

DIMENSIONAL TOLERANCE APPROXIMATION FOR REVERSE ENGINEERING APPLICATIONS

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1. Introduction

Reverse Engineering (RE) is the process of extracting design information from an existing part for which such information is unavailable or mislaid. It is desirable to create a complete CAD model from the part to benefit from the computerised analysis and manufacturing software. The first problem after the completion of the solid CAD model with detailed features is the accommodation of tolerances and constraints to the dimensional values and to the surface features. This process is conventionally a manual stage in the RE of the mechanical components, which is heavily dependent on the design expertise of the RE operator. This consequently requires technical expertise to be able to analyse the assembly to which the desired component belongs to, that can increase the cost of RE. Moreover it can be argued that such a method is a redesign of the desired component rather than RE.

CAD models, as one of the key inputs of many automated manufacturing and production systems, should include all the relevant and essential information on each and every feature of the component so it can be manufactured. For instance, a particular hole feature in a CAD model can be manufactured once the type, position, diameter, depth, surface finish requirement, including the tolerance on all of the parameters and constraints are known. It is understood that the initial dimension placed on the features in any drawing or CAD model should be the exact dimension that would be used if it was possible to work without tolerances [Oberg et al, 2004]. However the tolerancing is required to make the part cost effective and feasible to manufacture. In the case of sensitive parts or features, the tolerance should be defined in more detail including geometrical features such as waviness, cylindricity, perpendicularity.

In this research, the relationship between the surface finish information of a given feature and the dimensional tolerance requirement of the feature is investigated. The machining realisation of the feature is used to establish a typical dimensional tolerance requirement. This is an integration of visually determining the machining process and accurate measurement of the surface parameters. Although the initial RE tolerance typically has larger variations over the feature's dimensions due to its approximation nature, it is a reliable starting point to limit the tolerance deviation on the feature's dimensions for manufacturing purposes. It is possible to integrate the tolerancing procedure for the further automation of CAD modelling systems [Jamshidi et al, 2005] for RE applications.

2. Literature Review

Uncertainties in manufacturing bring non-uniformity to production, which results in differences in the products that are coming out of the same process. On the other hand Deming [Drake, 2001] states that the quality of the products is normally a direct function of the consistency of the individual parts that are produced in a production line. This inevitably requires more control over the manufacturing processes, which increases the cost of finished product. Moreover examples can be given of some features occurring on many products that do not require accurate dimensions. Therefore an optimum

solution should be thought of to minimise the cost of finished products while maintaining the functionality and other performances of the part. One approach the designers use is to define an allowable limit, or tolerance to the proposed dimensions, in a variety of in house (company) or international standard forms. In common practice, tolerances are permissible in directions that are less dangerous [Oberg et al, 2004].

Depending on the manufacturing processes different methods of tolerancing, including tolerancing based on the historical knowledge, machine capability and customer order, are used. For instance, a dimensional tolerance in a typical casting process should include issues with shrinkage, draft and minimum material for possible machining processes that follow and most importantly the capability of the selected casting process. The final tolerancing can be agreed between the manufacturer and the customer [Steel Founder’s Society of America, 2003] or extracted from the tolerancing standards such as, Castings System of Dimensional Tolerances (ISO 8062) and ANSI Y14.5M. Several studies have focused on tolerance analysis. Kandikjan et al [2000], introduced a scheme for the validation of dimensional tolerances by using the concept of control frames, theoretical dimensions and the available standards. Their scheme is practical for components with fewer features, but the number of controls increases exponentially with the increase in the number of dependent features. However this can be considered as a valuable starting point for justifying the tolerances in parts, as there are cases in which a part is over toleranced or under toleranced. Examples can be given in which an under toleranced part can satisfy all its tolerance requirements but proves to be impossible to use in its designated assembly. Over toleranced parts on the other hand increase the cost of the finished product. Despite the significant amounts of research on various areas of RE, little work has been done on dimensional and surface roughness tolerance accommodation for RE applications. In most of this research, the work has focused on the CAD model creation and cloud data modification for model improvement, which helps to bring the existing part’s design information to the CAD environment. However the parametric capabilities of even the existing CAD systems are not used for retrofitting tolerances. Benko et al [2002] have developed a method in which the typical large number of constraints in a cloud data gained by RE process is reduced by elimination of redundant constraint, such as redundant perpendicularity constraint, through mathematical constraint fitting.

3. Tolerance Approximation Method for Reverse Engineering

In the tolerance approximation process, the surface finish information, including the roughness and surface texture, is used to identify the original manufacturing process. Then, based on such information and typical tolerancing of similar manufacturing processes, the surface finish and the dimensional tolerance and constraints for individual features of the desired part are established. An overview of the method is shown in Figure-1 below. However the surface characteristics are used to estimate the required tolerance only as a guideline for further tolerance analysis and confirmation of the final tolerance.

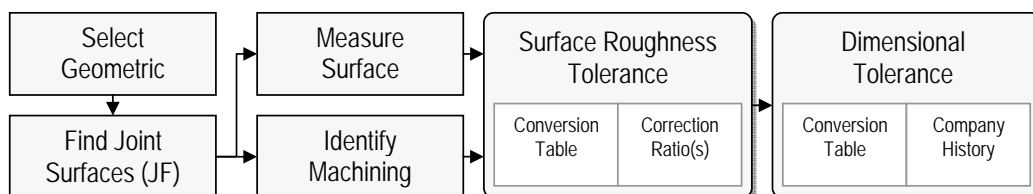


Figure 1. The process of tolerance approximation for surface and dimensional tolerance

3.1 Uncertainties in Reverse Engineering

The features of the primary CAD model, created by a comprehensive RE method, are typically in the same geometry and dimension with respect to that of the part. It is expected that such a CAD model is a very close replica of the initial design if the part is an unused one. However if the part is found to have been in service for a period of time or in a more unfortunate situation, damaged or defected, appropriate modifications and interactions to the CAD model especially on dimensioning and

tolerancing are required in order to extract the close to real and primary design information. The result of RE of any given component depends on the data acquisition methods and the post modelling software used, but the condition of the component is more vital, i.e. the validity of the CAD model created on a used component depends directly on the level of wear and damage that it gained throughout its life. An extensive list of damages that a part can potentially receive with relation to its service time can be created. For the purpose of discussion some typical defects are shown in Figure-2. For the unused parts there may also be corrosion due to long term storage. Therefore, prior to scanning and measurement, necessary preparation should be done and in all the stages of the RE including the modelling process, dimensioning and tolerancing, the existence of any possible defects should be considered. For the tolerance approximation method, the defects that are in direct relation to the surface finish and roughness like wear are of much concern, and the surface measurement on the damaged and worn areas should be avoided for better accuracy of the results if possible.

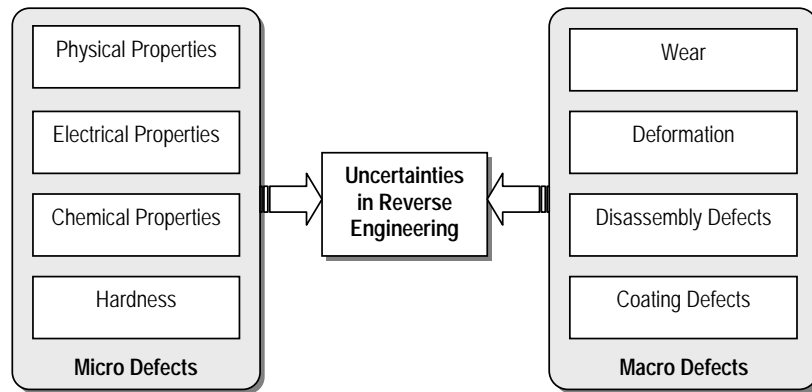


Figure 2. Uncertainties in reverse engineering of a used component

3.2 Machining Realisation and Surface Roughness Measurement

In the RE of a typical component it is possible to decide whether a feature has been machined or is left as cast. Also, in terms of machining, it is possible to determine what machining process was used, by careful observation of the part.

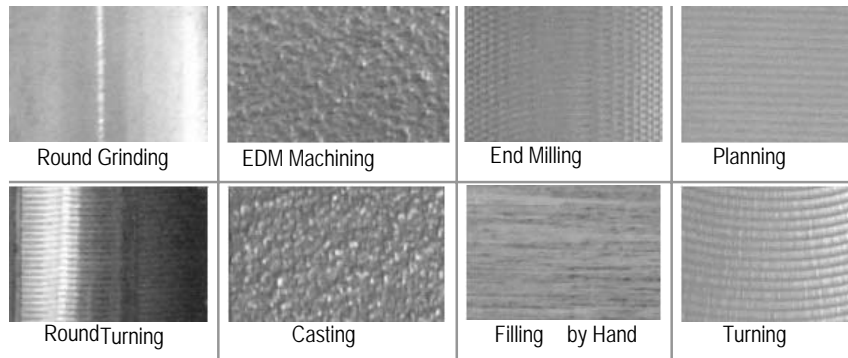
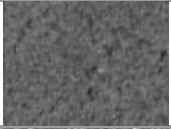
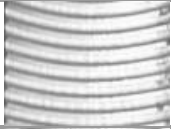

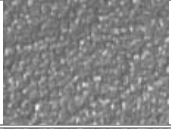


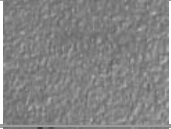
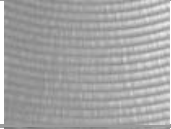

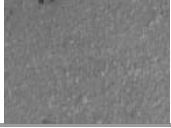
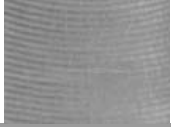
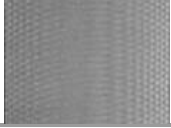


Figure 3. Surface texture made by different processes

Each machining process leaves a unique texture on the part surface, depending on several parameters including the part material properties, tool type and size, cutting direction, coolant, feature form, feed rate, feed speed, machine power. However similar casting or machining processes tend to leave analogous surface texture regardless of the other parameters. For instance, a face cutting tool used in a

milling machine on different components leaves lines of half circles, and flat grinding leaves parallel lines. Typical surface textures left by common manufacturing processes are shown in Figure-3. Different surface finishes produced by different processes can be distinguished easily in rough machining, but in the case of finer and smoother surface finishes, visual aids may be required. However the general texture of the part remains consistent even with different roughness values for the same process, as shown in Table-1.

Table 1. Comparison of surface finishes between different machining processes with similar Ra

Roughness Value (μm)	Sand Casting	Turning	End-Milling
50.0			
25.0			
12.5			
6.3			

The surface roughness properties of the desired part have to be measured for the extraction of surface characteristics by one of the conventional surface measurement methods (See Whitehouse [1997] for a review of existing surface measurement systems) and standards.

3.3 Tolerance Conversion Table

In order to estimate the surface roughness tolerance of the desired surface, a conversion table is introduced, in which the roughness tolerance is achieved based on the surface machining information. This table is in effect an inverse approach to the surface roughness produced by common production methods as specified in ASME B46.1-1995 [Oberg, 2004]. In this method, the machining requirement is determined by the visual inspection of the surface texture, which helps to narrow down the surface tolerance requirement. For instance if the surface texture suggests the process to be EDM, the typical surface roughness is between $Ra=1.60\mu\text{m}$ to $Ra=5.00\mu\text{m}$, however in less frequent applications of EDM the surface roughness can be as fine as $Ra=0.80\mu\text{m}$ to as rough as $Ra=12.50\mu\text{m}$. This knowledge gives a reasonable estimate of what the original surface finish tolerance could have been, for the problem of tolerances in RE, provided that the part is an unused one.

A better estimate over the original tolerance can be achieved by the measurement of surface finish. If the roughness is $Ra=4.50\mu\text{m}$ on a typical part with turning texture, one can expect the tolerance in the original design to be around $4.50\mu\text{m}$. This is because in the successful design of new products, the manufacturing capabilities, assembly requirement and functionality are kept in balance to minimise the cost. And although the trend in design is towards tighter tolerance and finer surface finishes, it is always advisable to widen the tolerance deviation to its maximum to minimise the cost of manufacturing and quality.

Although in Table-2 the maximum Ra limit for a turning process can be from as small as $0.03\mu\text{m}$ to as large as $25.0\mu\text{m}$, but the rational expectation for the majority of parts is that the desired part is a quality verified one when produced, therefore the maximum Ra values of less than $4.50\mu\text{m}$ is out of

question and only the upper limit for the surface roughness tolerance needs to be determined. This is particularly important for production cost effectiveness, thus careful consideration is required when increasing the upper limit of the tolerance. Therefore in the example above, a less risky strategy is to use the measured roughness as the new surface roughness tolerance, but if the part is a high quality one, i.e. the deviation from the actual tolerance happened to be minimal in that part, then the danger of over tolerancing will arise.

Table 2. Surface roughness produced by common production methods

Surface Texture (Original Machining)	Typical Roughness μm	Less Frequent Roughness μm
Flame Cutting	$12.5 < Ra < 25.0$	$6.30 < Ra < 12.5$ and $25.0 < Ra < 50.0$
Planing, Shaping	$1.60 < Ra < 12.5$	$0.40 < Ra < 1.60$ and $1.25 < Ra < 25.0$
Milling	$0.80 < Ra < 6.30$	$0.15 < Ra < 0.80$ and $6.30 < Ra < 25.0$
Electric Discharge Machining	$1.60 < Ra < 4.90$	$0.80 < Ra < 1.60$ and $4.90 < Ra < 12.5$
Turning	$0.40 < Ra < 6.30$	$0.03 < Ra < 0.40$ and $6.30 < Ra < 25.0$
Grinding	$0.10 < Ra < 1.60$	$0.03 < Ra < 0.10$ and $1.60 < Ra < 6.30$
Honing	$0.10 < Ra < 0.80$	$0.03 < Ra < 0.10$ and $0.80 < Ra < 1.60$
Sand Casting	$12.5 < Ra < 25.0$	$6.30 < Ra < 12.5$ and $25.0 < Ra < 50.0$
Investment Casting	$1.60 < Ra < 3.20$	$0.40 < Ra < 1.60$ and $3.20 < Ra < 6.30$
Die Casting	$0.80 < Ra < 1.60$	$0.40 < Ra < 0.80$ and $1.60 < Ra < 3.20$

3.4 Dimensional Tolerance Approximation

The approximation of dimensional tolerances is based on the relationship between the surface finish roughness of the surfaces that are involved in a particular dimension and the dimension itself. The surfaces attached to a dimension that is required to be $\pm 0.025\text{mm}$ due to an assembly requirement for instance, has to have a roughness value that can guarantee the uniformity of the surface. Consequently this affects the manufacturing or machining requirement of such surfaces. Therefore in the RE of a part, the machining realisation of such surfaces helps to firstly estimate the surface roughness tolerance as described in 3.2 and secondly, based on that, the dimensional tolerance. The company standard and design rules can also be used in connection to dimensional tolerancing based on the surface finish. For instance a typical milling machine process has several dimensional tolerances depending on the length of the desired dimension, which varies from company to company. The dimensional tolerance is again only an approximated value that can be used as a guideline for RE dimensional tolerances. This approximation may be satisfactory for insensitive parts, however for critical parts other measures including the assembly analysis, level of wear, and further design test must be considered. In the further progress of this research a secondary conversion table will be developed to include the typical dimensional tolerances with relation to the surface finish information.

3.5 Automated Tolerancing for Reverse Engineering

Automation in tolerancing can be achieved by using the tolerance estimation method described above. The process of attaching tolerances to the dimensioning and geometric features requires several stages, some of which need user entry and manipulation, such as feature and option selection, while several other processes are automated within the system. The entry to the system is therefore a complete CAD model with or without dimensioning information, and the output is the CAD model with all the necessary dimensional information including tolerance information. Figure-4 shows an overview of the tolerancing process, in which the internal processes of the system are shown in the double lined boxes. The tolerancing process can be integrated to a RE system [Jamshidi et al, 2005] for further automation of the CAD modelling processes.

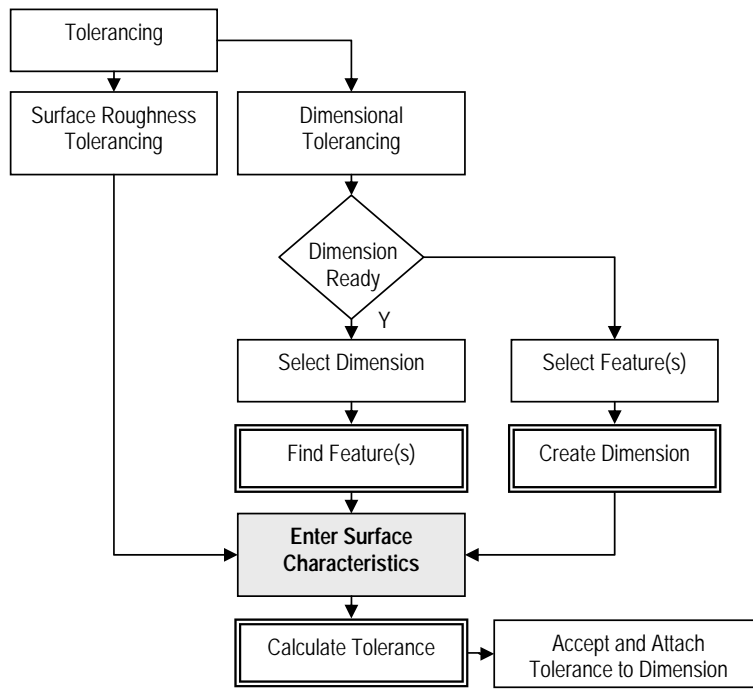


Figure 4. Algorithm of tolerance approximation method

The surface characteristic that are the user entries to the tolerance approximation system are divided into four main groups as shown in Figure-5.

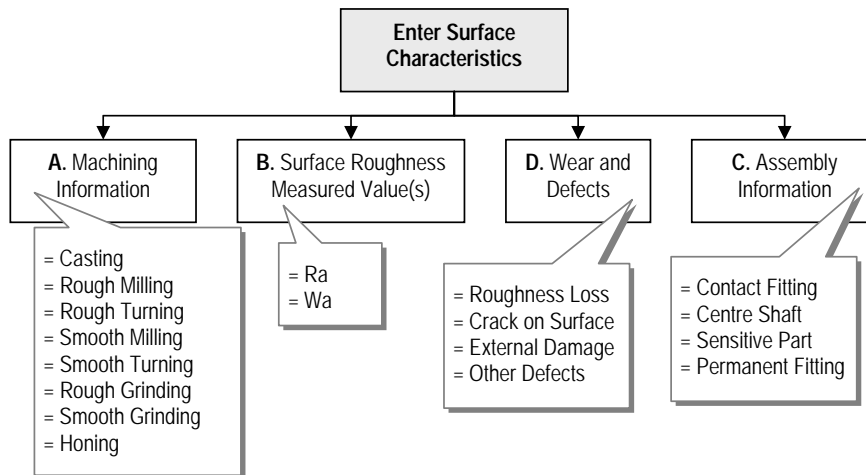


Figure 5. User options and entries in tolerance approximation method

The *Machining Information* as described in 3.2 are determined by visual inspection of textures of the desired surfaces, the *Surface Roughness* is measured by one of the conventional methods, information on the *Wear and Defects* applies to the used parts, and the *Assembly Information* highlights the sensitivity of the part and its desired features. In this paper only the Machining Information and the measured Surface Roughness are considered. The conversion table described in 3.3 is used to estimate the surface roughness tolerance based on the actual measurement result and also the machining process used.

4. Method Validation

The method is used to approximate the surface roughness and dimensional tolerances of several automotive components with various casting and machining features, and validated against the real and existing drawings of the similar components. Figure-6 shows an automotive front suspension assembly, for which the mounting bracket of the braking system is reverse engineered using Coordinate Measurement Machine (CMM) and Laser Scanner [Jamshidi et al, 2006], for complete and high precision CAD modelling. The nominal dimensional information in the resulting CAD model is based on the measured dimensions from the existing part. The machining and surface roughness measurement information is then used to estimate the dimensional and surface roughness tolerances of the original design.

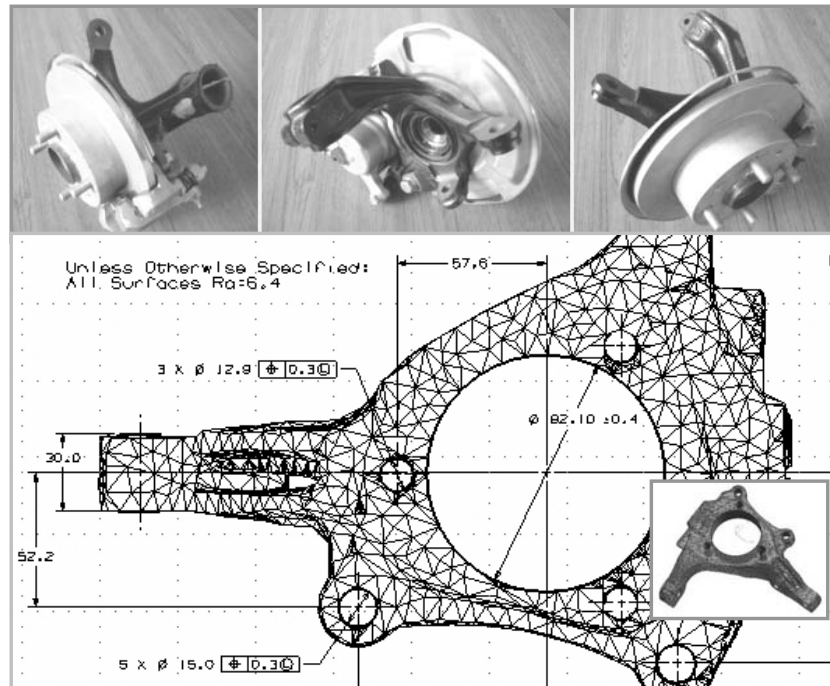


Figure 6. Tolerance Reverse Engineering of mounting bracket of a car brake assembly

As shown in Figure-6 the hole feature the diameter of 92.10mm which was the diameter measured by CMM and therefore put as the nominal diameter. The surface finish texture suggested that the hole was machined by milling machine, for which the surface roughness is estimated as $Ra=6.40$. The dimensional tolerance is also estimated as ± 0.4 based on the typical maximum tolerance for milling machining. The result of tolerance approximation was larger than the similar features' tolerance in the drawings by an average of less than 30% [Jamshidi, 2005], which may not be suitable to be relied on directly especially if these are sensitive parts. However, the advantages in using the method that can be summarised as: 1) Flexibility to the RE system user to approximate the tolerance without any design initiatives 2) Possibility to initiate the assembly and tolerance analysis of CAD models created by RE 3) Guideline for tolerance accommodation. A further benefit of the method is that if the CAD model is in parametric format, it is possible to create the CNC and NC machining codes in the lower or upper limit tolerances if necessary. For example if a defective part (that has lower limit tolerance in a particular feature) in an assembly needs to be remanufactured, it might be advisable to produce the part with the same dimensional values i.e. minimum dimension, which can be achieved by changing the parameters to lower limit in the CAD model prior to machining process programming.

5. Conclusion

Dimensional tolerances are required to be sensibly defined and presented in a way to guarantee the functionality of the part while minimising the manufacturing cost. In reverse engineering the design information including the overall geometry, surface finish and dimensional tolerances is extracted from scanning and analysing the existing part. However the tolerance accommodation is one of the challenging problems that is conventionally dealt with by design initiatives of the reverse engineering expert in a rather “redesigning” approach. In this work the existing information from the part machining and surface finish measurement result is used to estimate the surface finish and dimensional tolerance information. This method can be integrated into a reverse engineering system for further automation and user flexibility. A wear factor can be added in the tolerance approximation process in the further development of the system, by involving a correction ratio to the initial estimation. Assembly analysis can also be included to better estimate the dimensional and surface tolerances for higher sensitivity components.

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