INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.64

New methodology for the characterization of 3D model reconstructions to meet conditions of input data and requirements of downstream applications

Robert Joost ✉, Stephan Mönchinger and Kai Lindow

Fraunhofer Institute for Production Systems and Design Technology IPK, Germany

✉ robert.joost@ipk.fraunhofer.de

Abstract

In the field of 3D model reconstruction, manifold methods have been developed that derive CAD models from 3D scan data. Opposed to classical CAD modelling, where surface and solid modelling exist, a further diversification of modelling techniques is observed, caused by different methods to build up the geometry. This research introduces a new classification, the so-called Level of Complexities. It can be applied to the complete Reverse Engineering process chain and lays the foundation for further research on how to match requirements arising from all process steps and downstream applications.

Keywords: *reverse engineering, computer-aided design (CAD), decision making, design methodology, process modelling*

1. Introduction

1.1. Motivation

The goal of Reverse Engineering (RE), also known as 3D model reconstruction, is to derive a mathematical description of the geometry of a real-world object (Buonamici et al., 2018). This yields the so-called parametrized 'as-is' data, opposed to the ideal 'as-designed' data that is created during virtual product creation. The typical subsequent steps from physical object to CAD model are data capture, pre-processing, segmentation, features classification and modelling. The input data for this reconstruction is usually 3D scan data in forms of a point cloud, which is possibly supplemented with a mesh or additional data (e.g. RGB colour data). This scan data is obtained from sensors and techniques, such as stereolithography, lidar or photogrammetry (Ebrahim, 2015). Furthermore, there exists a variety of methods to reconstruct the geometry, resulting in diverse characteristics and model structures. Finally, the purpose that the 3D reconstruction serves, is manifold: Typically, in the context of mechanical engineering, the obtained model is used in downstream CAx applications, like tool path planning in CAM (Computer Aided Manufacturing) or setting up a simulation model (CAE, Computer Aided Engineering). Other subsequent applications like pure visualization or reducing storage space can be reasons to apply Reverse Engineering.

Having briefly described the process, it is evident that certain process steps constitute variables and prescribe conditions on preceding or subsequent steps. Some examples on how these variables may develop in the particular process steps are presented in Figure 1. Here, pre-processing, segmentation, features classification and modelling are combined as 'reconstruction method'. The broad aim of this paper is to point out the process-inherent dependencies. In practice, the physical object, and the subsequent application that is meant to be executed on this object or its virtual representation are given. These are the start and end nodes in our process. Thus, conditions will be imposed from these two nodes to the inner three nodes, here denoted as 'primary conditions'. All other conditions arise from the process in between and are denoted by 'secondary conditions'. In the following, a few exemplary dependencies are presented: The physical object is arbitrary, allowing different sizes, shapes, inner (possibly occluded) geometry, etc. This leads to the data capture being dependent on the physical object, for example the capture space depends on the object size, or the lightning condition on the object's location. Other characteristics can be influenced by the choice of the scanning device, such as point density. Furthermore, the choice or the feasibility of the reconstruction method might depend on the characteristics of the captured data. The downstream application imposes conditions on the reconstructed CAD model, e.g. existence of a complete model, certain file format or certain accuracy.

In this scope, we especially want to focus on possible conditions of the reconstructed 3D CAD model. A lot of research has been conducted on algorithms and techniques in 3D model reconstruction, but we found that there is a lack of a proper classification of the result's condition. Furthermore, we want to emphasise the need for matching requirements of downstream applications with this classification.

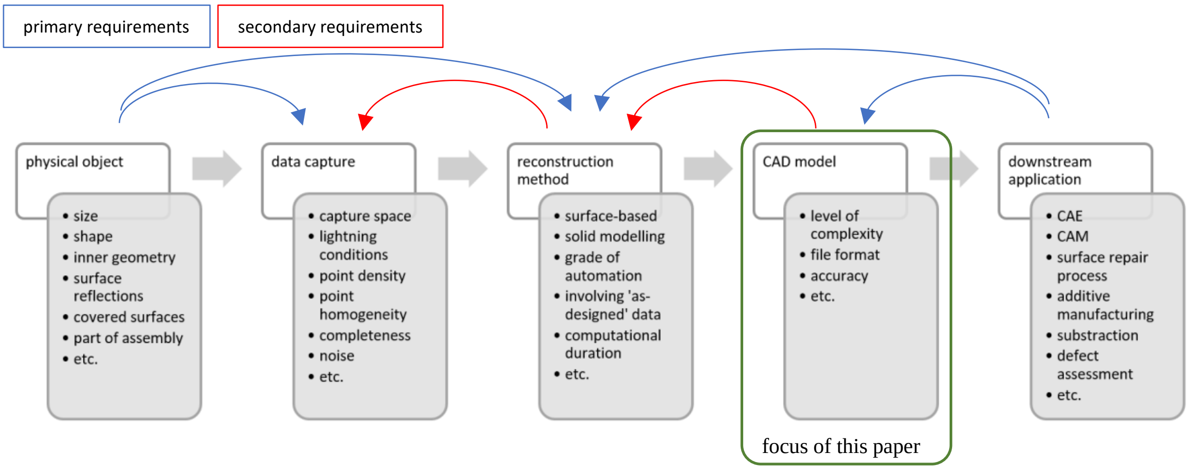

Figure 1. RE process steps and examples for their inherent variables and characteristics

To be able to decide which method or model constitution is best suited for a Reverse Engineering process, following questions need to be answered.

1. What is the minimal required complexity?
2. What is the maximal needed complexity?
3. What is the maximal feasible complexity?

The evaluation criteria to answer the first two questions are based on the requirements given by the downstream application. The complexity should ideally be ‘as little as possible’ and ‘as high as necessary’ to fulfil certain qualitative and accuracy criteria of subsequent use. The third question asks for the limits that might exist regarding technical realisation and feasibility or suitability in the specific context, including all process steps.

In this scope, we want to assess only highly automated solutions for 3D model reconstruction. The need for adaptivity and robust algorithms increases with higher geometric complexity of the real object, thus the amount and variety of different geometric shapes or features that the object consists of. No matter which reconstruction method is used, it becomes more difficult to create a generic algorithm that is able to deal with all the specific geometric particularities a model may hold.

The paper structure is as follows: Section 2 provides a literature review, where different approaches to reconstruct a model are presented. They are described in detail to give a proper understanding of this crucial step in RE. With this, we assure that all different modelling principles are represented. Next, in section 3, our new methodology will be explained, consisting of four different characterizations that we call 'Levels of Complexity' (LoC). The reviewed literature will be associated to these. To pre-empt, the literature review begins with rather complex methods related to LoC4, and ends with single-surface-approaches related to LoC1. The exemplary application of LoCs will be shown in order to point out their added value. In section 4, a discussion is provided, followed by summary and outlook in section 5.

2. State of the art

2.1. Classical CAD modelling techniques

In classical CAD modelling, there are two common approaches: surface and solid modelling (Aranburu et al., 2020). Within these approaches, there exist subcategories and different paradigms, but their major difference lies in the creation of the geometry: surface modelling describes a geometry only through the parametrized descriptions of surfaces and edges. The boundary representation (BREP) method relates to this approach. The object does not necessarily have to be a closed solid. Opposed to this, solid modelling implies, that a geometry is built up by model features (such as extrusion, revolve, etc.). The solid-enclosing surfaces are the result of those features, they are not explicitly modelled.

2.2. Literature review of 3D surface reconstruction methods

Many methods and strategies to tackle the reconstruction of larger and more complex shapes have been developed, whereof some crucial concepts are briefly presented in this section, including figures for their illustration. The emphasis lies on highly automated processes. In this scope, we focus on single solid models as subject of a 3D model reconstruction. Assemblies are neglected - the case of reconstructing assemblies can usually be reduced to reconstructing multiple single solid models (apart from assembly constraints). By far not all downstream applications for 3D reconstruction require a complete description of the object's shape - sometimes, only a single surface might be from interest which then would need to be reconstructed. Talking about the robustness or generality of a method or algorithm, we can keep in mind that respective requirements may be loosened in some cases.
To begin with, a highly sophisticated method by (Wang et al., 2012) that incorporates the complete RE process is presented (Figure 2). The approach aims to find a parametrized model for any kind of shape or object. The step of feature extraction is subdivided in solid features and surface features, enabling to perform both, solid modelling (extrusion, revolve, sweep, etc.) and surface modelling (quadratic, free-form, etc.). The model is then resembled by boolean operations for solids and surface trimming and stitching for BREP geometry generation.

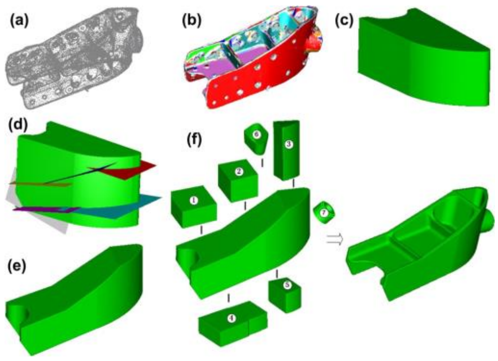

Figure 2. Complete model reconstruction (Wang et al., 2012): (a) point cloud (b) segmentation result (c) outer block extrusion (d) detected planes (e) trimming with planes (f) detecting all other features; resemble the model using boolean operations

Another method proposed by (Bénière et al., 2013) stands exemplary for feature-based reconstruction and detecting geometric primitives (Figure 3). It is designed to work on tessellated CAD data but the authors state that it can in general be deployed to 'as-is' scan data. The method is only capable to parametrize and assemble planes, spheres, cones and cylinders, no other CAD features or even free-from surfaces. It follows the BREP approach since faces are detected via edge detection and for assembling features, boundary curves are extracted and intersected.
The work by (Soni et al., 2009) describes the detection and reconstruction of geometric primitives. The authors present a semi-automatic approach that uses feature and edges extraction to anticipate the basic shapes that the scanned object is formed of. Also, free-form surface reconstruction is assessed, but their solution is not capable of combining geometric primitives modelling and free-form surface reconstruction.

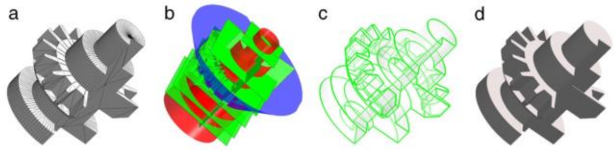

Figure 3. Model reconstruction (Bénière et al., 2013): (a) 3D mesh (b) extracted geometric primitives (c) reconstructed wires (boundaries) (d) final BREP model

According to (Lee et al., 2021), there exist studies and ongoing research on the application of deep learning for 3D model reconstruction. But it appears to them, that all reviewed methods end at the feature detection stage, thus the feature or surface modelling is still not covered by deep learning approaches. However, their presented approach reveals, that the used modelling method would be solid modelling, although it also is not capable of this crucial step. Therefore, we can expect similar results as in the literature presented above. In addition, all other models they refer to deal with CAD input data and detect design features. As an example, the method of (Shi et al., 2020) using multiple sectional view and (Zhang et al., 2018) using CNN on voxelized models might be able to be deployed to 'as-is' scan data, or at least meshed and closed-surface scan data.

Coming back to rule-based methods, the work presented by (Varady, 2008) covers most parts of the RE process, but is restricted to surface modelling in terms of BREP generation. In opposition to the aforementioned methods, no explicit solid modelling and boolean operations take place. A detailed analysis of the process for parametrization and BREP generation is shown in Figure 4 and briefly explained in what follows.

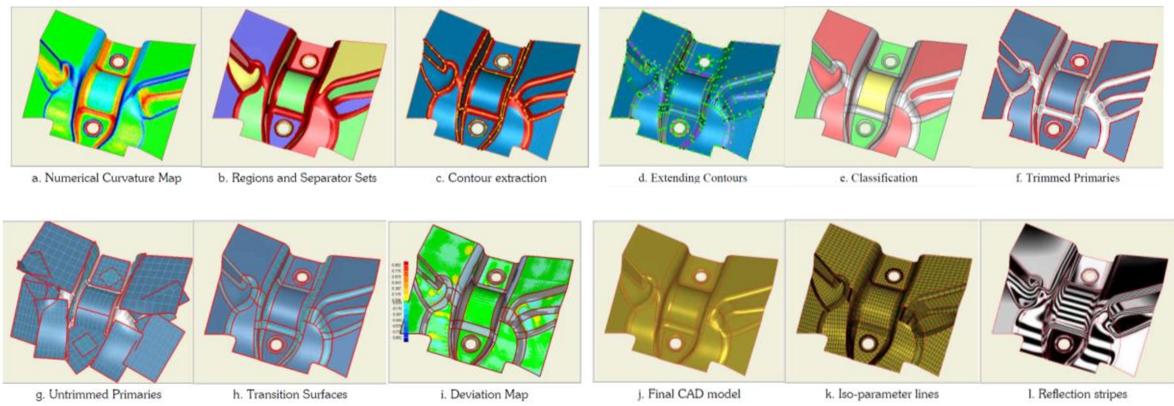

Figure 4. Surface reconstruction process (Varady, 2008)

The input is a triangulated point cloud properly pre-processed in terms of noise and size. The segmentation is shown in *a.* and *b.*, where first a curvature estimation and afterwards a surface-based segmentation is carried out, resulting in separation of "relatively flat primary regions" and "highly curved transitions" in red. The steps *c.*, *d.* and *e.* can be related to feature classification. In contour extraction, a curve network is developed in the transitions to find an initial separation of features, the so-called "feature skeleton". Next, via extending contours, the separating features are assessed and traced to finally have a valid distinction of surface-like regions and separating elements such as fillets. The regions are then classified as basic geometric entities such as planes, cylinders, cones, drafted extrusions or free-form surfaces. Afterwards modelling and surface fitting follows with steps *f.*, *g.* and *h.*. First the primary surfaces are developed according to their geometric feature type. Then they are extended to an untrimmed form. Next, the transition regions are developed in the same manner. Trimming the transition surfaces with the primary surfaces yields a complete parametric representation of the surface. In step *j.* the parametrization is translated into a CAD model.

The evident and often used approach to obtain a parametrized surface description is to combine several NURBS patches to form one surface. To this end, a network of quadrilateral patches is spread over the sample data. Each patch approximates the local section of the complete scan data. The seams of the network are the lines where patches meet. At these joints, continuity requirements have to be taken care of, in the sense that the local curvature is represented properly. An edge where two NURBS patches are stitched together can either be smooth (G^1 or higher continuity) or utilized to depict a sharp edge (G^0 continuity). The methods differ in terms of how the network is constructed: either arbitrary or oriented according to the curvature of the object. The latter case may yield better results for certain initial data because the control net takes the curvatures into account and rather flat surface may be approximated using less control points whereas sharp edges or tight radii can be approximated more precisely and locally. Wei et al. (2020) denote this approach as `functional decomposition'. Using curvature-based segmentation methods, the scan is separated into patches and the patch boundaries represent the control net. The author calls these curves 'characteristic curves'. In opposition to the aforementioned methods, no feature detection or assignment (e.g. planar, cylindrical, etc.) takes place, every patch is meant to be represented by free-form NURBS surface regardless of their characteristics (Figure 5). Usually the characteristic curves will not immediately create a quadrilateral grid, thus still this grid has to be generated, based on and following the curves network.

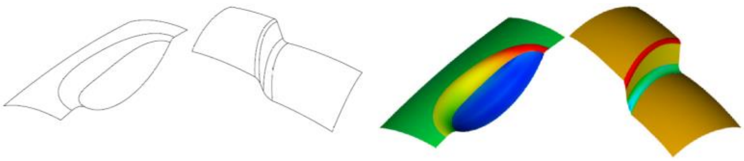

Figure 5. Characteristic curves (left) and functional decomposition (right) (Wei et al., 2020)

Considering the case of arbitrary quadrilateral NURBS networks, (Eck et al., 1996) present a sophisticated, fully automated solution. The work emphasizes two major problems: First, finding a proper grid of quadrilateral patches and second, enforcing at least G^1 continuity at the seams. The solution steps are briefly explained in what follows. In each step the sample points are parametrized according to the particular topology, meaning that the position of each point is correlated with a certain position on the topology. This enables tracking the parametrization while the topology changes and transforms. Initially, a relatively dense triangular mesh is fitted to the sample data that features the actual topology of the scan data. Consecutively, a coarser triangular mesh is generated. Based on this simpler mesh, a quadrilateral mesh is obtained by merging triangles and certain optimization schemes. This process does not take any curvatures into account. The quadrilateral mesh provides all base surfaces to fit the NURBS surface patches. The resulting approximated NURBS network is further optimized and refined by subdividing the quadrilaterals and repeating surface fitting until a desired error tolerance is achieved (Figure 6).

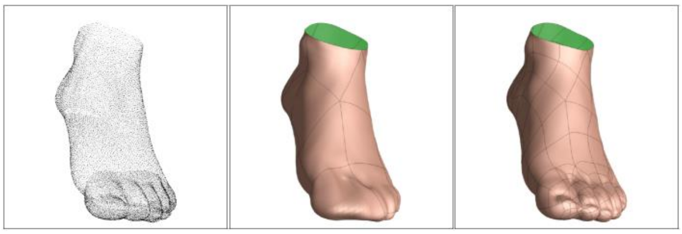

Figure 6. Example of surface reconstruction (Eck et al., 1996). Left: initial point cloud; middle: first NURBS approximation with quadrilateral network with 35 patches and 1.36% maximum error; right: refined network with 285 patches and 0.41% maximum error

Varady (2008) also provides an example of a NURBS patch network shown in Figure 7. It is a mixture of arbitrary and characteristic curves-following quadrilateral network. Some feature-separating boundaries are visible (marked in yellow) but these are by far not all. Therefore, in both examples (Figure 6 and Figure 7) we observe that the network does not follow any functional elements of the object. The foot is surely not describable by any regular geometry thus the purely free-form surface description is appropriate. Contrary to this, the mechanical part of (Varady, 2008) does exhibit geometry features like planar surfaces, cylinders, radii and sharp or highly curved edges, but the reconstruction does not take these features into account.

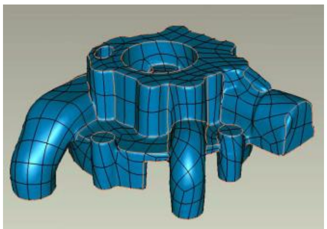

Figure 7. Example of surface reconstruction (Varady, 2008)

Both (Eck et al., 1996) and (Varady, 2008) rely on first determining a quadrilateral network on the topology and secondly define base surfaces to find initial parametrizations of the sample data. A tool to define the base surfaces is the so-called Coon's patch (Wei et al., 2020). Having found four sides of a patch in forms of NURBS curves, the Coon's patch is defined by interpolation of these boundaries. Farin et al. (1999) explain the principle and also proposes an optimized method that yields more adequate base surfaces.

Krishnamurthy et al. (1996) present a semi-automatic approach for a solely free-form surface reconstruction (Figure 8). The user needs to interactively draw boundary curves on the tessellated scan data to define an initial quadrilateral patch network, such that every segment is a "rectangularly parameterizable piece of the surface". However, the subsequent steps are fully automated and involve parametrization and subdivision of the patches ("spring mesh"), refining and resampling of the network as well as NURBS fitting ensuring G^1 continuity at the patch seams.

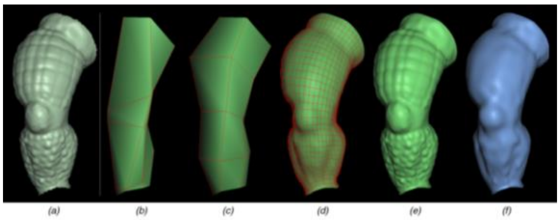

Figure 8. Example of a surface reconstruction (Krishnamurthy et al., 1996). (a) initial mesh of a single patch (b)-(d) refinement and reparameterization of NURBS control net, u and v isolines shown in red (e) final fitted NURBS surface (f) coarsened representation of the surface

Next to the aforementioned approaches, where a network of NURBS patches is deployed, previous work tried to reconstruct even complex shapes with a single surface. As an example, the approach of (Brujic et al., 2011) improves the approximation algorithm significantly such that a fitting of 800,000 sample points using a control net of more than 1,000 control points is achievable in reasonable amount of time and surface accuracy. Most other methods try to subdivide the network into patches small enough that only a few control points are sufficient per patch. This approach disregards the feature-detecting and boundary representing methods, since solely the overall shape is approximated, without any separated geometric features or edges. Additionally, the topology of the result is restricted to surface, sphere, cylinder or torus.

A further development in spline surface modelling are so-called T-splines. They have been developed to overcome the limitation of NURBS surface to only represent rectangular domains (Sederberg et al., 2010). T-splines allow T-junctions of the control net, meaning that a row of control points may terminate or begin in the interior of the surface. This enables a far more complex surface representation only using a single surface description (Figure 9).

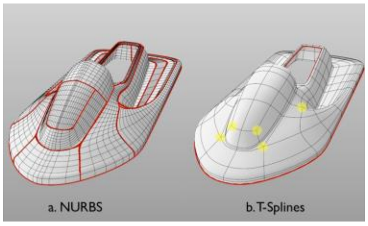

Figure 9. Modelling with T-splines in comparison to NURBS (Sederberg et al., 2010)

The mathematical formulation of T-splines is an extension of the original NURBS description, involving a new form of the control grid, called the T-mesh. Although the power and practicality of T-splines is evident, the major drawback is that it is not covered by standard CAD authoring systems and standard CAD file types.
The principle of CAD morphing completes the literature survey. This approach only works under the assumption that initial CAD data is available. The presented approach by (Chinn, 2021) originates from the field of Computer Aided Engineering (CAE) where simulations yield deformed finite element meshes that need to be reconstructed for further use. The author applies the method to the deformation of aircraft wings and turbine blades (Figure 10). He states that all 'as-designed' CAD geometries (surfaces, boundaries) first need to be transformed to NURBS geometries. Afterwards, the surfaces need to be associated with mesh nodes lying on the surface, similar to the above described point inversion. The approach of (Ben Makhlouf et al., 2019) is comparable.

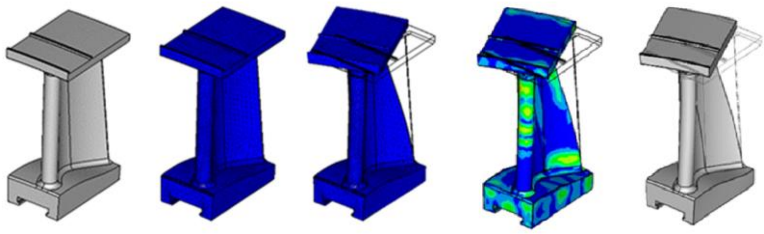

Figure 10. CAD morphing approach (Chinn, 2021). From left to right: 1. original CAD model 2. undeformed mesh 3. deformed mesh 4. fit error of morphed CAD 5. final morphed CAD geometry

3. Development of the LoC methodology

After having presented several approaches to carry out a parametric surface reconstruction of complex shapes in section 2, we can deduce that they differ with regards to the degree of complexity the result has. Therefore, we establish the so-called 'Level of Complexity' (LoC). This new designation is meant to describe different elaborations of the reconstructed CAD model and helps to categorise and correspond to the approaches described in the state of the art. The following diagram depicts the hierarchy of the LoCs. In what follows, their characteristics are described briefly.

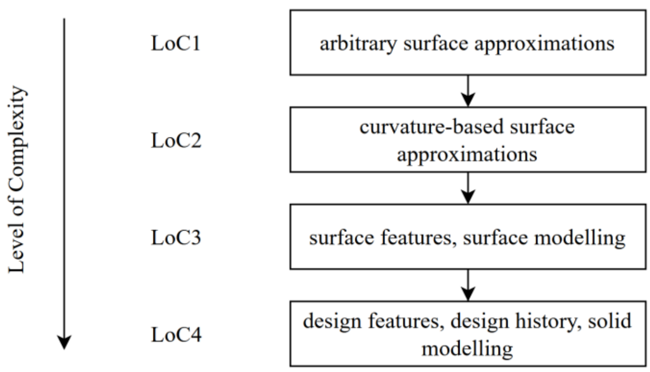

Figure 11. Level of Complexities of the reconstructed CAD model

3.1. LoC1: arbitrary surface approximations

The most basic kind of parametric surface reconstruction is the approximation with arbitrary surfaces. It refers to the principle that has been similarly applied in the work of (Eck et al., 1996), (Varady, 2008) and (Krishnamurthy et al., 1996) (Figure 6, Figure 7 and Figure 8): The sample points are approximated with an arbitrary quadrilateral network of NURBS patches. No functional decomposition, feature detection or even geometric primitive detection takes place, the surface is only described by free-form surfaces. The patch boundaries do not correspond to the characteristic curves of the scan. Other approaches described in section 2 can also be classified as LoC1: In the case of (Sederberg et al., 2010) a T-spline of NURBS network is created, but the principle is comparable. Even the approximation with a single NURBS surface, like presented by (Brujic et al., 2011) belongs to this group, but it is very limited regarding the geometric complexity.

3.2. LoC2: curvature-based surface approximations

An enhancement of LoC1 can be achieved, if the base surface network follows the functional decomposition method by (Wei et al., 2020) (Figure 5). The local curvature is considered such that transitions between topologically differing patches, like sharp edges, radii or fillets are represented. The resulting surface parametrisation is able to depict the geometric structure and exhibits basic separation of features. To emphasise, no surface features are detected by means of classifying the parametrization. The model's surface still consists of a purely NURBS surface network representation like in LoC1. It is expected, that the accuracy at characteristic curves (e.g. sharp edges) is higher compared to LoC1, since they can be modelled using G^0 continuities.

3.3. LoC3: surface features, surface modelling

LoC3 includes the surface feature classification and parametrization of the sample data. Using a segmentation method, the scan data is decomposed in functional patches. These patches are classified and a geometric type is assigned (planar, cylindrical, free-form, etc.). Then the parametrization takes place and the parametrised geometric elements are modelled and merged to obtain a BREP CAD model. This approach refers to the surface modelling technique. The geometric elements are not built up using CAD design features (this would be LoC4), but modelled directly, therefore, no actual design history is created. The work of (Varady, 2008) (Figure 4) belongs to this complexity level.

3.4. LoC4: design features, design history, solid modelling

The highest degree of complexity, denoted by LoC4, represents a sophisticated CAD model that exhibits design features, including geometric primitives and solid modelling as well as a design history. Solid primitives or bodies are merged with boolean operations. Surface features are modelled using surface design features such as loft or sweep. True free-form surfaces are modelled as in LoC3, using surface parametrization and BREP surface modelling. The methods of (Wang et al., 2012), (Bénière et al., 2013) and (Soni et al., 2009) (Figure 2 and Figure 3) are categorised in this LoC4.

3.5. Exemplary application of LoCs

In this section, the added value of the methodology using the LoCs is exemplary shown. We therefore consider a few fictional, but from our experience typical downstream applications (Table 1). For each use-case, we denote a specific requirement. Now, the LoC's can be assigned to the use-cases by checking their suitability. Furthermore, we now know the range of minimal required and maximal needed complexity, if more than one LoC is possible.

Table 1. Exemplary application of LoCs: Matching requirements with suitable LoCs

Downstream application	Requirement	LoC1	LoC2	LoC3	LoC4
Additive surface repair	Free form surface description of defect surface for CAM planning	x	x	x	
2D-3D-mapping	Mapping and locating sections of 2D images onto a 3D model	x	x	x	x
Redesign of object	All solid features need to be modifiable				x
FEA	Using volumetric elements and application of boundary conditions on functional surfaces		x	x	x
Feature-detection	Feature-Classification in order to select appropriate post-processing tool			x	x
Real-time volumetric shape determination	Fast generation of surface describing the object	x	x		

4. Discussion

The developed LoCs provide a simple and effective methodology to classify existing RE algorithms and tools. Compared to the classical modelling methods, LoC4 relates to solid modelling, whereas LoC1-3 are forms of the surface modelling approach. BREP modelling in the sense, that the boundaries also display functional boundaries (or characteristic curves) is only given in LoC2 and LoC3. Thus, the two major classical modelling techniques have been diversified in order to represent the different existing approaches. As already mentioned, the classifications may not always be clearly separated in practice. Some presented approaches combine several aspects of different LoCs.

The reconstruction methods LoC3 and LoC4 possibly introduce larger errors and deviations compared to LoC1 and LoC2. The formers are based on finding geometry features, such as planar or cylindrical surfaces or solids. The real-world object might have deviations with respect to this ideal description of the geometry. Applying the approximation of such scan sections with idealized geometry could imply larger deviations between reconstruction and scan. Opposed to this, LoC1 and LoC2 only use pure free-form descriptions, which theatrically allow an arbitrarily exact fitting to underlying scan data. However, it might be desired to introduce simplifications using features while allowing a certain larger accuracy tolerance, in order to obtain a model which is better manageable.

Regarding the completeness of this methodology, it is conceivable to include the direct use of the scan data for downstream applications, possibly denoted as LoC0. This is motivated by the fact, that for some applications, (e.g. 3D printing for fast prototyping), a mesh might already be sufficient. Speaking against this inclusion is the fact that it would leave the scope of 3D model reconstruction in our sense, since the actual RE process (segmentation, feature classification, modelling) is not involved.

The proposed decision process is rule based, driven by requirements as well as experience. It is conceivable to transfer this decision-making to an AI model. This model could be trained on historical data, using different downstream applications, different RE algorithms as well as the actual 'as-is' geometry. The investigation of whether such a model could be successful remains for future research.

In conclusion, the benefit of the developed methodology lies in the ability to assign and narrow down suited reconstruction methods based on the given requirements of the particular downstream application. Being able to choose the correct minimal required complexity can reduce time and costs, since the CAD model does not exhibit unnecessary and overdone characteristics. Furthermore, the (probably costly and far-reaching) choice for a suited RE software or toolkit can be assisted. Applying further requirements modelling and matching through the upstream processes reveals feasibilities and supports correct choices. A complete decision methodology using the LoCs as essential link between physical object and downstream application finally would enhance and accelerate putting RE process chains in practice.

5. Summary and outlook

We presented a new approach to classify characteristics of models that are generated through 3D model reconstruction methods. An extensive literature review has been conducted. The methods have been analysed in detail to gain an understanding of functioning and differences regarding their approaches. An exemplary application to fictional use-cases has been shown, pointing out how specific requirements of downstream applications can be evaluated and matched with the LoC of the reconstructed model.

For future work, the LoCs could be evaluated with respect to certain process-inherent performance indicators, such as accuracy, computational time or geometry limitations. As a next logical step, the complete process chain needs to be assessed further. The identification of primary and secondary requirements with regards to specific applications, data capture instruments or object types needs to be focussed on. The long-term goal is to provide a complete methodology to support deciding which methods, tools and hardware need to be used for a given tuple of real-world object and downstream application. Next, typical real-world downstream applications could be assessed in order to verify and validate our approach. Implications and possibilities that arise with available 'as-designed' data can be evaluated. The approach of CAD morphing has already been mentioned, which relies on the presence of 'as-designed' data. This might help if the scan data does not cover the complete object surface, but a complete model without gaps is needed. Furthermore, it is not always required to generate a complete model from the scan data - for specific applications, it might be sufficient to only reconstruct a fraction or certain detail of the object. This could be subject of further investigation. Finally, the above discussed option of extending the methodology to a certain LoC0, and allowing raw mesh or point cloud data as input option for downstream applications, could be pursued and evaluated.

Acknowledgement

I would like to thank both my supervisors of my master thesis, Prof. Volker Mehrmann and Stephan Mönchinger, for their support and motivation.

References

Aranburu, A.; Justel, D.; Angulo, I. (2020): Reusability and Flexibility in Parametric Surface-based Models: A Review of Modelling Strategies. In: Computer-Aided Design and Applications, 18 (4), pp. 864–874. https://doi.org/10.14733/cadaps.2021.864-874.

Ben Makhlouf, A.; Louhichi, B.; Mahjoub, M. A.; Deneux, D. (2019): Reconstruction of a CAD model from the deformed mesh using B-spline surfaces. In: International Journal of Computer Integrated Manufacturing, 32 (7), pp. 669–681. https://doi.org/10.1080/0951192X.2019.1599442.

Bénière, R.; Subsol, G.; Gesquière, G.; Le Breton, F.; Puech, W. (2013): A comprehensive process of reverse engineering from 3D meshes to CAD models. In: Computer-Aided Design, 45 (11), pp. 1382–1393. https://doi.org/10.1016/j.cad.2013.06.004.

Brujic, D.; Ainsworth, I.; Ristic, M. (2011): Fast and accurate NURBS fitting for reverse engineering. In: The International Journal of Advanced Manufacturing Technology, 54 (5-8), pp. 691–700. https://doi.org/10.1007/s00170-010-2947-1.

Buonamici, F.; Carfagni, M.; Furferi, R.; Governi, L.; Lapini, A.; Volpe, Y. (2018): Reverse engineering modeling methods and tools: a survey. In: Computer-Aided Design and Applications, 15 (3), pp. 443–464. https://doi.org/10.1080/16864360.2017.1397894.

Chinn, A. (2021): New approach for accurate, robust morphing of CAD geometries. Facilitates bi-di transfer between analysis-testmanufacture and design. Available at https://www.enginsoft.com/expertise/new-approach-for-accurate,-robust-morphing-of-cad-geometries.html, accessed 13.11.2021.

Ebrahim, M. A.-B. (2015): 3D Laser Scanners' Techniques Overview. In: International Journal of Science and Research (IJSR)).

Eck, M.; Hoppe, H. (1996): Automatic reconstruction of B-spline surfaces of arbitrary topological type. In: SIGGRAPH '96: Proceedings of the 23rd annual conference on Computer graphics and interactive techniques, pp. 325–334. https://doi.org/10.1145/237170.237271.

Farin, G.; Hansford, D. (1999): Discrete Coons patches. In: Computer Aided Geometric Design, 16 (7), pp. 691–700. https://doi.org/10.1016/S0167-8396(99)00031-X.

Krishnamurthy, V.; Levoy, M. (1996): Fitting Smooth Surfaces to Dense Polygon Meshes. In: SIGGRAPH '96: Proceedings of the 23rd annual conference on Computer graphics and interactive techniques. https://doi.org/10.1145/237170.237270.

Lee, H.; Lee, J.; Kim, H.; Mun, D. (2021): Dataset and method for deep learning-based reconstruction of 3D CAD models containing machining features for mechanical parts. In: Journal of Computational Design and Engineering, 9 (1), pp. 114–127. https://doi.org/10.1093/jcde/qwab072.

Sederberg, M. T.; Sederberg, T. W. (2010): T-Splines: A Technology for Marine Design with Minimal Control Points. In: Chesapeake Powerboat Symposium.

Shi, P.; Qi, Q.; Qin, Y.; Scott, P. J.; Jiang, X. (2020): A novel learning-based feature recognition method using multiple sectional view representation. In: Journal of Intelligent Manufacturing, 31 (5), pp. 1291–1309. https://doi.org/10.1007/s10845-020-01533-w.

Soni, K.; Chen, D.; Lerch, T. (2009): Parameterization of prismatic shapes and reconstruction of free-form shapes in reverse engineering. In: The International Journal of Advanced Manufacturing Technology, 41 (9-10), pp. 948–959. https://doi.org/10.1007/s00170-008-1550-1.

Varady, T. (2008): Automatic Procedures to Create CAD Models from Measured Data. In: Computer-Aided Design and Applications, 5 (5), pp. 577–588. https://doi.org/10.3722/cadaps.2008.577-588.

Wang, J.; Gu, D.; Yu, Z.; Tan, C.; Zhou, L. (2012): A framework for 3D model reconstruction in reverse engineering. In: Computers & Industrial Engineering, 63 (4), pp. 1189–1200. https://doi.org/10.1016/j.cie.2012.07.009.

Wei, J.; Lin, G.; Yap, K.-H.; Hung, T.-Y.; Xie, L. (2020): Multi-Path Region Mining For Weakly Supervised 3D Semantic Segmentation on Point Clouds.

Zhang, Z.; Jaiswal, P.; Rai, R. (2018): FeatureNet: Machining feature recognition based on 3D Convolution Neural Network. In: Computer-Aided Design, 101 (6), pp. 12–22. https://doi.org/10.1016/j.cad.2018.03.006.