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Vorwort

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Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

Fraunhofer ITWM

Geometric characterization of particles in 3d

with an application to technical cleanliness

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September 6, 2011

Abstract

Continuously improving imaging technologies allow to capture the complex spatial geometry of particles. Consequently, methods to characterize their three dimensional shapes must become more sophisticated, too. Our contribution to the geometric analysis of particles based on 3d image data is to unambiguously generalize size and shape descriptors used in 2d particle analysis to the spatial setting.

While being defined and meaningful for arbitrary particles, the characteristics were actually selected motivated by the application to technical cleanliness. Residual dirt particles can seriously harm mechanical components in vehicles, machines, or medical instruments. 3d geometric characterization based on micro-computed tomography allows to detect dangerous particles reliably and with high throughput. It thus enables intervention within the production line. Analogously to the commonly agreed standards for the two dimensional case, we show how to classify 3d particles as granules, chips and fibers on the basis of the chosen characteristics. The application to 3d image data of dirt particles is demonstrated.

Keywords: intrinsic volumes, isoperimetric shape factors, bounding box, elongation, geodesic distance, technical cleanliness.

1 Introduction

In a variety of applications in materials science, biology, or engineering, size and shape of particles have to be measured, see e. g. [20, 18, 10, 7]. While [20, 18] use 3d image data and [7] 3d point clouds, the typical particle analysis is still based on 2d geometric characteristics for which very detailed standards describe how to obtain them from microscopic images [2]. However, 3d shape can not be captured completely by 2d images of sections or projections.

In 2d there appear two classes of objects, that is granular and fibrous particles. Length and width of the object can be compared, it is however not possible to tell how thick objects are. When the third dimension is available, naturally three classes can be distinguished: granules, chips and fibers. Granular objects are characterized by comparable width in each dimension, while chips, or flakes, are instead flat and wide objects. Long and thin objects are fibers or needles.

In this paper we introduce unambiguous geometric characteristics for 3d shape and size based on digital 3d images as obtained e. g. by micro-computed tomography. Motivated by the application to technical cleanliness we suggest additionally criteria for classifying an object as granule, chip, or fiber.

Technical cleanliness is a key issue in a variety of areas, in particular in the automotive industry. During the production, residual particles collect on the surface of mechanical components, thus creating a contamination that might affect the expected durability and performance of the assembled products. The damage that the dirt particles can cause depends on their chemical composition, size, and not the least shape. Indeed, it depends on how the mass of the particles is arranged in space whether a particle can penetrate a gap or not. For example, a small granular object can be stopped, while a thin but very long fiber will slip through.

2 Particle characterization

In [2] standards for particle characterization in 2d are presented. In particular, two classes of parameters are distinguished: one describing the size and the other the shape. The purpose of this section is to proceed analogously, generalizing the features to the 3d case and introducing new features arising naturally with the growth of dimension.

The geometric parameters outlined in the following are well defined in continuous Euclidean space. However, we are interested in estimating them based on digitized images. Therefore, from now on we assume the particles to be polyhedral sets resulting from digitization w. r. t. an adjacency system in 3d. That is, the particles are assumed to be composed of polyhedra, polygons, edges, and vertices of the chosen adjacency system where all vertices of these elements are vertices of the lattice on which the image data is given. For more details see [14].

2.1 Intrinsic volumes and isoperimetric shape factors

The easiest way to describe the size of an object is via the volume that can be calculated from the segmented image by simply counting the number of pixels constituting the particle. The surface area can also be measured from the digitized data by a suitably weighted sum of boundary configurations, see [14].

Volume V and surface area S, together with integral of mean curvature M and Euler number χ form the set of intrinsic volumes of three dimensional compact sets – a basic set of object characteristics [12]. The integral of mean curvature has dimension one and is proportional to the mean width for convex particles. It can be robustly estimated from a digitized image via a discretization of the Crofton formula [14]. The Euler number, also known as the Euler-Poincaré characteristic, conveys topological properties of a set. It equals 1 for all convex bodies and can be extended additively to the convex ring of unions of convex bodies. Roughly speaking, the 3d Euler number is the sum of the number of connected components minus the number of tunnels plus the number of holes. We refer the reader to [14] for detailed definitions and algorithms to estimate these quantities from digitized images.

V, S and M can be used to define *isoperimetric shape factors* [19] as follows

$$f_1 = 6\sqrt{\pi}\frac{V}{\sqrt{S^3}}, \quad f_2 = 48\pi^2\frac{V}{M^3}, \quad f_3 = 4\pi\frac{S}{M^2}.$$

All shape factors are normalized to equal 1 for balls. f_1 takes values between 0 and 1, while f_2 and f_3 are larger than 1 for polyconvex objects. Deviations from 1 describe deviation from the spherical shape. Indeed, the first shape factor f_1 is often called *sphericity*. In Table 1, values for some sample particles are displayed. Due to discretization errors, the shape factors calculated on a digitized ball are not exactly 1, but close to this value.

These parameters represent a complete system of shape factors based on the intrinsic volumes, in the sense that other combinations of V, S, and M can not carry more information than what is already contained in f_1, f_2 and f_3. Nevertheless, motivated by special applications, in the literature other shape factors derived from the above do occur. For instance, by raising f_1 to the power of 2 and multiplying it by a suitable normalization factor, in [16] the *compacity factor* is defined as

$$I_C = 6^3 \frac{V^2}{S^3}.$$

It is equal to 1 for cubes and thence tells how close a particle is to have a cubic shape.

2.2 Size: length, width, and thickness

The volume returns a measure of how big an object is, but yields no information about how the mass of the object is arranged in space. In 2d, length and width are measured based on microscopic images [2]. Standards for larger particles describe measurements of length, width, and thickness using calipers [1]. In 2d, length obviously coincides with the maximal diameter. The width is then the length of the projection onto the line orthogonal to the maximal diameter's direction.

We generalize these concepts to 3d using a cuboidal box bounding the particle and being of minimum volume. That way, size can be well defined since the edge lengths of the minimum volume bounding box are invariant under rotations. That is, the minimum volume bounding box is unique, but for orientation. For instance, a sphere is bounded by a cube with edge length equal to the diameter and with arbitrary orientation. Analogously, cylinders with circular cross section admit infinitely many minimum volume bounding boxes, but all with the same size. Therefore it makes sense to speak of uniqueness of size referring to the lengths of the edges which, sorted in decreasing order, are, respectively, *length*, *width*, and *thickness* of the particle.

In Figure 1, the size of a chip-like ellipsoid is represented. Note that this definition of size is independent of the isoperimetric shape factors, thus carrying different information.

In the following, we take a closer look at the algorithm for computing the particle size. The choice of the algorithm is motivated and the main steps of the implementation are outlined. Finally, the application of the algorithm to a real object is treated.

A polyhedron has in general no face lying on a face of its minimum volume bounding box. This can be seen e. g. by the example of a regular a tetrahedron for which just the edges lie on the faces of its minimal volume bounding cuboid. More general, there is no easy geometric rule that can be exploited to design a fast exact algorithm. The only exact algorithm [15] is of cubic complexity in

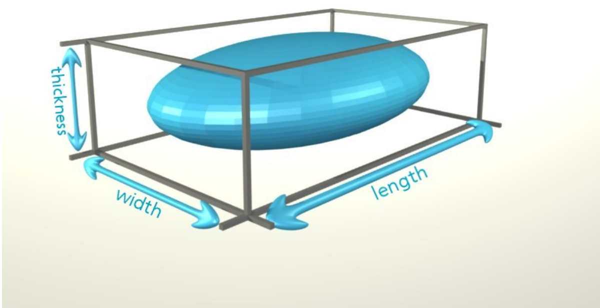


Figure 1 Ellipsoid and its minimum volume bounding box.

the number of points – computational costs which are in general too high for applications. Therefore, we rather apply an algorithm approximating the real minimum volume bounding box in nearly linear time.

Due to the convexity of cuboids, a box bounding an arbitrary particle bounds its convex hull, too. Thus the first step of the algorithm is to calculate the convex hull and use its vertices as input for the algorithm [3] computing the minimum volume bounding box of a point cloud. Computation of the convex hull is based on the QuickHull algorithm [4], which performs a search on all the points of the object and returns the subset of those forming the convex hull. This computation is exact and results in a remarkable reduction of the number of points.

Given the convex hull, a supporting bounding box B^* is constructed. Let the diameter of a point set be the distance between the two furthest points in it. The diameter is the first edge of B^*. Then all the points are projected onto the plane perpendicular to the direction of the diameter. The diameter of the projected point cloud in this plane is found and used as the second edge of the box. The direction of the third edge is now fixed, its length is the distance between the two points with largest distance between each other in this direction. Thus B^* is determined.

In general, the box B^* is not the bounding box of minimum volume. However, based on B^*, the final minimum volume bounding box can be efficiently approximated. A grid is defined on the faces of the box. For each direction induced by this grid, a bounding box with an edge parallel to the given direction is computed. In [3] it was proved, that this yields a good approximation of the real minimum one. This procedure is based on the observation that, once a direction is fixed, it is easy to calculate the exact minimum volume bounding box with one edge lying in that direction. The length of the edge is of course determined by the diameter in that direction. As above, all the points in the set are then projected on the plane perpendicular to the direction. However, now on the plane, the exact minimum area bounding rectangle of the point cloud can be calculated. With a 2d version of the QuickHull algorithm, the convex hull is calculated. The convex hull is guaranteed to have an edge lying on an edge of the minimum area bounding rectangle [6]. Therefore by testing all enclosing rectangles generated by edges of the 2d convex hull, the exact one can be found. This rectangle is the cross section of the searched cuboid, which is thus completely defined. The accuracy of this algorithm is determined by the fineness of the chosen grid on the surface of B^*.

In practical application, we use a grid of 10 parallel lines on each face of B^*. The 1000 points generated on the intersections induce 840 different directions, that is the number of bounding boxes tested. Let us consider the ellipsoid displayed in Figure 1. The number of vertices of its convex hull is 655. The computation of the minimum volume bounding box takes about 3 seconds under Windows on an Intel Xeon E550 (2.27 GHz core speed, 48 GB RAM, two processors). In this case, the real minimum volume bounding box is analytically known, so the error can be calculated by comparing its volume with the one of the box returned by the algorithm. The error is 0.2% and does not depend on the orientation of the particle. Indeed, the tested directions are chosen from B^*, whose edge directions induce a reference system depending on the particle orientation.

As a first step of the algorithm, we computed the convex hull of the particle. This can be used further to characterize particle shape, by defining the *convexity factor* as the ratio between the volume of the particle and the volume of its convex hull. Theoretically, it is exactly 1 for convex particles, but practically some computational errors can occur due to the discretization and the calculation of the volume of the convex hull. Moreover, the surface roughness also reduces the convexity factor. Still, we can consider a particle to be convex if the convexity factor is larger than 0.9.

2.3 Size: elongation and inner diameter

Length, width and thickness do not convey an exhaustive description of the size of a particle.

The diameter of a point set measures of the maximal extension of the point set in space. When the point set is a particle, the diameter is the largest (Euclidean) distance between two points in the particle, often called *maximal Feret diameter*. It is larger or equal to the length, being equal in the case of a sphere for example, but larger for a cube or a parallelepiped, where it corresponds to the length of the space diagonal.

The characteristics introduced so far do neither yield the length of an unwound fiber nor a measure of thickness that can be used to decide whether the particle can slip through a gap. In order to define characteristics of this type, we temporarily restrict to particles with no holes nor tunnels (this case will be treated in the end of the section).

By the unwound length of a fiber, we understand the curve length of the shortest path within the particle connecting its end points. In order to generalize this definition suitably to arbitrary particles, we replace Euclidean distance by geodesic distance: let x and y be two points in the particle. They can be connected in many ways by continuous paths inside the particle. The shortest of these paths is the geodesic arc between x and y and its length is the geodesic distance, see [8]. From this definition, we can properly define for arbitrarily shaped particle an analog of the "real" length of a fiber: it is the length of the longest geodesic arc within the particle. Bearing in mind [2], we call it *elongation*. The advantages of this definition are manifold. First of all, it does not depend on what type of particle we are considering, whether it is fibrous or granular or star shaped. Second, it is a robust definition, meaning that if the particle is slightly deformed, its elongation also varies minimally. Finally, efficient algorithms can be implemented to estimate it from digitized images.

Here, in order to estimate the geodesic distance between two points, we implemented a generalization to 3d of the algorithm introduced in [17]. The idea is to translate the distance measure between points in the particle into a cost function f: the optimal cost corresponds to the shortest path. Then the algorithm estimates the path along which integration over f is minimal. In order to compute the elongation of the particle, that is the longest path, we proceed in two steps: first, an arbitrary starting point within the particle is given and the geodesic distance to all other points of the particle is calculated. One of the points realizing the maximum geodesic distance is then used as starting point for a second run of the same algorithm. The maximum distance obtained in this second step is the elongation of the particle.

Note that for arbitrary particles, the paths realizing the elongation are not unique, e. g. for star shaped objects, including sphere and cube. Note also that the elongation defined this way does not coincide with the curve length of the medial axis of a fiber, see Figure 2.

Given the elongation L_g, the so called *geodesic index*

$$IG_g = \frac{\pi L_g^3}{6V}$$

can be used to compare particles [16]. It equals 1 for balls and gets larger, the more elongated a particle is, where by elongated we understand thin and long, no matter how arranged in space. Values for some example particles can be found in Table 1.

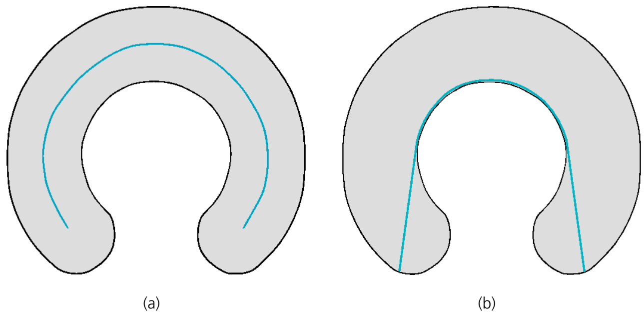


Figure 2 Particle cross section with medial axis (left) and maximal geodesic path (right).

Let us now consider the "real" thickness of a fiber. A rigorous definition can be given by saying that it is the diameter of the largest ball that can be completely contained in the particle. We call it *inner diameter* or *maximal local thickness*. It can be estimated via spherical granulometry or via Euclidean distance transform, see [14]. Spherical granulometry can be seen as a simulation of a sieving procedure: letting grains through a sieve of increasing hole size will separate the grains depending on their maximal thickness. This idea was first introduced by Matheron [9] and properly defined in terms of mathematical morphology as a sequence of openings, i.e. erosions followed by Minkowski additions, with balls of increasing radii. Thus the spherical granulometry yields the volume weighted thickness distribution of the particle. However, if just the maximal local thickness is needed, the Euclidean distance transform (EDT) assigning to each foreground pixel the distance to the nearest background pixel, is preferable due to the fact it can be computed much faster. The maximum of the EDT of an object is an estimate of what we called the "real" thickness of a particle.

The maximal local thickness is meaningful for all particle types. For instance, the thickness of the minimum bounding box will not tell anything about the real thickness of a bent chip whereas this information can be obtained with the maximal local thickness. Moreover, if the particle is formed by a big core connected with thinner threads, then the maximal local thickness yields information about how large this core is, which also determines whether the particle will go through a gap or not.

For what concerns particles with holes or tunnels, the problem is twofold. On the one hand there is the question of what elongation and maximal local thickness actually mean in that case. On the other hand one has to prove that the algorithms return the desired values. The elongation of a torus, for instance, is the length of the path within the object connecting two diametrical opposite points on the surface. Something analogous is obtained by considering a ball with a spherical hole in the center, i.e. a spherical shell. For isotropic objects, the proposed algorithm returns the right result. However, if the cross section of the object is, for example, rectangular with a rectangular hole, such as in Figure

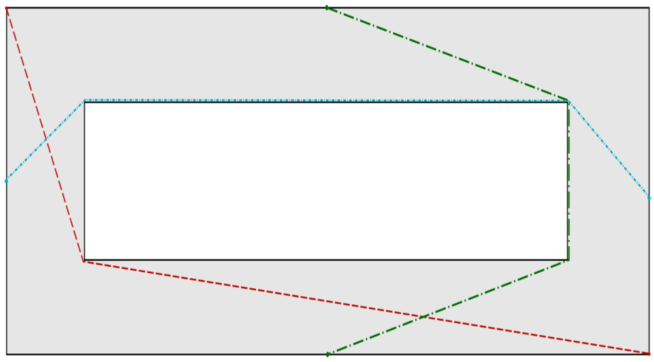


Figure 3 Cross section of a three dimensional object with a rectangular hole. Three geodesic paths obtained applying the algorithm with different starting points. The elongation is realized only on the red path.

3, then the algorithm will fail to find the maximum geodesic length within the particle. Indeed, each of the three paths drawn in Figure 3 is obtained as the result of the algorithm with different starting points, yet their lengths are different. Since in this case the result depends on the starting point, a possible practical solution is taking a random set of starting points instead of only one, then taking the maximum result. Similar considerations can be made in the case of the maximal local thickness. Applying the algorithm to a torus, the diameter of a vertical section is returned, while for a spherical shell, the distance between the external and the internal surfaces. Both these measures are what is theoretically expected.

An alternative approach for particles with a hole is to morphologically fill the hole before starting the analysis. Comparison of the data for the original object and for the "filled" object yields an even more detailed characterization. For a hollow sphere for example, the ratio between the two elongations obtained that way, would return a measure for the size of the hole.

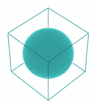
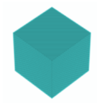
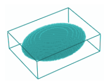
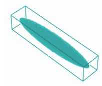
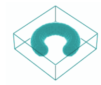
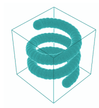
						
volume [px]	179 579	91 125	49 977	24 941	22 773	216 862
Euler number	1	1	1	1	1	1
length [px]	70.00	45.00	79.60	120.00	60.92	116.78
width [px]	70.00	45.00	59.70	19.40	53.25	116.78
thickness [px]	70.00	45.00	20.00	19.40	14.61	96.23
maximal Feret diameter [px]	70.00	76.21	80.00	120.00	61.38	150.24
shape factor f_1	0.992	0.827	0.651	0.583	0.529	0.236
shape factor f_2	0.989	0.733	0.511	0.188	0.148	0.007
shape factor f_3	1.000	0.923	0.851	0.471	0.428	0.094
elongation [px]	72.07	78.41	79.38	120.00	98.59	639.12
elongation index	1.09	2.77	5.24	36.28	21.99	630.29
maximal local thickness [px]	70.03	45.00	20.1	20.1	15.48	20
convexity factor	1.00	1.00	1.00	1.00	0.62	0.27

Table 1 Particle features for some reference shapes.

3 Classification

3.1 Classification based on size

A first classification can be induced by the measures of the minimum volume bounding box. For example a cuboid can be easily classified by calculating its aspect ratios. Let l, w and t be length, width and thickness respectively, then

- $l \sim w \sim t \quad \rightarrow$ granule,
- $l \sim w \neq t$ or $l \neq w \neq t \quad \rightarrow$ chip,
- $l \neq w \sim t \quad \rightarrow$ fiber.

In other words, granules are all those particles with comparable length, width, and thickness. Fibers are prolate objects, that is they are characterized by a length much larger than the width, which is instead comparable to thickness. All the other particles are chips, for example a disc has length and width equal, while an ellipsoid such as the one in Figure 1 has all measures different. This kind of classification was first introduced in the PhD thesis of T. Zingg in 1935 [21]. He applied this procedure in the field of mineralogy in order to classify rocks by their shape. A diagram, the so called Zingg-diagram, is particularly helpful to visualize how this classification works, see Figure 4. In mineralogy, two measures differ if the ratio of the smaller over the bigger one is larger then 2/3. However, this threshold may vary on the application field and typically in technical cleanliness particles are considered fibrous if their aspect ratio is 1:10.

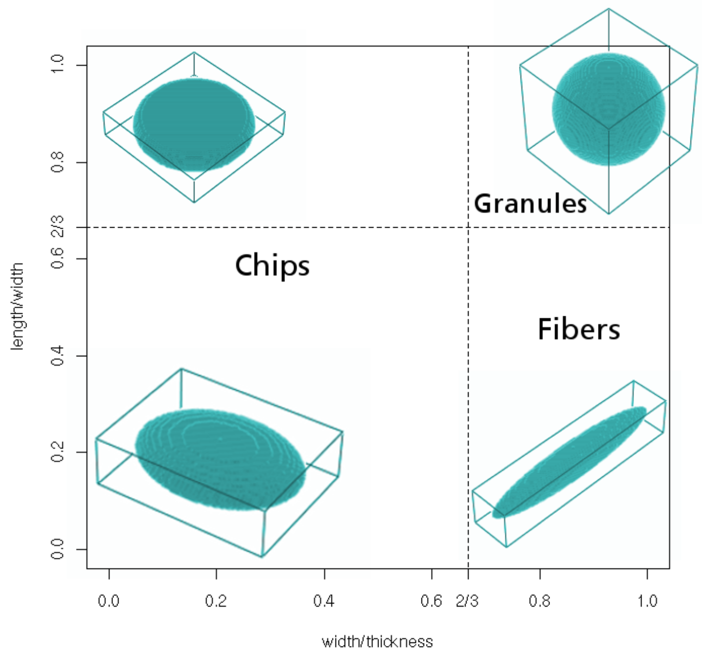


Figure 4 Zingg-diagram with thresholds at 2/3.

Though this classification based on the size can be applied to every particle, it does not always reveal the real class of a particle. Indeed, it fails for peculiar arrangements in space, such as for all those particles that are bent or twisted as for example the ones displayed in Figure 5. Therefore, the shape factors defined above must be taken into account, too, in order to have a reliable classification.

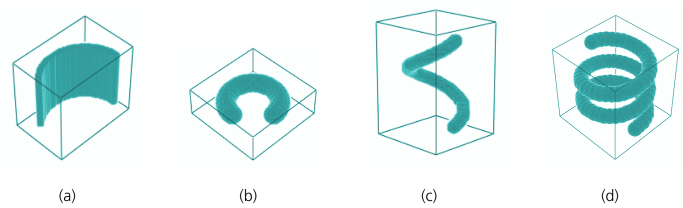


Figure 5 Examples of particles for which the classification based on the size of the minimum bounding box fails.

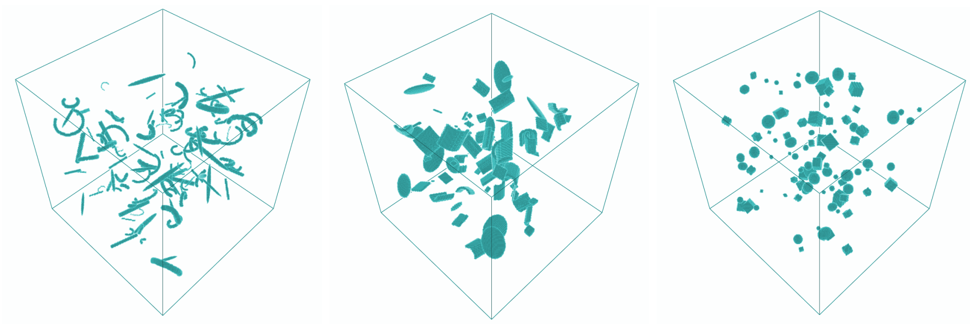
3.2 Classification based on shape factors

We simulated datasets for each class separately and tested if there are significant differences in the isoperimetric shape factors and if they can be thus used for a further classification. In Figure 6, samples for each class are shown. The particles used are ellipsoids and cuboids with different aspect ratios, cylinders, rounded chips, arcs of helices and arcs of tori, randomly oriented in space.

Figure 7 displays graphs of each shape factor plotted against the increasing volume of the particles. For large particles, the shape factors can really be used to separate the classes, while for smaller volumes, values are overlapping and it is not clear how to define meaningful thresholds.

Note that the particles sampled here are all geometrically regular shapes, while the real particles will be more complex and can present a rough surface, hence a higher error might occur in the computation of the shape factors. Therefore, it is wise to choose large thresholds.

The classification based on shape is accomplished as follows:
(1) $f_3 \leq 0.5 \rightarrow$ fiber,
(2) $f_1 \leq 0.7 \rightarrow$ chip,
(3) $f_1 > 0.7 \rightarrow$ granule.
It is important to perform the classification in the given order: with the aim to correctly classify chips, first of all the fibers must be extracted. This is motivated by the first graph in Figure 7, indeed both fibers and chips have typically small values of f_1.



(a) (b) (c)

Figure 6 Simulated samples of fibers, chips and granules separately, random size and orientation. Rendering with MAVIparticle [5].

3.3 Discussion

As motivated above, the shape factors do not help in distinguishing the classes of small particles. Moreover, it is sensible to assume, that if a particle is formed by “not many pixels”, then the classification based on the size is reliable. This is due to the fact that the arrangement in space of a small particle in general can not be in such a complex shape that induces length, width and thickness of a wrong class. We suggest to set this threshold at 400 pixels.

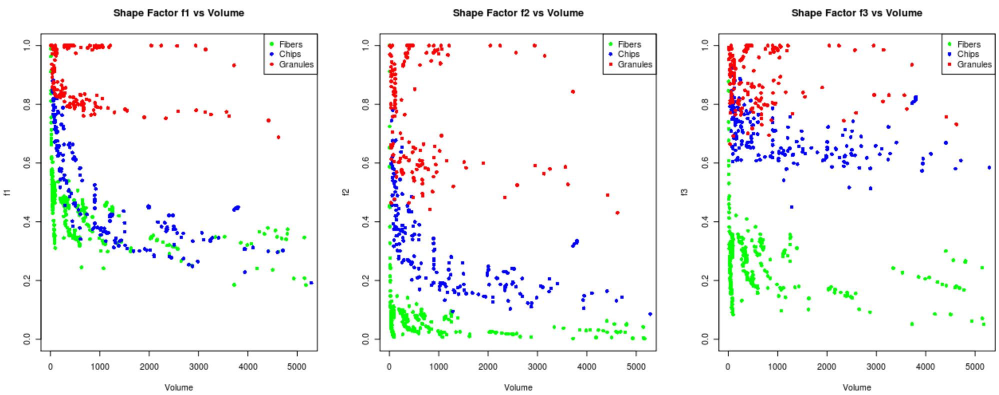


Figure 7 Isoperimetric shape factors plotted against volume of the particles. Each color represents a class: green for fibers, blue for chips and red for granules.

On the other hand, for very small objects, classification is not interesting and the discretization errors are to high. Thus we will classify only particles constituted by more than 64 pixels. This threshold is chosen since a cube formed of 64 pixels has edges only 4 pixels long, thence averagely there is not enough freedom to arrange the pixels in a wide variety of shapes.

The shape characterization relies not the least on the classical isoperimetric shape factors from integral geometry. Being ratios these shape factors are particularly prone to discretization errors, see e. g. [11] for an overview of problems as well as possible solutions. Nevertheless, since we restrict to large particles that typically do not have an inner structure, this type of error is not expected to affect the classification. More precisely, in [13] it was proved that the estimates of the intrinsic volumes are unbiased for compact sets being morphologically regular w. r. t. all line segments connecting vertices of the lattice unit cell. See also [14, Theorem 3.1].

It is worth mentioning, that a criterion to distinguish at least fibers from other types could be based on the elongation index. As Table 1 shows, its value is much higher for fibrous particles than for the other types. However, this has not yet been systematically tested.

In [16], the complex shapes of intermetallic particles originating from the solidification process of aluminum alloys are analyzed. Morphological parameters to characterize their shapes in 3d are collected and used to perform a classification by clustering. However, here we aim at globally defining the three classes of typical 3d shapes, due to the application in technical cleanliness as described in the following section. Therefore, a threshold classification is preferable.

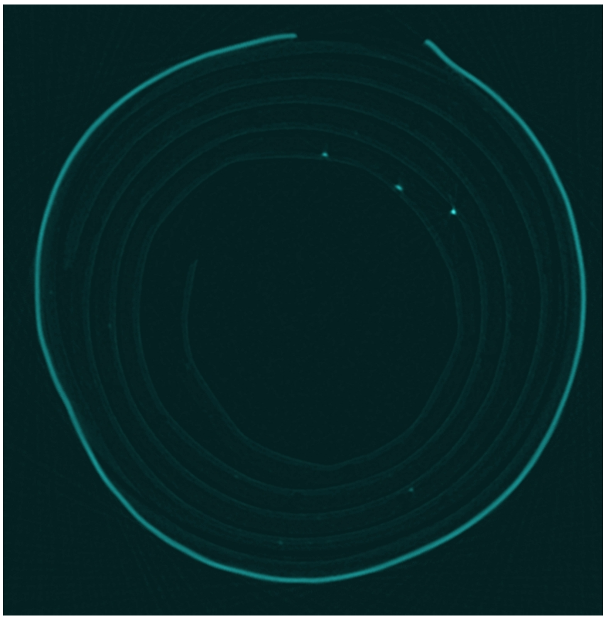


Figure 8 A section of the micro tomographic imaging of a sample. The filter membrane is rolled in a steel cylinder, only a few dirt particles can be seen. Gray value image, colored to enhance visualization.

4 Application to technical cleanliness

To guarantee the required level of technical cleanliness, components must be analyzed during the production process. Indeed, it is mainly on the factory line that residual dirt collects on the surface of mechanical parts. Thence intervening before the assembling process is of crucial importance. The dirt particles are collected from the surface of the components on a filter membrane. This is then rolled and inserted in a plastic or steel cylinder to be imaged via micro computed tomography. The plastic cylinder will not appear in the resulting image, while the steel cylinder will. Steel is indeed used as a reference material to calibrate the materials in the sample on the basis of their gray values.

In Figure 8, one can see a section of the volume image produced by μCT. The steel cylinder has a high gray value, while the filter membrane a very low one. The dirt particles are usually quite sparse and in this image only three can be clearly seen (brighter points on the membrane). Once the data are binarized, the steel cylinder can be removed. In Figure 9, a volume rendering of the corresponding binarized data set is presented. Only the dirt particles occur.

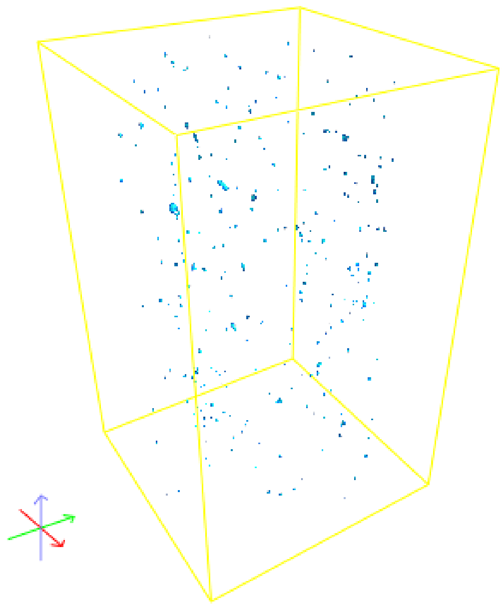


Figure 9 3d rendering of a sample of dirt particles. Binarization from a tomographic image, pixel size = 7.41 μm, image size 8.75 x 8.75 x 9.44 mm. Visualization by MAVIparticle [5].

The visualized sample consists of only 365 particles. In order to have a more relevant sample, in the following we consider a larger dataset formed by 1061 particles. The mean volume is 2.49·10^6 μm^3 (259 pixels). Using the thresholds mentioned in Section 3.3, the particles are labeled as 'small', 'medium' or 'large' depending on the numbers of pixels of which they are formed. Here there are 469 small, 406 medium and 186 large particles. The small particles will not be analyzed further. In order to classify medium and large particles, we exploit the minimum volume bounding box and the isoperimetric shape factors, respectively. Despite the particles shapes are not as regular as the sample particles above considered, the geometric parameters can still be used to produce a reliable classification.

In Figure 10, the aspect ratios of the minimum volume bounding boxes of the medium particles are drawn in the Zingg-diagram. We define a fiber a particle with width and thickness comparable (ratio $<$ 2/3) and length much larger than the width, that is ratio of width over length smaller than 1/10, as the standards in technical cleanliness require. With these thresholds, there are 216 granular particles, 190 chips and no fibers among the medium particles in the sample. For what concerns the large particles, instead, the shape factors f_1 and f_3 are taken into account as described in Section 3.2. In Figure 11 each isoperimetric shape factor is plotted against the volume. The classification is represented by the different colors. There are 9 fibers, 66 chips and 111 granules. The largest particles in the sample are fibers.

Gathering all the data regarding medium and large particles, we see that the sample is composed of 55.2% granules, 43.3% chips, and only 1.5% fibers. However, though fewer, fibers constitute 13.7% of the total volume.

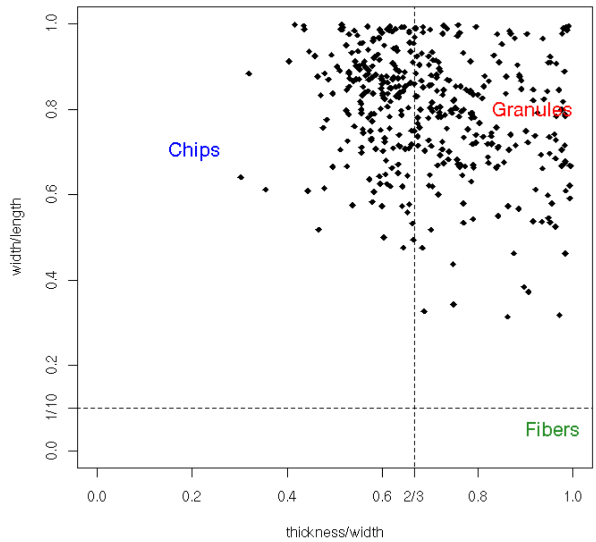


Figure 10 Zingg-diagram of the medium particles in the sample.

Once the classification is fulfilled, one can further analyze the sample by means of the other parameters introduced. All particles have Euler number equal to 1, i.e. no particles have holes or tunnels. Moreover, one could be interested in knowing how the largest fibers are arranged in space. With this aim, size parameters can be compared, for example length and elongation or thickness and maximal local thickness, to see how twisted the fiber is. If the convex factor is much smaller than 1, then the fiber might be curved, the more it is, the largest the elongation index will be.

In Table 2, three of the largest particles in the sample are shown and their features are displayed. Each of them belongs to a different class. Since they are all large particles, the classification is based on the isoperimetric shape factors. Moreover, the elongation index is also typically different for each particle, being 10 times larger for the fiber than for the granule. None of the particle present a concavity, though the fiber has a very rough surface, thus the convexity factor is equal 0.91. The mean gray values of the particles do vary strongly, indicating different material compositions.

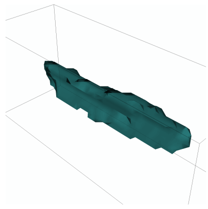
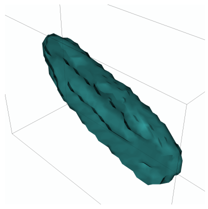
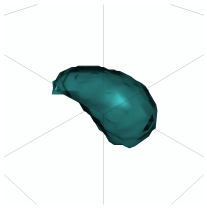
			
pixel size = 9.88 μm	fiber	chip	granule
mean gray value	264	48.47	410
volume [px]	823	2968	1023
volume [μm^3]	793 726	2 862 429	986 612
Euler number	1	1	1
length [μm]	341.18	393.81	149.05
width [μm]	86.44	160.56	132.93
thickness [μm]	49.14	74.44	91.45
shape factor f_1	0.48	0.56	0.86
shape factor f_2	0.19	0.33	0.73
shape factor f_3	0.44	0.69	0.89
elongation [μm]	340.86	398.56	166.38
elongation index	26.12	11.58	2.44
maximal local thickness [μm]	4.47	7.21	9.17
convexity factor	0.91	0.95	0.97

Table 2 Features of three large particles from the sample. Images and computation of characteristics with MAVIparticle [5].

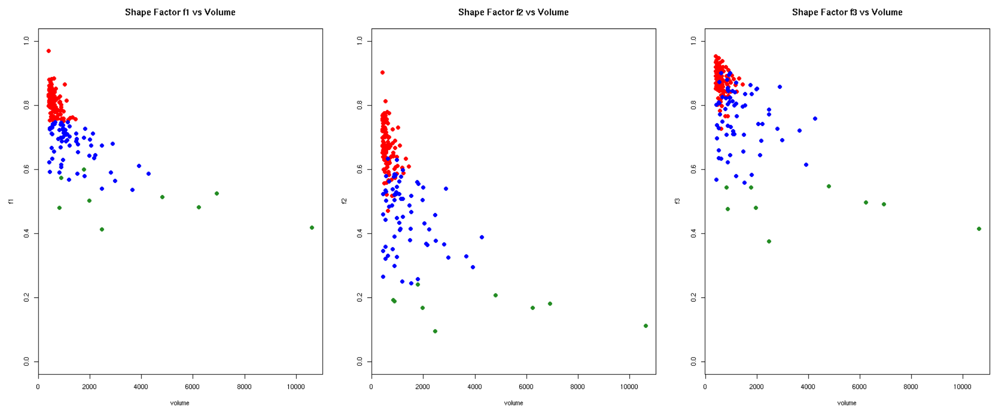


Figure 11 Shape factors of large particles in the sample plotted over the volume and classification. Each color represents a class: green for fibers, blue for chips and red for granules.

5 Conclusion

Spanning from classical geometric methods via mathematical morphology to stochastic geometry, a variety of shape descriptors has been collected. That way, 3d shapes can be characterized by well defined parameters. Given this unambiguous description of arbitrary objects, a classification can be obtained, too. We propose two approaches to classify objects. One based on the size, i.e. on the measure of the edges of the minimum volume bounding box, the other based on the isoperimetric shape factors. It is possible to merge the two approaches by observing that the size classification is more significant for small objects, while the shape factor classification is more reliable for large ones.

In Section 4, an application in the field of technical cleanliness has been outlined. The method has proven to be effective: the particles' shape in the sample can be characterized and a classification into three classes can be efficiently performed. As a result, the residual dirt can be analyzed and the danger that it can cause can be estimated.

Nevertheless, technical cleanliness is not the only possible application field. Indeed, the parameters proposed convey a thorough characterization of any type of three dimensional shape and can therefore be used in other application scenarios. Once the geometric features of the objects are calculated, the classification can be easily adapted as desired.

6 Acknowledgment

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References

[1] ASTM D4791. Standard test method for flat particles, elongated particles, or flat and elongated particles in coarse aggregate, 2010.

[2] ASTM F1877. Standard practice for characterization of particles, 2003.

[3] G. Barequet and S. Har-Peled. Efficiently approximating the minimum-volume bounding box of a point set in three dimensions. *Journal of Algorithms*, 38(1):91 – 109, 2001.

[4] M. de Berg, O. Cheong, M. van Kreveld, and M. Overmars. *Computational Geometry: Algorithms and Application*. Springer, 2008.

[5] Fraunhofer ITWM, Department of Image Processing. MAVIparticle – modular algorithms for volume images – particle analysis. `http://www.mavi-3d.de`, 2011.

[6] H. Freeman and R. Shapira. Determining the minimum-area encasing rectangle for an arbitrary closed curve. *Commun. ACM*, 18:409–413, July 1975.

[7] K. Huebner, S. Ruthotto, and D. Kragic. Minimum volume bounding box decomposition for shape approximation in robot grasping. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, pages 1628 –1633, May 2008.

[8] C. Lantuejoul and F. Maisonneuve. Geodesic methods in quantitative image analysis. *Pattern Recognition*, 17(2):177 – 187, 1984.

[9] G. Matheron. *Random Sets and Integral Geometry*. Wiley, New York, 1975.

[10] L. A. Merson-Davies and F. C. Odds. A morphology index for characterization of cell shape in candida albicans. *Journal of General Microbiology*, 135(11):3143–3152, 1989.

[11] R. S. Montero and E. Bribiesca. State of the art of compactness and circularity measures. *International Mathematical Forum*, 4(25-28):1305–1335, 2009.

[12] J. Ohser and F. Mücklich. *Statistical Analysis of Microstructures in Materials Science*. Wiley, Chichester, New York, 2000.

[13] J. Ohser, W. Nagel, and K. Schladitz. The Euler number of discretized sets – on the choice of adjacency in homogeneous lattices. In K. R. Mecke and D. Stoyan, editors, *Morphology of Condensed Matter*, volume 600 of *LNP*, pages 275–298, Berlin, 2002. Springer.

[14] J. Ohser and K. Schladitz. *3d Images of Materials Structures – Processing and Analysis*. Wiley VCH, Weinheim, 2009.

[15] J. O'Rourke. Finding minimal enclosing boxes. *International Journal of Parallel Programming*, 14:183–199, 1985. 10.1007/BF00991005.

[16] E. Parra-Denis, C. Barat, D. Jeulin, and C. Ducottet. 3d complex shape characterization by statistical analysis: Application to aluminium alloys. *Materials Characterization*, 59(3):338 – 343, 2008.

[17] C. Petres, Y. Pailhas, Y. Petillot, and D. Lane. Underwater path planing using fast marching algorithms. In *Oceans 2005 - Europe*, volume 2, pages 814 – 819 Vol. 2, June 2005.

[18] C. Redenbach, R. Ohser-Wiedemann, R. Löffler, T. Bernthaler, and A. Nagel. Characterization of powders using micro computed tomography. *PPSC*, 2009. Submitted.

[19] D. Stoyan, W. S. Kendall, and J. Mecke. *Stochastic Geometry and Its Applications*. Wiley, Chichester, second edition, 1995.

[20] A. Velichko, C. Holzapfel, A. Siefers, K. Schladitz, and F. Mücklich. Unambiguous classification of complex microstructures by their three-dimensional parameters applied to graphite in cast iron. *Acta Materialia*, 56:1981–1990, 2008.

[21] T. Zingg. *Beitrag zur Schotteranalyse*. Mineralogische und Petrologische Mitteilungen 15, Zürich, 1935.

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