between features.

RE methods based on independent fitting of surfaces are among the less expensive ones in terms of computational costs; furthermore, they are the most suitable whenever the desired fitting goal is only related to the minimization of the distance with respect to the 3D data. On the other hand, the interpretation of the final model is uniquely driven by the results coming from the segmentation and classification phases. For these reasons, independent fitting of surfaces is sometimes exploited as starting point for more complex fitting algorithm.

4.1.2. Constrained fitting

Constrained fitting is one of the most investigated and developed approaches to CAD reconstruction. This class of methods introduces a series of geometrical constraints within the generated analytical surfaces and features, enforcing them during the 'fitting' step. Parallelism of axes and orthogonality between planes are some examples of the constraints practically characterizing every mechanical part and which are typically considered in this technique. The constraints can be either known a priori or inferred from a first analysis of the geometrical features of the reconstructed surfaces (e.g. two planes describing an angle of 89.9° could be recognized as orthogonal and the corresponding constraint imposed). Moreover, even symmetries and regularities (i.e. feature patterns) could be identified and considered in the constraint set.

Although the enforcement of known or inferred constraints in the fitting step entails a slight detachment of the analytical surfaces from the corresponding segmented point cloud regions, the reconstructed model tends to respect the design intent. An example of results obtained following a constrained fitting approach are reported in Fig. 3 [86].

The introduction of geometrical constraints within the reconstruction of digital models has been firstly mentioned in [83], where the authors assert that 'particularly for man-made objects, there are many important geometric properties, such as symmetry, parallelism, orthogonality, concentricity, etc., which represent essential information'. Specifically, the authors highlight the potential improvement achievable by introducing of this kind of high-level information on the reconstructed models, but

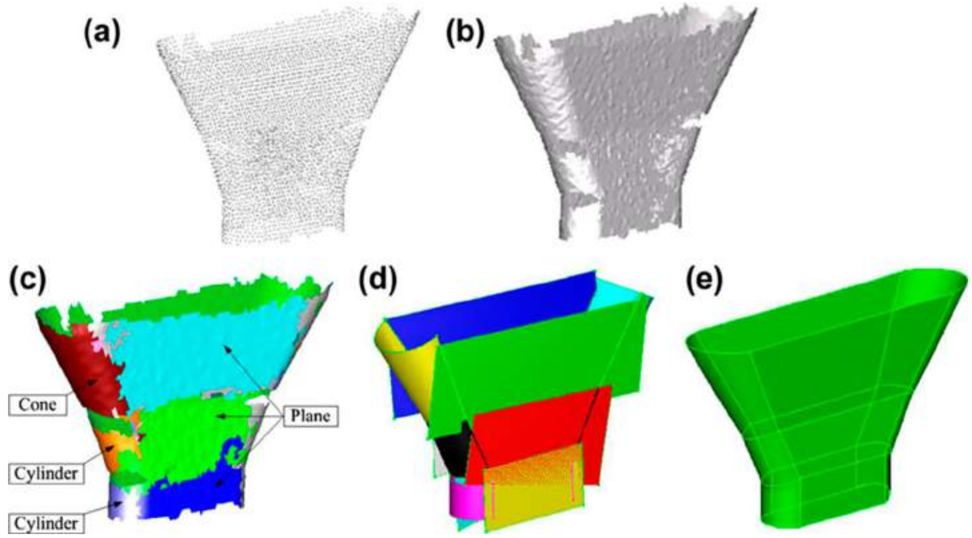

Figure 3. Constrained fitting framework (taken from [86]): a) Point cloud of multiple quadratic surfaces; b) triangular mesh; c) segmentation result; d) individual fitting of surfaces; e) constrained fitting result.

also suggest to carefully consider possible errors that could arise from deducing the relations to be enforced.

This aspect is particularly relevant in engineering applications as stated in [52], since couplings or functional surfaces are likely characterized by tight geometric constraints and regular geometric primitives, such as those described in [83]. In order to determine the 'correct' constrain set, two main strategies can be identified in literature: user-guided and automatic. The first strategy, applied in [33,89,90,70], is based on user input. This approach takes advantage from the designer knowledge on the functioning and the structures of engineering features of the object to be reconstructed; in fact, the reverse engineer is usually aware of the type of surfaces and relations included in the original design. In other words, this strategy offers the substantial advantage of relying on human expertise since it exploits the designer's insight and avoids meaningless mistakes due to a fully automated process. Nevertheless, it shifts on the user the burden of detecting and selecting the surfaces subject to constraints by means of a graphic interface, as well as the task of making them explicit; moreover, the definition of a non-valid set of constraints due to contradicting impositions is a scenario that needs to be considered and prevented [15].

The second strategy consists of the automatic identification of constraints and regularities [54,52,85,53]. The goal is to identify possible relations between features by analysing a model obtained with a first-attempt reconstruction (i.e. without the introduction of constraints) and then searching for relations that are already satisfied in the model within a certain tolerance. Among the multiple constraints automatically recognized, it is subsequently necessary to identify a constraints subset that is i) 'coherent' (i.e. composed by constraints that can coexist at the same time) and ii) significant for the considered application (i.e. a constraint set, generated considering the object functioning, that is advantageous for future modeling operations). Both these challenging aspects have been deeply investigated in the literature: accurate descriptions, and examples, of the possible solutions can be found in [15] and in [89]. It is worth to note that automated identification of constraints currently represents a critical issue affecting reconstruction methods based on partial-to-none user interaction; not by chance, a statistical analysis on the geometric constraints and regularities recurring in engineering parts is reported in [60], suggesting that this information can be exploited to commit the constraints' identification task.

Early works based on constrained fitting are generally limited to the reconstruction of simple primitives (e.g. lines and planes) and adopt different strategies to enforce the constraint set. For instance, a Kalman filter combined with linearized constraints set and an iterative method based on the linearization of non-linear constraints have been proposed in [66] and [36], respectively.

Most common approaches, nowadays, are mainly based on a constrained fitting formulation aiming at minimizing an opportune objective function. One of the most acknowledged formulation is the one of Eq. 1, strictly related to the Lagrange multipliers problem [89]. The basic idea is to minimize the error term $E(p)$ composed by the summation of two parts: the former is related to the equivalent unconstrained problem and it is responsible for the 'surface approximation error', that is, the distance between the analytical surfaces/features and the corresponding 3D data; the latter represents a contribute related to equality constraints. Specifically, in Eq.1, $\boldsymbol{p}$ is the set of surface parameters, $\boldsymbol{F(p)}$ is the surface approximation error, $\boldsymbol{C_k}$ is the $\boldsymbol{k}$-th element of the constraints set and $\boldsymbol{\lambda_k}$ is the $\boldsymbol{k}$-th weight associated to the constraints.

$$E(p) = F(p) + \sum_{k=1}^{M} \lambda_k C_k \qquad (1)$$

Since the constrained fitting problem is basically treated as a minimization problem, a range of algorithms can be employed to solve Eq. 1. Among them, the Levenberg-Marquardt based algorithm, where the constraints are expressed in a quadratic matrix form, has been applied in [89]. The method is tested in a series of case studies, showing the improvement obtained with respect to an unconstrained reconstruction process. Unfortunately, the complex formulation of constraints, the requirements of a convex solution space and of an appropriate initial guess for the solving algorithm represent the main restrictions of such an approach. For these reasons, in [90], an extension of the work presented in [89] has been proposed to partly cover some of the open issues.

Whichever is the algorithm devised for minimizing $\boldsymbol{E(p)}$, the above mentioned mathematical formulation is nowadays widespread and it has been, in effect, applied in several engineering approaches (e.g. [85,89,33,50,81]).

Another important aspect related to functional minimization is inherent to the choice of an appropriate initial guess in optimization routines. Generally a non-trivial task, this aspect falls beyond the aim of the present work; just to provide an example on how this problem has been addressed in the RE-related literature, the approach described in [69] deserves a mention; in this work, evolutionary algorithms are applied to a dense population of possible solutions and allow to overcome the need of a valid user-supplied initial guess.

A constrained fitting approach applied to the reconstruction of B-REP profiles is proposed in [16] in order to improve the quality of adjoining surfaces that are characterized by smooth transitions on a common edge; by enforcing tangency between lines and circles that constitute the model wire structure, this solution aims to overcome the poor performance exhibited by the *surface intersection* method [24], which is commonly applied in this context. The authors extend their work in [15], developing an efficient implementation for a constrained fitting approach considering a broad set of constraints and surfaces; experimental results and examples are, as well, provided. The authors particularly focus on the problem of inter-dependent constraints, which is a challenging aspect considering the formulation proposed in [89]. In [52], an extension of [15] considering the fitting of multiple types of surfaces (planes, quadrics, drafted/revolution/extruded and freeform surfaces) upon a pre-segmented mesh is proposed. The actual constrained optimization is carried out by solving a system of non-linear equations, where several regularities are described. Two standing out peculiarities should be mentioned: 1) the identification of a significant coordinate system, whose principal axes are aligned according to most of surface features, 2) the *snapping* of dimensions of the reconstructed features on a reference grid, which is automatically built analysing the model itself.

More recently, the constrained fitting problem has been confronted with by using non-deterministic algorithms; a RANSAC (RANdom SAmple Consensus) based fitting is proposed in [56] taking into account only simple primitives: basic relations between them (i.e. orientation, placement, equality in dimension) are automatically inferred in a first unconstrained fitting round and the method is successfully tested using synthetically generated and impaired 3D point clouds.

A relevant application field for constrained fitting is recently represented by reconstruction methods working on 2D cross-sections (slices) of 3D data, e.g. [85,50,61], which have been also implemented in some commercial RE software. In this framework, the constraints are firstly enforced to 2D entities (e.g. splines, lines, circles); the complete 3D reconstruction is eventually performed by fitting the reconstructed 2D slices, usually along extrusion, loft or swept paths. The most interesting and innovative approaches dealing with this issue are discussed in Section 4.3.

Proving the wide range of applications and the significance of the constrained fitting approach throughout the whole RE field, in [81] a constraint-driven optimization is implemented for the generation of 3D freeform surfaces respecting a G1 continuity constraint on the common boundaries.

As previously mentioned, fitting strategies not considering geometrical constraints usually generate CAD models affected by a series of inaccuracies, resulting in a waste of time and money spent in order to 'repair' them [91]. The relevance of obtaining a usable CAD model is widely recognized in the literature, e.g. [52,91]; a potential solution is represented by the so-called *beautification* step [53,54,52] which aims at correcting and improving a model imposing geometrical constraints and relations at the end of an unconstrained reconstruction. Methods adopting such a technique usually rely on analyses of the generated geometry or feature tree and infer possible regularities and relations. The recognition of both local and global relations in B-REP models, such as symmetries

[59] or congruencies [35], have been thoroughly investigated. In [54], a method to efficiently determine and solve a valid constraint system by implementing beautification is proposed. This method performs an identification and prioritization of constraints based on their significance and the probability of their existence in CAD models. Specifically, the constraint system is processed and inconsistencies of the identified regularities set are pruned by using graph-based operations.

According to [85], methods based on beautification step likely suffer a penalty gap since 'the reconstruction accuracy cannot be guaranteed because the original point cloud is not considered during adjustment'; nevertheless, the gain achieved in terms of lower computational burden with respect to methods based on constrained optimization makes this strategy rather appealing [54].

On a general level, constrained fitting based methods represent an effective solution to assure the compliance of the reconstructed model with a set of geometric constraints and to reduce the gap between the reconstructed digital model and the original designer intent. Nevertheless, a relevant issue concerning this approach is related to the implementation's complexity of geometrical constraints. For the interested reader, a thorough description of a common analytical formulation of both 2D and 3D geometric constraints is provided in [15]. It has to be noted that the efficiency of a reconstruction strategy is strictly related to the simplification of the number of mathematical relations describing the regularities of a geometric model; incidentally, standing out results can be achieved introducing auxiliary objects (i.e. synthetic geometric objects that serve as convenient reference entities for constraints definition) among the considered geometrical entities [52].

4.1.3. Reconstruction based on 2D mesh sections

An alternative strategy undertaken by several authors relies on the exploitation of reconstruction cues extracted from 2D cross sections of the original mesh (e.g. [85,50,67,49,68,6]). This concept is, in some way, inspired by the traditional 3D modeling framework, where parametric 2D sketches are used as basis to generate solids and surfaces by means of advanced functions (e.g. extrusions, sweeps, revolutions). Accordingly, this class of methods attempts at extracting 2D sketches from cross sections of the mesh or, more generally, at retrieving geometric information of the object on multiple planar sections.

A significant work dealing with this topic ([67]) performs the reconstructions of 3D objects starting from cross-sections of the point cloud (excerpted from a user-specified direction) and eventually solving two minimization problems to obtain the final 3D model. First, the actual 2D shape of each cross-section is approximated by performing a boundary extraction process and subsequently fitting the result by using optimal quadratic rational Bezier curves. The resulting parametrized and independent 2D features are, then, used as input of the second optimization stage to obtain connected and related 2D features. Specifically, inter-cross section (e.g. tangency, parallelism, etc.) and intra-cross section constraints (e.g. point co-linearity, curve translation, etc.) are enforced in the minimization functional to support parameterization and editing of the output model. Furthermore, the authors provide an interesting insight on the actual reconstruction of solid parts, which is carried out using extrusion/sweep functions, considering both the case of similar and non-similar adjacent cross-sections, aiming to obtain a final CAD model that is as much coherent as possible with respect to the connected features.

In [85], an approach concerning the generation of traditional CAD features (extrude, revolve, sweep, loft, blend) by involving a constraint-based reconstruction of 2D contours is proposed. The process starts with the slicing of the mesh with a sectional plane, aiming to create a 2D point set; subsets characterized by the same underlying curve representation are subsequently identified by means of a segmentation phase. In detail, six types of curve segments are sequentially identified: line, circle (arc), ellipse, parabola, hyperbola, and B-Spline curve. Then, according to the parameters of fitted curves, the potential constraints between curves are detected and verified. By applying those constraints, the fitting on the whole point set is performed to achieve the constrained 2D contour. Depending on the CAD feature used for building the model (e.g. extrusion, loft, etc.) the procedure could be repeated for several sectional planes. In [50] a similar method is applied to fit a parametric 2D curve composed of lines, arcs and B-Spline (see Fig. 4) to a series of segments extracted from a

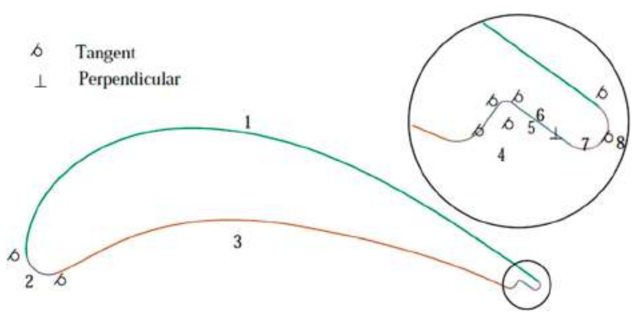

Figure 4. 2D Constrained Fitting applied to the reconstruction of an aerofoil surface (taken from [50]).

section of the mesh according to pre-recognized feature points, under the imposition of constraints between the parametric curves (e.g. position, parallelism, orthogonality). The constrained optimization is first converted into an unconstrained non-linear optimization problem by means of a penalty function method and then solved applying a modified Levenberg-Marquardt procedure. A detailed description of the algorithm proposed in [50], focusing on the constraints definition for B-Spline curves, is provided in [49].

The choice of a convenient set of cross-sections to be used in the reconstruction process is a common issue shared among the above-mentioned methods. The effectiveness of strategies based on 2D sketches is expected to be affected by both the position/orientation of cross sections, as well as the number of slices used in the reconstruction process. On the other hand, an excessive density of similar cross-sections might result in an unnecessary computational burden. Hence, an effective selection procedure considering such aspects is required to improve the overall efficiency. Identification of similar point clouds' slices can be performed by means of principal component analysis and skeleton extraction [67]. A different solution is proposed in [39], where the problem of identifying significant mesh cross sections with a convenient arrangement and distribution along multiple sweep feature is considered, in order to generate high quality surfaces. Similarity measure between mesh cross sections is evaluated by performing a neighbourhood analysis and the most significant ones are subsequently extracted. Finally, an affinity propagation analysis is applied to cluster the sections into separate sweep features, generating the final CAD model. In [6], an initial user input is exploited to indicate the sweep direction and identify the possible sections to be used in the reconstruction; moreover, starting from the user suggestion, a flood-fill algorithm is used to automatically identify the mesh region to be considered in the reconstruction.

2D-based reconstruction strategies have been successfully and extensively applied for the reconstruction of specific categories of parts characterized by a suitable geometry. The most significant example, in this context, is represented by the CAD reconstruction of turbine blades; indeed, their shape is almost perfectly matched by a sequence of 2D profiles (i.e. *aerofoils*) which evolve continuously throughout the radius of the turbine. In this specific application, a reconstruction based on the information obtained from mesh cross sections is the most convenient and significant approach from an engineering perspective. Other examples of applications of reconstruction strategies to turbine blades can be found in ([50,61,87,92]).

Eventually, 2D and 3D data are occasionally exploited in synergy. In particular, 2D images can be exploited to refine the information provided by 3D acquisition systems as in [58], or to obtain clues from the part texture/shading/profile to guide the reconstruction.

Other interesting applications are provided in [68,87] where silhouettes of facetted models extracted from orthographic views are used to obtain information on the geometry of the part. Such an information is exploited to perform the retrieval of a CAD model within a database, using a hand-drawn sketch designed by the user as query.

From a general perspective, reconstruction methods based on 2D mesh sections take advantage from the relatively less complex approach to the reconstruction problem: the generation/fitting of 2D profiles upon the original mesh cross sections proves to be cheaper from a computational point of view; conversely, the effectiveness of this class of methods is strictly related to the correct identification of the most significant 2D profiles to be used in the reconstruction process.

4.1.4. Knowledge-based methods

Even though the increasing performance and the costs reduction of computers represent a breakthrough in the field of RE, human intervention and interaction are still key features in many phases of the reconstruction process. For instance, in several of previously discussed RE procedures, the setting of thresholds required to properly perform the segmentation algorithms or the selection of suitable cut planes in 2D mesh sections methods represent tasks that are usually demanded to user's expertise and overview. On the contrary, a great deal of efforts should be put for their automatic implementations. Such a concept can be ultimately summarized asserting that a full automated RE process is not convenient since '[. . .] computers are good at data analysis and fitting operation; and humans are good at recognizing and classifying patterns' [33]. Starting from this consideration, a well-established new class of RE techniques that explicitly rely on human capabilities to provide or retrieve high level *knowledge* or *information* can be identified. Hence, several methods for *knowledge-based* reconstruction broke through scientific literature in the last decade.

Prior information can be exploited for explicit feature recognition and geometric constraints assignment. In the Knowledge-Based Reverse Engineering (KBRE) method [27,26,5], the authors introduce a user-driven knowledge analysis phase in order to decide if a feature of the scanned part has a functional or a manufacturing purpose. Starting from a 3D point cloud, a RE user can choose, via the devised KBRE tool, a list of available (i.e. stored in a database) manufacturing and functional features to be associated with the 3D segmented areas; once the features are selected, a fitting on the 3D point cloud is performed (materialization phase) by means of a specific algorithm. The final output of the method is a functional and structural skeleton representing the assembly of the features of the parts and describes the design intents.

A knowledge-based strategy adopting a probabilistic approach has been proposed in [19], addressing the reconstruction of 3D CAD models from point cloud data acquired in industrial environments, with particular focus on cylindrical parts (pipeline). An existing 3D model, defined upon a set of geometrical parameters $\boldsymbol{M_0}$, is used as an initial reference of the model to be reconstructed. This prior knowledge, along with the point cloud $\boldsymbol{C}$, is used to infer the set of geometrical parameters $\boldsymbol{X}$ of the reconstructed model in accordance to the Bayesian framework. Specifically, as reported in Eq.2, the reconstruction problem is expressed as the maximization with respect to $\boldsymbol{X}$ of a posterior probability $\boldsymbol{\pi}$ that, in turn, is proportional to the product of a data likelihood term $\boldsymbol{P_D}$, which accounts for the similarity of the final CAD model to the point cloud, and a prior term $\boldsymbol{P_P}$, which describes the closeness to the a priori configuration.

$$\pi(X|C, M_0) \propto P_D(C|X, M_0) \times P_P(X|M_0) \qquad (2)$$

The final model is built in an iterative fashion, by introducing at each iteration a new element belonging the a priori 3D CAD, evaluating the functional on specific subsets of the available cylinders by means of an ad-hoc greedy algorithm and, finally, saving the configuration that scores the best value.

It is worthy of mention that some methods developed for inspection, monitoring and maintenance purposes of complex engineering objects like factories or plants can be also included in the class of knowledge-based RE strategies. For this kind of application, in fact, matching the 3D model to the actual state (scanned data) is often necessary.

For instance, the method proposed in [30], aims at matching basic geometrical features (e.g. cylinder, torus, cuboid) reported in a 3D CAD reference model of a complex engineering object (i.e. plants) to the point cloud acquired on the actual object, in order to detect if they are fully, partially or not present. After a stage of features and connectivity recognition carried out on the reference CAD model, a list of basic geometric feature along with their main parameters (e.g. position, radius, length, etc.) and a connectivity graph are obtained. Then, for each feature, a corresponding bounding box is considered in 3D the point cloud and an iterative algorithm is applied to modify only the position and the orientation of the feature, in order to maximize the number of points whose distance from the feature surface is less than a prescribed tolerance. The ratio between such a number and the total number of points in the bounding box is subsequently computed; the feature classification is finally accomplished by means of a threshold-based detector.

More recently, a knowledge-based 3D reconstruction method of as-built industrial instrumentation models, based on the comparison between the actual and the expected topological structure of a power plant, has been presented in [74]. Interestingly, the graph representation of the actual topological structure is itself obtained by processing an acquired 3D point cloud of the scene and relaying to geometrical and topological prior knowledge. Indeed, the extraction of sets of the 3D point clouds belonging to pipelines is initially performed by exploiting the knowledge of pipelines' radii, as reported in the piping and instrumentation diagrams (P&ID) which are considered available. In second instance, a region grouping algorithm supported by a prior 3D CAD database of instrumental pieces is used to detect and extract the 3D point clouds belonging to valve and other equipment. At the end of these processes, graph representations of the scanned scene are obtained: each node is associated to a specific portion of the 3D point clouds (potentially representing a part of an object) and reports its geometrical descriptors (position and dimensions), whereas each edge represents the space adjacency relation between the connecting nodes. Such graphs are, then, compared with a set of analogous ones describing the expected configuration (i.e. derived only by means of the P&ID and of the prior 3D CAD database of instrumental pieces) by matching the geometrical descriptors of the corresponding nodes. Hence, a similarity score can be associated between each pair of matched graphs; by selecting the most matching nodes, the best-matched 3D CAD model of instrumentation is retrieved. Finally, a registration stage is performed by applying an iterative closest point (ICP) algorithm.

As can be deduced from the papers mentioned above, the key trait shared among most methods that rely on the knowledge-based paradigm is represented by the retrieval of 3D CAD and shape models in an opportunely devised database. Even though this topic is not directly related to the issue of RE, raising interest has emerged in last decade on this issue because of the increasing amount of available 3D models, especially in the Internet [77]. On the other hand, probably due to the early-stage of the proposed knowledge-based techniques that have been applied so far to relatively simple scenarios, authors involved in RE framework do not currently seem to be particularly concerned about this issue. However, whether knowledge-based methods are going to be thoroughly developed, the application to more challenging case-studies as well as to more complex practical scenarios will predictably require an integration of 3D CAD model retrieval.

As a general trend, most of the discussed knowledge-based methods that rely on low or even no user interaction has been tested to deal with a low number of basic geometrical shapes. As the number of detectable features grows, a severe complexity burden is expected due to all the possible components interactions. On the contrary, knowledge-based methods that require the user cooperation to accomplish some key tasks (e.g., classification of features, constraints definition) have been successfully applied on more complex case studies.

4.2. Freeform surfaces

A well investigated class of reconstruction methods is represented by *surface-based* ones [85] that performs the RE process by using *freeform surfaces*, based on B-Spline or NURBS [13,71]. The general problem of adapting a single freeform surface on a point cloud has been extensively investigated and several solving strategies and algorithms have been proposed [17].

Two main advantages, such as the possibility of performing a reconstruction that requires little-to-none user assistance [81,28], and the capability of reproducing any 3D shape, ensure these techniques a wide application field.

In [28], a fully automated method that aims to produce a G^1 B-Spline reconstruction starting from a set of 3D points is described, together with a concise review of early methods dealing with freeform reconstruction. The authors evaluate a series of meshes (both triangular and quadrilateral) to perform the reconstruction, in subsequent steps starting from the original point cloud; the resulting meshes are used as basis to generate a final B-Spline surface by means of a least squares fitting process. An example of the obtained result is represented in Fig. 5.

A novel B-spline surface reconstruction method is proposed in [81]: starting from triangular meshes, which are simplified in a preliminary step, a well-known edge recognition method [43] is applied to identify the feature boundaries to be preserved in the surface generation phase. Based on the information obtained, a convenient curve net is generated and B-splines surfaces are fitted to the meshes, imposing G1 continuity in a *constrained fitting* approach.

Among the topics dealing with surface-based reconstruction, the identification of features boundaries and edges is one of the most relevant [75]. A significant improvement on the final result, especially on the preservation of the original feature edges, can be achieved by building an appropriate net of curves based on the edges of the original features. Referring, for instance, to the reconstruction of the object depicted in Fig. 6a, a consistent result characterized by a curve net almost perfectly following its edges is depicted in Fig. 6b. On the contrary, the result of a poor freeform reconstruction process is showed in Fig. 6c, where several typical defects caused by a ‘wrong’ curve net are visible. Such defects, along with a general smoothing effect usually introduced by freeform reconstruction, become particularly significant when dealing with mechanical parts.

In effect, freeform surface methods generally generate an aesthetically pleasing result and potentially very little deviation errors, but they do not allow to retrieve any additional level of information in the reconstructed model beyond the mere 3D geometry. In other words, no geometrical feature is generally identified by using these approaches, thus limiting the subsequent use of the generated model (at least for engineering purposes). Nevertheless, freeform methods can be combined with feature-based reconstruction ones allowing the reconstruction of complex mechanical parts. In fact, mechanical parts are often composed by both primitives and freeform surfaces, proving the usefulness of hybrid

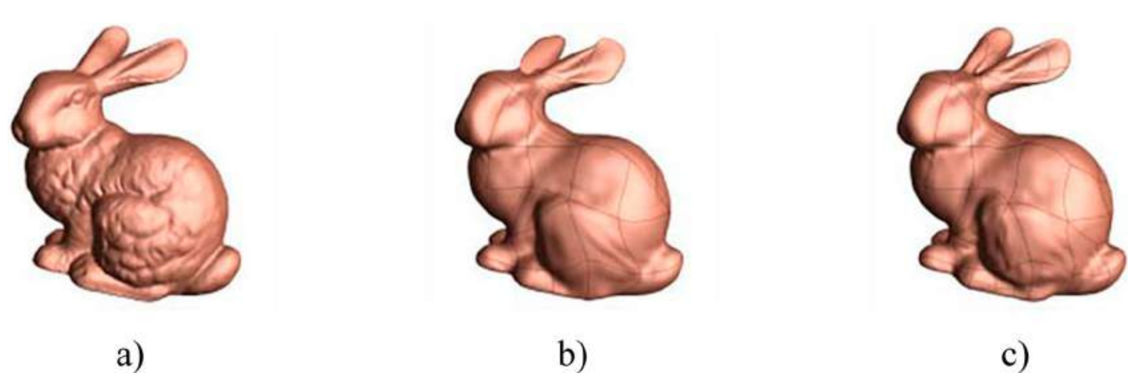

Figure 5. Freeform surface reconstruction example (taken from [28]): a) Initial mesh: 69473 facets; b) reconstruction performed with B-Spline surfaces (72 patches); c) Adaptive refinement of the obtained result (153 patches).

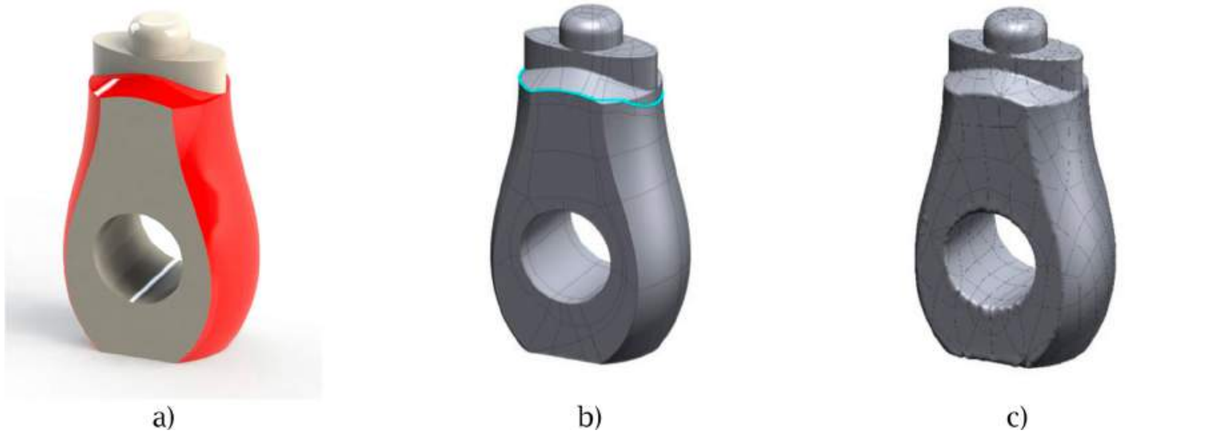

Figure 6. Comparison of results obtained with different freeform reconstruction strategies; a) Physical part: red surfaces can be satisfactorily described only by freeform surfaces; b) freeform reconstruction performed using an edge-based curve net (the highlighted curve follows only partially the edge profile of the original part); c) freeform reconstruction result obtained using a poor curve net. All the digital models have been produced by the authors using dedicated RE software.

strategies [85] which integrate feature-based techniques with fitting of parametric NURBS or B-Splines [13,51]. As demonstrated by the model depicted in Fig. 6a, freeform surfaces should be used for the reconstruction of the red parts in the final object because they cannot be satisfactorily described using primitives or other traditional CAD features. For this reason, a brief description of a couple of methods dealing with hybrid strategies is provided below.

Wang et al. [86], presented an approach where the reconstruction process, thanks to an appositely devised segmentation system, can handle various types of conventional CAD features (i.e. extrusion, revolution, sweep, loft) as well as B-Spline surface features. In [85], 2D freeform profiles are considered in a contour-based reconstruction method. The identified profiles are used as starting point in the creation of 3D CAD features. The authors state that the introduction of generic 3D freeform surfaces is a key aspect that needs to be studied in their future work, integrating the generation of NURBS surfaces with trimming/stitching operations to cope with the reconstruction of complex 3D models.

A hybrid strategy, performing an independent fitting of both 'traditional' features (i.e. planes, quadrics, swept surfaces) and freeform surfaces is presented in [46]. The authors describe in detail the registration and the merging of point clouds, as well as the following segmentation procedure that is adopted to distinguish between the different kind of surfaces. The applicability of their method is limited to four-sided freeform surfaces (i.e. surface patches enclosed by four boundary edges), defined using a B-Spline formulation; the surfaces are modeled upon the corresponding segmented areas using a least-square fitting approach. The authors test their method starting from synthetic point clouds, impaired by random noise applied on each coordinate component, with a maximum magnitude of 1 percent of the average sampling density of the point cloud.

It is noteworthy that most commercial software systems (e.g. CATIA, Geomagic Design X, Siemens NX, Leios2, Polyworks, etc.) offer tools to perform a surface-based reconstruction starting from mesh, usually involving the fitting of NURBS patches on the mesh itself. Accordingly, these instruments are established and used quite often by designers, depending on the type of application; as an example, in [34] the authors take advantage of a freeform surface to reconstruct a turbine blade.

As a general trend, recent developments in both freeform reconstruction and hybrid approaches are mostly oriented to the development of computationally efficient fitting algorithms [88] to speed-up the process.

5. RE software systems and tools

The universe of RE-oriented software systems is wide and heterogeneous. Due to the growing interest in CAD reconstruction, a great effort has been recently devoted to develop new tools to be integrated in commercial RE software systems as well as to increase the efficiency of the proposed solutions. Latest technical improvements are distinctly oriented towards the development of systems that are well integrated within the traditional design framework, in order to provide engineers with both useful and easy-to-use instruments. Commercial systems draw fully both from scientific literature and from in-house industrial research, implementing solutions which privilege interactive approaches generally limiting the necessary computation power/time. Obviously, algorithms used in such systems are commonly undisclosed, so it is not possible to directly compare them with the ones coming from the literature.

Among software packages, two main categories can be identified, as also proposed in [23]: i) dedicated RE systems and ii) traditional CAD software packages offering a suite of tools to cope with CAD reconstruction. In this study, the considered RE systems are Geomagic Design X, Polyworks, Leios2 and Autodesk Powershape, while the CAD systems equipped with RE suites are Autodesk Inventor 2017, Siemens NX, Solidworks ScanTo3D, PTC Creo Parametric Restyle and Autodesk Fusion 360.

Dedicated RE software systems are specifically built to deal with RE problems; indeed, they can easily handle various formats of 3D data (e.g. STLs, .asc, .ply, etc.) and are appositely designed to perform ad-hoc tasks, such as point cloud and mesh-based operations. Most advanced systems are also equipped with parametric CAD modeling functionalities that allow the user to generate parametric features and surfaces as in a traditional CAD environment, as well as a modeling engine capable of creating a fully editable feature tree, which is a useful tool for downstream applications.

On the other hand, CAD systems allows to obtain the best 3D modeling performances, even though efficient handling of meshes/point clouds is usually missing. However, recent trends in the industrial engineering field, such as the rapid growth of additive manufacturing processes, advancement in 3D scanning technologies and the rise of various potential applications for CAD reconstruction, have encouraged the improvement of RE functionalities in CAD software. Not by chance, most renowned CAD systems (e.g. Solidworks, Siemens NX, PTCCreo, CATIA, etc.) are currently capable of handling STLs files and perform mesh-based operations up to a certain complexity; furthermore, they offer a series of RE tools to address CAD reconstruction needs that, although not comparable with the solutions provided by dedicated software, can be considered satisfactory for many applications.

Taking, for instance, into consideration the segmentation step, even though both systems (RE dedicated and CAD) allow automatic identification of relevant regions, the achievable results are considerably different as demonstrated in Fig. 7, where a comparison between the segmentation results obtained by using a RE dedicated software (i.e. Geomagic Design X) and a CAD software package (i.e. Siemens NX®) is proposed. Fig. 7a presents a satisfactory region division that 'follows' each independent surface of the object; quite the reverse, the poor segmentation depicted in Fig. 7b provides little-to-none useful information.

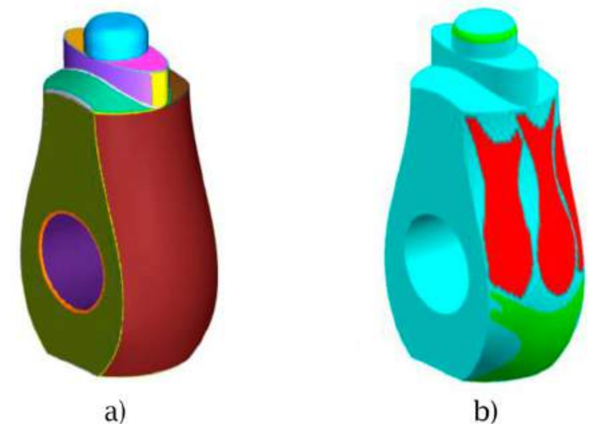

Figure 7. Comparison of results obtained by the authors using two different segmentation tools: a) Segmentation performed in a dedicated RE software (Geomagic Design X); b) Segmentation performed in a CAD environment (Siemens NX®).

Dealing with the modeling phase (i.e. the topic mainly covered in the present survey), both CAD with RE functionalities and RE dedicated software allow the generation of surfaces/features, providing the capability of building a geometrical feature tailored on a segmented/classified region or extracting information on its position and dimensions from the 3D data. Most common and simple tools are limited to the generation and fitting of a single low-level geometric feature or primitive (e.g. plane, sphere, cylinder, etc.) for each single segmented region. Less advanced systems offer this type of tools to perform an 'artisanal' reconstruction, since the CAD model is built using only Boolean operations and independent fitting of surfaces. Occasionally, sculpting and surface-editing tools are offered as RE tools in these systems (e.g. Autodesk Fusion 360 [93]) to enable the user to manually adapt generated CAD surfaces to the reference data. These approaches, however, usually leads to the loss of symmetries, constraints and high-level geometrical relations. Advanced systems, on the other hand, allow a range of possible reconstruction tools that are hereby described:

- **Fitting of primitives** (i.e. spheres, cones, planes, cylinders, tori) to segmented regions, as in lower-level systems.
- **Fitting of revolution and extrusions features** – this type of tools is capable to automatically extract the best 2D profiles to be used as extrusion/revolution profiles. Moreover, the corresponding extrusion/revolution axis can be automatically inferred or imposed by the user.
- **Fitting of high-level modeling functions over mesh** (e.g. loft, sweep); as in the previous case, most

advanced tools can extract the required 2D profiles and to understand the orientation/direction of the function. Guiding curves can be imposed, as in traditional modeling, to improve the result.

- **Mesh-based sketches** – some systems offer tools to automatically draw 2D sketches based on cross sections of the mesh. The section parameters can be controlled by the user; information provided by multiple parallel sections can be used to obtain an average profile of the mesh in a given range.
- **Geometric constraints imposition** - this is one of the most useful and recently implemented functionalities. The user can select geometrical constraints to be considered during the generation/fitting of features (e.g. parallelism between axes) over mesh. Such constraints can be imposed either as initial guess to correctly start the fitting or rigidly enforced during the reconstruction. The most advanced performances are, with this respect, offered by Geomagic Design X®, which allows the user to consider a single geometric constraint in its revolution/extrusion wizards. Unfortunately, no software currently supports advanced geometrical constraints (e.g. multiple simultaneous relations in a single fitting feature, imposition of known values such as angles or distances, etc.).
- **Automatic filleting** – the radius of the fillet to be applied is directly extracted from the mesh.
- **Direct Link to CAD** – RE systems are occasionally capable of exporting CAD models to traditional CAD environments, providing a direct link that preserves the CAD modeling features and its feature tree. This feature remarkably improves the efficiency of the whole reconstruction process, limiting the possibility of errors and the loss of time that the use of exchange formats entails. For instance, an 'automatic feature recognition' step to be performed after the import of a non-parametric model in a CAD environment is no more needed.
- **Advanced Parametric Modeling Engine** – the offer of an advanced modeling environment is obviously taken for granted in CAD systems, but it's a non-predictable feature of RE dedicated software packages. Currently, a number of systems offer limited modeling performances (e.g. Boolean operations, primitive generation and intersection) that do not comprehend, as instance, a full feature tree describing the modeling history of the reconstructed part. This fact imposes significant limits on the usefulness of generated models, particularly when editing necessities are encountered.

The type of tools offered by most important software systems are provided in Tab. 2. By comparing Tab. 1 and Tab. 2, it can be noted that the development of software tools generally proceeds in a different direction w.r.t. the modeling strategies discussed in Section 4.

The overall best performances to cope with CAD reconstruction applications are nowadays provided by Geomagic Design X® [1]: its environment is equipped with really effective tools covering both the point cloud/mesh-based and the modeling operations; furthermore, noticeable modeling performances, comparable to a traditional CAD software, are obtained thanks to a really advanced modeling engine as well as a direct link with most spread CAD software (e.g. Solidworks®).

Another performing RE dedicated system is Polyworks® by Innovmetric [47]; it provides parametric sketches and really good auto-surfacing tools. Unfortunately, its modeling performances are rather limited: solids and surfaces must be generated in external systems, transferring the sketches by using built-in export add-ins.

Regarding CAD system performances in RE applications, their capabilities often prove to be sufficient and convenient for the final goal. Nevertheless, main limitations generally arise in the processing of mesh and point clouds; for instance, importing or handling of large

Table 2. Comparison of RE tools among state-of-the-art RE and CAD systems.

	Geomagic Design X [1]	*Polyworks* [47]	*Autodesk Powershape*[1] [11]	*Leios2 EGS* [29]	*Autodesk Inventor 2017* [10]	*Siemens NX* [72]	*Solidworks ScanTo3D* [73]	*PTC Creo Parametric Restyle*[25]	*Autodesk| Fusion 360* [93]
Primitive fitting	✓	✓	✓	✓	✓	✓	✓	✓	
Advanced parametric modeling engine	✓				✓	✓	✓	✓	✓
NURBS surface fit	✓	✓	✓	✓	✓	✓	✓	✓	✓
Revolution/Extrusion surface fitting	✓		✓					✓	
Mesh-based sketches	✓	✓				✓	✓		✓
Geometric constraints imposition	✓			✓	✓	✓			
Export tools – Direct Link to CAD	✓	✓							
Automatic filleting	✓								

[1] Formerly Delcam Powershape

files can often represent non-trivial (or even difficult) tasks.

A noticeable example of a CAD system equipped with a high-quality suite of RE tools is Siemens NX® [72]; a basic segmentation tool, the capability of fitting primitives and freeform surfaces to mesh data and a useful deviation tool to evaluate the differences between the reconstructed CAD model and the original data are provided to the user. In addition, Siemens NX® instruments allow the creation of mesh-guided 3D splines and the generation of cross sections of the mesh that can be used as reference to create 2D sketches.

Proving the high interest in RE problems shown by producers of traditional CAD systems, Autodesk Inventor supplies new RE oriented tools starting from the latest version (Autodesk Inventor 2017®, [10]). The novel capabilities consist of an improved handling of mesh data, fitting of primitives (i.e. planar, conic, sphere and torus surfaces) and the imposition of constraints between mesh and solid models [10].

It is the authors' opinion that a software-based reconstruction guided by a user currently represents the most robust approach for designers dealing with CAD reconstruction. In fact, only this framework allows to obtain a parametric CAD model that is both adequately parameterized and in a format suitable for the designer needs. Conversely, most of the automatic techniques discussed in Section 4 ordinarily produce non-parametric digital models according to solid model standards (i.e. IGES, STEP, B-REP files), which do not contain information about the model feature tree, its composing features and geometrical constraints and relations [67]. Thus, a feature recognition step is commonly required in order to use such models in a CAD environment and to interpret them; this additional step exacerbates the complexity of the overall process, introducing an additional source of errors.

Important drawbacks that need to be considered are the imposition of a time-consuming framework and the necessity of a highly skilled user to guide the reconstruction. The designer insight and his knowledge on the part to be reconstructed represent valuable information to be exploited in the reconstruction process. The software-based approach partially succeeds in this, allowing the user to control the reconstruction chain; the possible, although limited, imposition of known constraints that is permitted in most advanced systems enriches the level of design intent retrieved at the end of the process. According to these premises, future development will be likely oriented towards the introduction of high-level geometric relations and multiple constraints between the reconstructed features.

6. Conclusions

In this work, a survey of CAD reconstruction strategies has been presented; particular effort has been spent to provide both a description and a classification that can be useful for engineers and designers dealing with actual RE problems, aiming to supply a valuable overview of the tools and methods available in literature.

The analysis of the state of the art is, also, particularly relevant for commercial RE tools: indeed, CAD and RE software packages are regularly updated. Urged by market competition, continuous efforts are dedicated to the development of new reconstruction tools as well as the achievement of better performances. Moreover, the universe of RE-related software systems has been widening in most recent years, according to the increasing interest in CAD reconstruction solutions. For all these reasons, a picture of available software tools has been presented in Section 5. Similarly, in Section 43, a classification of CAD reconstruction approaches proposed in the scientific literature has been reported.

It is important to note that a complete benchmark of the reconstruction performances of the presented approaches would be extremely complex to perform, since they should be evaluated on multiple case studies selected in order to be: i) significant, capable of highlighting weaknesses and strengths of various approaches; ii) capable of not biasing the study, i.e. with a geometry and characteristics not particularly favorable for a specific method. This is a challenging issue, especially because every method presents a remarkable sensitivity to a specific reconstruction aspect.

Even in case one would be willing to follow this approach, the enterprise would be made practically very hard to carry out: the implementation and testing of methods presented in Section 4 would require a huge effort for some of them or could prove to be practically impossible for others (since not all the necessary implementation details are provided by the authors). Finally, it is also to be considered that the results generated by the presented methods are quite different and not easily comparable; indeed, a mere deviation analysis performed between the original data and the reconstructed models would not be sufficient to consider the multiple positive/negative aspects characterizing every method.

With these considerations in mind, the proposed survey provides insight into the wide variety of methods dedicated to the RE field, underlining strengths and weaknesses, as well as distinguishing features of the considered strategies. Even though, as already mentioned, dedicated RE software offers quite satisfying reconstruction performances, the entire process is still time consuming and-highly specialized RE skills are required to the users. Nevertheless, the human contribution in the reconstruction procedure can significantly improve the obtained result, with special reference to the representation-specific combinatorial structure (e.g. feature tree) and the retrieved design intent. It is important to note that, when using dedicated software packages, the obtained result is heavily influenced by the capabilities of the designer as well as by her/his confidence with RE tools. Concerning the methods presented in Section 4, which are generally oriented towards an automatic or semi-automatic approach to RE, their applicability and practical usefulness is mainly limited by two common factors. Firstly, the format of the geometrical models generated by most of the analysed techniques are not easily spendable in CAD environments, typically requiring a *feature recognition* phase in order to be editable. Furthermore, the computational costs associated to complex steps (e.g. automatic identification of geometric constraints, constrained fitting, fitting of multiple surfaces), that are part of the most advanced methods, generally hinder their practical usefulness. Hence, user-guided tools (like the ones generally preferred in commercial RE systems, presented in Section 5) are more commonly used in real-life applications.

Summing up, the main gaps of the whole RE framework that can be identified are:

- **Poor exploitation of the a-priori knowledge on the reconstructed object**

For the most part, in fact, engineering knowledge about the shape of the object that needs to be reconstructed is not exploited at the beginning of the RE process; if properly spent, this type of information (e.g. geometric regularities, known dimensions, etc.) could allow a more effective reconstruction and the achievement of a more accurate result.

With this respect, possible improvements could be achieved by adopting semi-automatic methods performing the fitting of template CAD models [32], that is the process of adapting an a-priori determined topology upon the reference data. This might represent one of the most convenient strategies adopted to exploit a-priori known information on the reconstructed part. As deeply discussed in Section 4.4, a high computational burden typically distinguishes this approach; currently, it has been successfully applied to a limited set of very basic geometries [70]. However, future improvements might allow further tests on more complicated models and expand the related field of applicability. The usefulness of automatic or semi-automatic methods, in general, could increase in the near future; specifically, beneficial improvements of PCs calculating capacities and the development of optimization algorithms tailored to specific applications might potentially represent game changers of the whole RE framework.

- **RE tools and reconstruction strategies are badly integrated in the product design framework.**

Generally, it is the authors' opinion that future works, dealing with CAD reconstruction of mechanical parts, will be principally oriented towards the development of reconstruction methods that are well-integrated into the traditional product design framework, following the principles enunciated in Section 2. The current RE framework imposes, in fact, the adoption of tools that are not familiar to the designer and, ultimately, it forces the learning of an entire new skill set. As a result, future studies should be oriented to the progress of strategies exploiting tools that are known to designers and that reduce the knowledge gap imposed to engineers dealing with their first approach to RE.

- **Limited usability of generated CAD models**

The possibility of easily spending the produced result (i.e. CAD model) for applications beyond the reconstruction phase is as important as the dimensional accuracy of the obtained model itself. Regrettably, this issue is partially addressed by the discussed methods; only the choice of a commercial software-guided approach performed by a competent user currently assures a directly spendable and accurate result.

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