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Alexander Smirnov, Nikolay Shilov, Andrew Ponomarev, Thilo Streichert, Silvia Gramling, et al.. Analytical Detection of a Mesh Vertex Being on the Inside of a Round Through-Hole. 18th IFIP International Conference on Product Lifecycle Management (PLM), Jul 2021, Curitiba, Brazil. pp.215-224, 10.1007/978-3-030-94399-8_16 . hal-04195220

HAL Id: hal-04195220

<https://inria.hal.science/hal-04195220v1>

Submitted on 4 Sep 2023

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Analytical Detection of a Mesh Vertex Being on the Inside of a Round Through-Hole

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Abstract. Design is one of the first stages of the PLM process. However, for each newly designed mechanical part, it is essential to test it for durability in different usage conditions (‘stress evaluation’). Before the production of real test samples, it is reasonable to check the model numerically via the 3D Finite Element Simulation method. Even though the simulation produces good results, in certain conditions these can be unreliable. As reported in a previous publication, the reliability of results was checked by the developed AI models. However, it was noticed that due to the modeling specifics the developed models could not distinguish between unreliably evaluated vertices belonging to round through-holes, and reliably evaluated vertices located on inner radiuses. This required development of an algorithm capable to distinguish between these cases. The paper presents the developed analytical algorithm based on geometrical computations and ray tracing. The results are illustrated on components from the automation equipment producer Festo SE & Co KG.

Keywords: Hole detection · Mesh processing · Analytical evaluation of mechanical parts

1 Introduction

Design is one of the first stages of the PLM process. However, newly designed mechanical parts that are subject to various loads and stresses during operation require careful testing for durability in different usage conditions (‘stress evaluation’). Before real test samples are produced, the model is usually tested numerically, which makes it possible to save on time and expenses. In the considered scenario, this numerical test is done via finite element simulations [1–3]. This is an essential PLM step. However, stress simulations may produce results that can be interpreted only by experts. Nonreliable results (“failures”) can arise from, for example:

- overlapping components in the imported CAD file,
- contact of different (rigid) components,

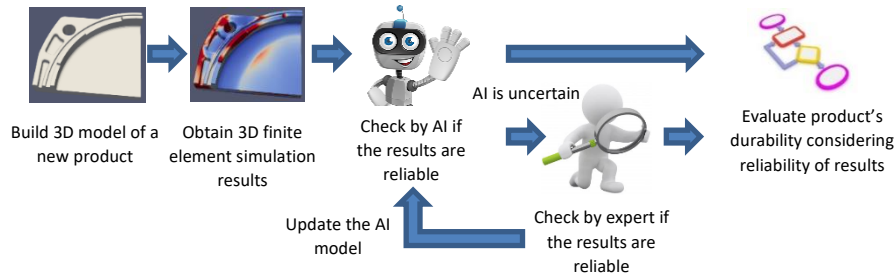


Fig. 1. The automated process of evaluating new product's durability [4].

- equal treatment of tensile and compressive stress.

Manual validation of the simulation results' reliability is a time-consuming process. Besides, the participation of humans in this process may lead to errors since the interpretation of the results is not always easy.

In [4] the authors proposed an approach to automate this process using various AI & ML models (fig. 1). The paper considered various approaches to the classification of mechanical parts represented as 3D meshes including (i) machine learning approach, relying on geometric feature engineering, (ii) 2D convolutional neural networks, and (iii) 3D convolutional neural networks. The experiments showed that for the available dataset the accuracy of the classification was very high. However, the further usage of the developed approach in production and the introduction of new types of mechanical parts revealed a problem in the developed models.

The problem was in the way of analyzing relevant mesh vertices. Since the analyzed parts were rather big and complex, only fragments of parts were considered for the classification. The introduction of bigger parts with more complex structures showed that a fragment around a vertex lying in a hole of a relatively large radius was indistinguishable from that lying in an inner radius, which is not a part of a hole (fig. 2). However, the simulation results for the former vertices should be considered unreliable, while those for the latter vertices are reliable. Increasing the size of the fragment was not considered as an option since in the future the approach is planned to be applied to parts of various sizes.

As a result, it was decided to develop an approach that will identify if a given mesh vertex belongs to a hole. Besides, it will be necessary to identify if it is a round through-hole since otherwise, the simulation results are treated differently. The contribution of the paper is an algorithm solving the above task analytically, which is independent of the component and hole sizes. The results are illustrated via a running example based on components from the automation equipment producer Festo SE & Co KG.

The paper is structured as follows. Sec. 2 describes the task set and available dataset. It is followed by a state-of-the-art review. Sec. 4 presents the developed approach. The results are summarized in the "Results and Conclusions" section.

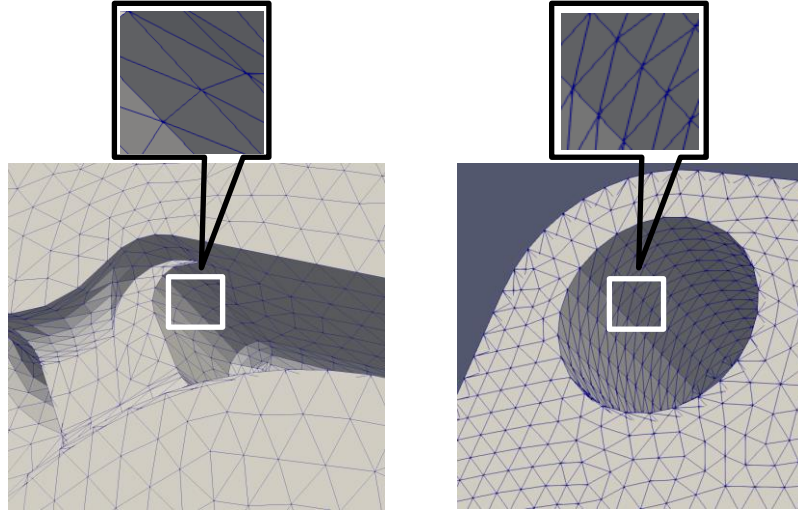


Fig. 2. Fragments of the inner radius (left) and the hole (right).

2 Problem Definition

The source data for the described classification problem is stored as VTU mesh files [5]. Depending on the complexity and curvature of a part the number of points (vertices) per inch can be different (the smoother the surface, the lower density of the points is used and vice versa). The average number of vertices in a model is around 5000 but it differs significantly from model to model. For symmetrical components, the models can represent 1/2 or 1/4 part of the component. However, if the component is not symmetrical, the model represents the whole part.

All the components have gone through the procedure of stress evaluation via the finite element simulation. As a result, the vertices of the components are assigned with the so-called safety factor (SF), which is defined as the ratio between the allowable mechanical load and the mechanical load obtained as a result of the simulation. That means that the higher the SF, the more robust is the simulated component. For this reason, the SF is used as the metric of meeting the mechanical requirements by the analyzed part. Since different simulations can be applied to a part, there can be several samples related to the same part but having different SF evaluations.

To make the decision regarding the stability of the part, the minimum SF value is considered to be above a certain threshold. That is why it is important to analyze if the calculated SF is reliable or not. The reliability check is done in an iterative way: If the vertex with global minimum SF is not reliable, the vertex with the second-lowest local minimum SF is validated, and so on until a reliable minimum is found. This reliable SF minimum has to be above the given threshold for the part to be considered to be mechanically stable. Otherwise, it needs to be re-engineered.

In the available dataset, the labels refer to the global minimum. As a result, only the global minima are used for model training and checking.

The dataset consists of 1280 simulation results manually classified by an expert based on the evaluation of the reliability of the global minimum. 21 of them are classified as unreliable due to the minimum SF vertex being inside a round through-hole.

3 State of the Art Review

The problem of detecting holes in 3D components has been studied by researchers though there are not many works on this topic.

The first group of approaches is based on grouping vertices that form a surface. For example, the authors of [6] divide the model into components via an analysis of planes that form these components. In work [7] partially written by the same authors, the algorithm has been improved mainly based on plane and contour identification. These algorithms work well for models with sharp contours [8] as those presented in the above works. However, in our work, the parts mostly produced via casting often do not have contours between different planes (fig. 3). As a result, such approaches cannot be efficiently used to solve the problem at hand.

Another group of approaches is based on cutting parts with planes and analyzing resulting sections [9]. Though not very computationally expensive, this approach is quite powerful. It is used for a number of tasks related to the analysis of 3D shapes for various purposes. For example, in [10] cross-sections are used for skeleton and shape matching. The closest to the considered task work is presented in [11]. The authors cut the part with multiple random planes in order to identify holes. This approach seems to be the most suitable for the given problem though it is necessary to avoid building multiple cutting planes for the performance reason.

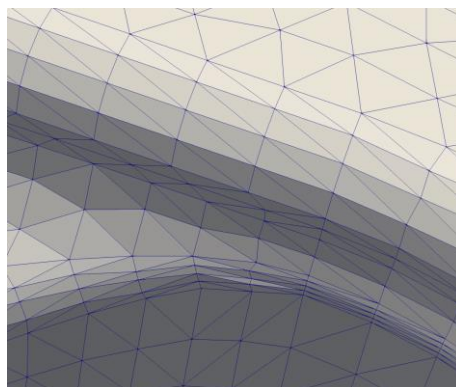


Fig. 3. Soft borders of a part produced via casting.

4 Approach

The developed approach is based on three main steps. First, a symmetry axis of the possible round hole is found. Then, the shape of the hole is analyzed in order to define if it is an internal round hole. Finally, a check is carried out if the hole is through or blind. Below, these steps are described in detail.

4.1 Finding the symmetry axis of the possible hole

Let's assume that the considered vertex (point A) is on the component's surface inside a hole. In order to find the symmetry axis, the following calculations are carried out. Here, a tetrahedral mesh is considered as an example, but the algorithm does not depend on the type of the mesh (it can be equally applied to, for example, a hexahedral mesh).

1. Consider faces that are adjacent to point (A).
2. Calculate centers (B_0, \dots, B_5) and normals of these faces B_0C_0, \dots, B_5C_5 .

Fig. 4 illustrates the faces adjacent to point A , and their centers. Arrow B_0C_0 in fig. 5 illustrates an example of such a normal to the corresponding face.

3. Calculate vectors N_0, \dots, N_5 , which are orthogonal to the normal of the analyzed point and to the normal of the faces.

An example of such normal (N_0) to vectors AC_A and B_0C_0 is shown in fig. 5. If this is not possible (the normals of faces and normal of the analyzed point are parallel) the analyzed surface is considered to be a plane, which cannot be a part of a hole; so the algorithm stops.

4. Calculate the mean vector N to vectors N_0, \dots, N_5 taking into account the direction.

This vector is considered to be parallel to the center line (symmetry axis) of the hole. The reason for calculating the mean is that the meshes are not always perfect but built with a certain inaccuracy (imperfections / irregularities due to the finite element mesh), and the calculation of the mean is aimed at reducing such an inaccuracy.

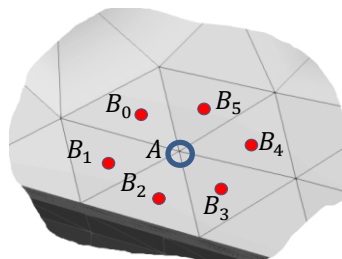


Fig. 4. Centers of surfaces adjacent to point A .

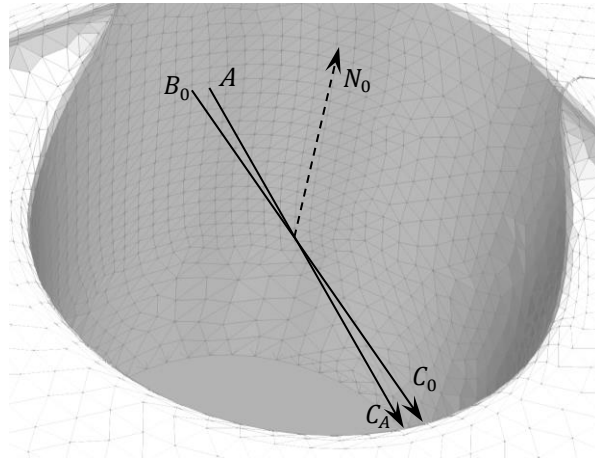


Fig. 5. Calculating the symmetry axis of the hole.

4.2 Analysis of the shape of the hole

When the direction of the center line of the supposedly existing hole is determined, it is possible to evaluate its shape and to make sure that it is a hole and not a cylinder with the analyzed point being on the outer surface. This is done via building the section of the part by the plane defined by the analyzed point A and vector N . An example of such a section is shown in fig. 6.

Using this section the following tasks are solved:

1. Check if the point is on a section fragment border.

Since the border is actually a set of points (S_0, \dots, S_5 in fig. 6), this check is done via measuring the distance between the analyzed point A and the two nearest segments of the border (S_1S_2 and S_2S_3 in fig. 6) and comparing it to a given threshold. In order for

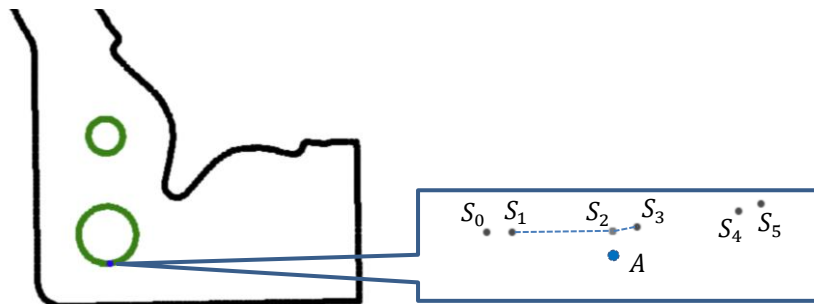


Fig. 6. Measuring if point A belongs to a section fragment border.

the algorithm to be robust against the size of the analyzed parts, the thresholds are suggested to be proportional to the mean size (calculated as a cubic root of the bounding box's volume) of the analyzed part (e.g., 0.0005 of the mean size of the part)

2. Check if this section fragment is an inner element of the part.

This is done via the simple calculation of the enclosure level of the section (inner elements have even level numbers and outer elements have odd level numbers). In fact, in the training set, the maximum enclosure level is 2.

3. Check if this section fragment is a circle.

Since the normal of the cutting plane is aligned with the symmetry axis of the hole, the section fragment corresponding to a round hole is a circle. The check is done via approximating the points of the section fragment with a circle and measuring the difference between the distances between the points and the center of the circle with the radius of the circle. These differences are compared to a given threshold, which is proportional to the radius of the circle (0.1 of the radius).

If all of the above three conditions are met, the analyzed point is considered to be on a surface of a round hole.

Unfortunately, there are some parts, where one side of a hole is higher than the other side, and if the analyzed point happens to be on the higher side (fig. 7), it is not located on a section fragment corresponding to a circle. For this purpose, the cutting plane is shifted "up" and "down" along normal N , and the projection of point A to the corresponding plane along N is analyzed.

This procedure is illustrated in fig. 8. In the fragment of the section formed by the original cutting plane (fig. 8, a), the analyzed point (indicated with an arrow) is on a border, which is not a circle. With one step "down" (the size of the step is defined proportionally to the mean size of the part, namely 0.03 of the mean size), the section looks like that shown in fig. 8 (b). Finally, after several steps, the goal is reached: the

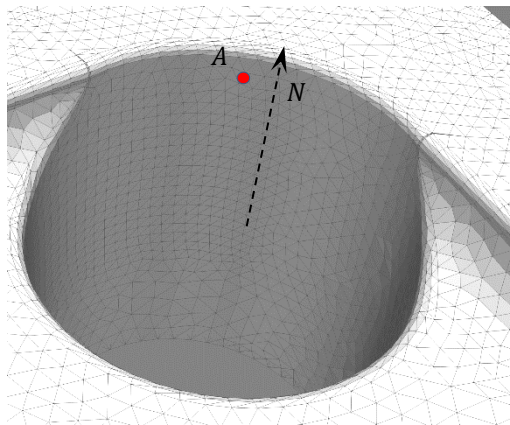


Fig. 7. Point located on a higher side of a hole.

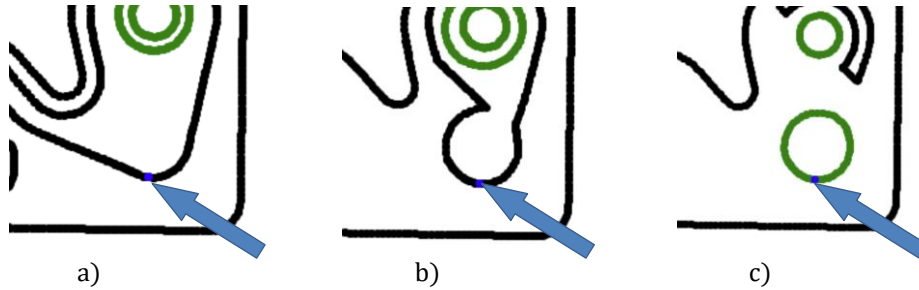


Fig. 8. Centers of surfaces adjacent to point A .

projection of the analyzed point is located on a round fragment (fig. 8, c). The checks related to shifting the cutting plane “up” and “down” stop as soon as the point’s projection is not located on a border anymore.

4.3 Checking if the hole is a through-hole or a blind hole

Finally, it is necessary to make sure, that the identified hole is a through-hole. The above procedures will identify that the point is located in a round hole not only for through-holes but also for situations shown in fig. 9 (“blind holes”). However, simulation results for such points are considered to be reliable and they should not be detected with the proposed algorithm. This check is done via the following algorithm (fig. 10):

1. Find point A' , located on the normal of the analyzed point A , at the distance of Δ from it.

The value of Δ is selected proportional to the mean size of the part (e.g., 0.002 of the mean size).

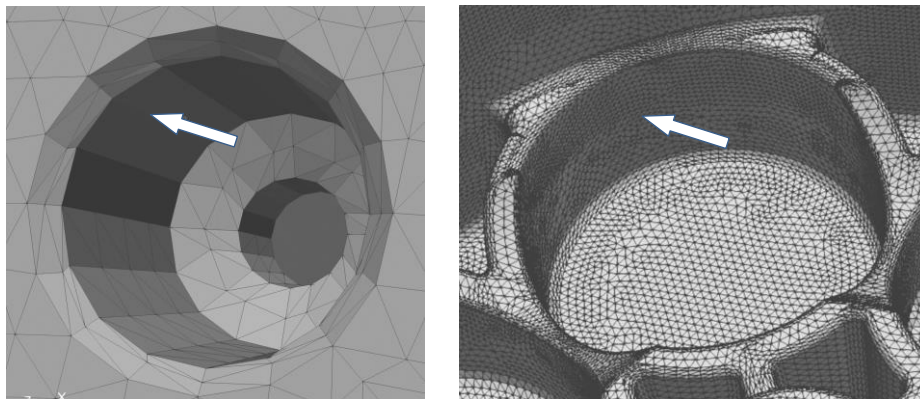


Fig. 9. Blind holes (analyzed points are indicated with arrows)

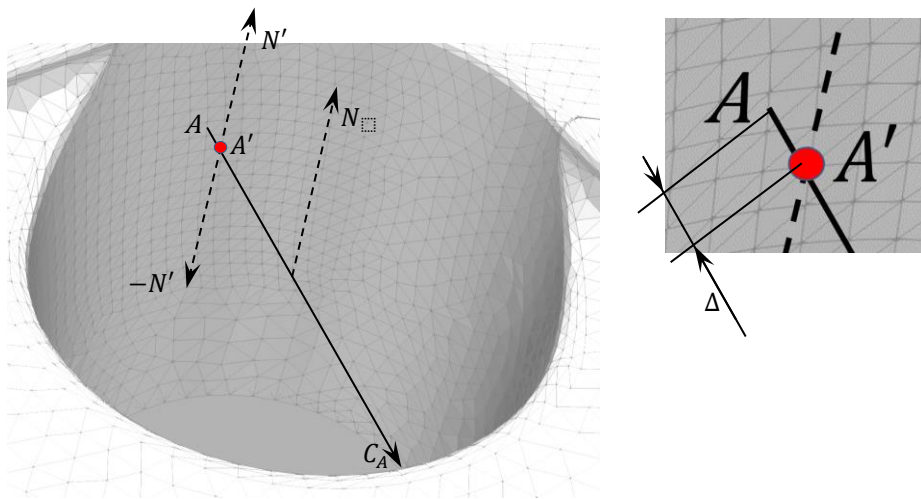


Fig. 10. Checking if the hole is a through-hole

2. Find vectors N' and $-N'$ starting from point A' and aligned with previously defined vector N (corresponding to the center line of the hole).
3. Check if rays starting in point A' and aligned with N' and $-N'$ do not intersect the part.

If this check is successful, the point is considered to be in a round through-hole.

5 Results and Conclusions

The paper proposes an algorithm for identification if a given point in a 3D mesh lies on a surface of a round through hole or not. It is a part of an essential PLM step aimed at checking the durability of new mechanical parts in different usage conditions before real test samples are produced.

The proposed algorithm is based on analyzing mechanical part's sections built by cutting the part via specifically defined planes, as well as ray tracing. The algorithm testing was done for a labeled dataset consisting of 1280 simulation results. In 21 of them, the analyzed point is located in a round through hole. The processing of the whole dataset took around 39 minutes 23 seconds (about 1.9 seconds per sample) on an Intel Core i9-10900X 3.70GHz CPU and produced the perfect result (no errors).

The potential limitations of the algorithm are as follows:

1. The quality of the results depends on the parameters used in the algorithm. Currently, all of them are defined in relation to the mean size of an analyzed part. Unfortunately, these parameters are a compelled means to overcome inaccuracies related to the models themselves (imperfections / irregularities due to the finite element mesh).
2. Checking if the hole is through might fail for complicated shapes, however, the analyzed dataset does not include such parts.

Despite the above limitations, the algorithm showed good results confirmed by the experiment and is successfully applied in the company.

Acknowledgments. The paper is due to the collaboration between SPC RAS and Festo SE & Co KG (the case study), and State Research no. 0073-2019-0005 (the framework and methods).

References

1. Reddy JN (2009) *An Introduction to the Finite Element Method*, 3rd ed. McGraw-Hill
2. Fine L, Remondini L, Leon J-C (2000) Automated generation of FEA models through idealization operators. *Int J Numer Methods Eng* 49:83–108. [https://doi.org/10.1002/1097-0207\(20000910/20\)49:1/2<83::AID-NME924>3.0.CO;2-N](https://doi.org/10.1002/1097-0207(20000910/20)49:1/2<83::AID-NME924>3.0.CO;2-N)
3. Boussuge F, Léon J-C, Hahmann S, Fine L (2015) Idealized models for FEA derived from generative modeling processes based on extrusion primitives. *Eng Comput* 31:513–527. <https://doi.org/10.1007/s00366-014-0382-x>
4. Smirnov A, Shilov N, Ponomarev A, et al (2020) Validating Results of 3D Finite Element Simulation for Mechanical Stress Evaluation using Machine Learning Techniques. In: *Proceedings of the International Conference on Innovative Intelligent Industrial Production and Logistics*. SCITEPRESS - Science and Technology Publications, pp 13–23
5. Kitware Inc. (2005) *File Formats for VTK Version 4.2*. <https://vtk.org/wp-content/uploads/2015/04/file-formats.pdf>. Accessed 16 Jun 2020
6. Wang Y, Liu R, Endo S, Uehara Y (2010) A Novel 3D Model Segmentation Approach. In: *Computer Graphics and Imaging*. ACTAPRESS, Calgary, AB, Canada
7. Wang Y, Liu R, Li F, et al (2012) An effective hole detection method for 3D models. In: *2012 Proceedings of the 20th European Signal Processing Conference (EUSIPCO)*. IEEE
8. Yuan Yao, Lingxia Kong, Qingxi Hu (2009) A boundary identification method for 3D closed triangle mesh. In: *2009 IEEE 10th International Conference on Computer-Aided Industrial Design & Conceptual Design*. IEEE, pp 870–873
9. Umetani N, Schmidt R (2013) Cross-sectional structural analysis for 3D printing optimization. In: *SIGGRAPH Asia 2013 Technical Briefs on - SA '13*. ACM Press, New York, New York, USA, pp 1–4
10. Sellamani S, Muthuganapathy R, Kalyanaraman Y, et al (2010) PCS: Prominent Cross-Sections for Mesh Models. *Comput Aided Des Appl* 7:601–620. <https://doi.org/10.3722/cadaps.2010.601-620>
11. Muraleedharan LP, Kannan SS, Karve A, Muthuganapathy R (2018) Random cutting plane approach for identifying volumetric features in a CAD mesh model. *Comput Graph* 70:51–61. <https://doi.org/10.1016/j.cag.2017.07.025>