An edge identification method for gap in-line measurement based on fillet assumption

Qijian Zhao, Pengfei Sun, Yu Cao and Liangxin Zhang

Abstract
The optical measurement technology could reduce manual work and improve quality in assembly. The confocal scanning scheme is proposed to measure the narrow gap in-line but it is hard to identify the edges of a gap. This paper proposed an edge definition and presented an edge identification method for gap measurement. The edge profile is defined as a part of a circle, which could be identified by the shutter time feature. The defined edge point could be calculated by fitting the edge profile, and then the width of a gap section is calculated by two edge points. The width of a gap can be evaluated by the average of several gap sections. The experimental results indicate that the repeatability of the method is less than 2 \( \mu \text{m} \) and the precision of the measurement is higher than \( \pm 2.5 \mu \text{m} \). The proposed method is feasible for in-line measurement application in assembly.

Keywords
Edge identification, fillet assumption, gap evaluation, confocal scanning, in-line measurement

Introduction
The assembly gap is usually applied to indicate the assembly quality in some assembly task such as the car body assembly, tip clearance in turbine, clearance of Gyro motor, etc. These gaps are measured for adjustment or record by manual gauge in past. To reduce the manual work and improve assembly quality, the optical measurement methods are applied for automation measurement such as vision measurement and line laser scanning. The inductive sensor is also applied for the gap measurement but it is improper for in-line measurement.

The measurement result of the vision measurement and line laser scanning is difficult to satisfy the measurement requirement as the gap is narrow (< 100 \( \mu \text{m} \)). The image calibration and edge identification limit the precision of the vision measurement; the related works show that improving precision needs plentiful data and complex intelligent algorithm. However, the data is often lack or limit in some cases. The line laser scanners have been applied in the in-line measurement of the car body assembly, which the line laser scanner could measure the width of a gap in \( X \) direction and the height of the surface in \( Z \) direction. The resolution of the line laser scanner in \( X \) direction is much lower than \( Z \) direction, which is unable to obtain high-precision measurement results.

Higher precision measurement method is required in some engineer cases. The external gap of the container used in underwater vehicle should be controlled as it affects the streamline. This external gap ranges arrange 10–100 \( \mu \text{m} \) and should be measured to evaluate whether the shell is assembled tightly. To satisfy this requirement, the measurement range should cover 10–100 \( \mu \text{m} \) and the precision should be higher than 5 \( \mu \text{m} \).

The proposed measurement method for the gap
A confocal scanning based method is proposed to measure the narrow gap in line. The in-line measurement scheme for a gap is illustrated in Figure 1, which consists of a high precision movement mechanism, a confocal chromatic displacement sensor and the fixture. The high precision movement mechanism is applied for...
counting the length between edges of the gap. The confocal chromatic displacement sensor is mounted on a movement mechanism to identify the edges of the gap.

The gap measurement steps are:

1. Fixture of the movement mechanism is firstly mounted near to the workpieces so that the measured surface is in the measuring range of the sensor, and the gap is in the movement range of the mechanism.
2. Mechanism is moved through the gap and the sensor records displacement.
3. The measurement data of the sensor is evaluated for identifying the edges of the gap.
4. The movement velocity and time between the edges of the mechanism are applied to calculate the width of the gap.

The crucial step of this method is the identification of the gap edges. There are many factors (e.g. form error of the surface, measurement angle of the sensor, etc.), which could make the edge vague. With the effect of these factors, some data arrange edge could be unreliable. So the measured data cannot be applied immediately. This paper proposes an identification method of the edge to solve this problem.

The related works of the edge identification

The edge of a workpiece is obtuse and vague in microscope. The research of the Groeger et al. shows that the real edge is a zone and the nominal edge is a line in the zone (see in Figure 2), which the shape of the real edge zone is important to the gap measurement.

Some works focus on the shape of cutting edge, since the shape could affect the efficiency of cutting. Some works of the cutter indicate the edge of a workpiece could be approximately treated as a part of circle or ellipse in a section, for example, Lv et al. explored the effects of cutting edge radius on cutting force, tool wear and life in milling. It is called fillet assumption in this paper and some contributions have been made based on this assumption. Vopát et al. used the cutting edge radius to indicate the performance of plasma discharges in electrolyte. Bernard et al. applied the edge radius to study the thermo-mechanical effect on cutting, which shows the larger edge radius could increase the roughness. Arefin et al. established a contact relationship between the tool edge and the workpiece, which the cutting performance of vibration-assisted machining is evaluated based on the relationship. Luo et al. developed a novel mechanistic model for carbon fibre-reinforced plastics/Ti-6Al-4V stacks based on the character of cutting edge radius. Li et al. adopts the cutting edge radius and the workpiece material to investigate the size effect in micro end milling. Yang et al. formulated an analytical modeling of residual stress in orthogonal cutting by tool edge radius effect. These contributions show that the assumption is reliable and we could also apply it for the edge identification.

The shape of an edge could be measured by optical method or even microscope, which is evaluated by the edge radius. Zhang et al. proposed a measurement method for high-precision cutting edge radius of diamond tools by atomic force microscope. Song et al. proposed a new method for hard whirling tool edge reconstructing based on fractal interpolation, in which the edge radius is measured and reconstructed in a section. Zhao formulated a modelling and detection method for cutting edge radius, which could predict the radius precisely. Wu et al. established an in-situ measurement system to measure the waviness of rounded cutting edge of diamond tool, which shows the edge could be measured in-line. The works of the edge measurement indicate that it is possible to measure a part of the edge zone by the optical measurement method such as the confocal scanning. The measurement precision of the optical method is limited by the measuring angle, unfortunately, the measuring angle is increasing when the measure points approaches the real edge. In
other words, the precision of the measuring results near the real edge is lower than the measuring results remote to the real edge.

To promote the precision of a gap by the optical method, this paper applied the fillet assumption to predict the profile near real edge based on the measuring points in edge zone, which the measuring angle of the measuring point is small. An edge definition is proposed and a gap evaluation method is also provided based on this definition.

**The edge identification method and the gap evaluation method**

**The assumption and the definition for the edge identification**

The definition of the edge is theoretical foundation of the edge identification. Firstly, two assumptions are applied to assure the accuracy and robust of the edge identification method.

**Assumption 1:** The section profile of the real edge could be approximately treated as a fillet.

**Assumption 2:** The geometrical error of the surface is small enough, which could not affect the form of the edge.

The actual form of the edge is important for the identification of the edge. The actual form of the edge can be approximate to a fillet in most of the cases. In other words, the section profile of an edge (as detailed in Figure 3) could be regarded as a part of circle.

The geometrical error in the assumption includes orientation error and form error. The orientation error means the angle of the out flank and gap flank, and the form error means the variation of the flank and edge surfaces. As illustrated in Figure 3, if the orientation error is large, then the gap could be narrow near the measured surfaces but wide inside. The geometrical error could make the width of the gap variation inside, in this case, the width of gap inside is hard to evaluation by the measurement method. The form error could affect the section profile of the real edge, if it is large enough, the form edge could be uncertain and difficult to identify.

According to these assumptions, the edge zone can be regarded as a small fillet and we could use a circle to fit the measured data of the section profile of an edge. And the edge zone and the nominal edge could be defined by definition 1 and 2, which is illustrated in Figure 4.

**Definition 1** (Definition of the Edge Zone): The surface between \( P_1 \) and \( P_2 \) is the edge zone, when the \( P_1 \) is the cross line or cross point between fitting profile and out flank and the \( P_2 \) is the cross line between fitting profile and gap flank.

**Definition 2** (Definition of the Nominal Edge): The nominal edge is a plane, which is perpendicular to the out flank and passes through the \( P_2 \), when the \( P_2 \) is the cross line between fitting profile and gap flank.

When the edge in a section is evaluated, the edge zone is a line profile, the nominal edge is a straight line and the \( P_1 \), \( P_2 \) are the cross points. Since the edge zone is treated as a fillet, the position of \( O_1 \) and \( P_2 \) is same in \( Z \) direction.

**The identification of the edge**

The gap measuring method could only capture a section of the edge zone in one measurement and the problem of the edge identification is to find the \( P_2 \) and the nominal edge, which is a cross point and a straight line respectively. But the \( P_2 \) could not be measured as the max measuring angle is limit.

To solve that, we proposed to fit the edge profile by a circle and calculated the position of \( P_2 \) based on the centre point and radius of the fitting profile.
Then the crucial problem is how to find the profile for fitting. The cross point $P_1$ is ambiguous, which could not identify by the measuring data. In addition, the measure precision decreases as the measuring angle increases and a part of the profile near measure limit is unreliable for fitting profile. The shutter time of the sensor is applied to solve this problem.

Four groups of data can be record in one measurement that is displacement, shutter time, optical intensity and peak. The sensor controls optical intensity in a small range by adjusting shutter time to keep the measurement result (displacement) reliable. The shutter time has upper limit which determined by the sampling frequency. When the measuring angle increases, the shutter time increases to keep the optical intensity. If the measuring angle is too large, the shutter time reaches upper limit and the optical intensity cannot keep in the range.

This principle could be applied to find out a point set of the edge profile, and the method to find the point set is detailed as:

1. When the shutter time of a measuring point is twice larger than the average value, the measuring point is regarded as a point of edge profile, which the point is marked as $x_1$.
2. When the shutter time of a measuring point reaches upper limit, the measuring point is considered as an unreliable point that would not be used for fitting edge profile, which the point is marked as $x_2$.
3. The measuring points between $x_1$ and $x_2$ are a point set of edge profile (detailed in Figure 5), and then the fitting profile could be fitted by this point set.

The point set is fitted to a circle by least square method. The position of the circle centre and the radius of the circle are obtained, which are marked as $O_1(x_o, z_o)$ and $R_1$. The position of the edge point $P_2$ is marked as $(x_{p2}, z_{p2})$ and is calculated as:

\[
\begin{align*}
    x_{p2} &= x_o + R_1 \\
    z_{p2} &= z_o
\end{align*}
\]

The edge point of each measured section could be identified by the method above.

**Gap evaluation method**

Based on the definition of the nominal edge, the width of a gap is the length between $P_2$ and $P_3$, where the $P_2$ and $P_3$ are the two cross lines between fitting profiles and gap flanks.

A gap should be measured several times in different sections. In a section, the $P_1$, $P_2$, $P_3$ and $P_4$ could be treated as points (detailed in Figure 6) and the width of the gap in this section could be calculated. As the width in several sections is obtained, the width of the gap could be evaluated by their average value.

The position of the $P_2$ and $P_3$ in a section could be calculated by the method in Section 2.2 that is:

\[
\begin{align*}
    x_{p2} &= x_{o1} + R_1 \\
    z_{p2} &= z_{o1} \\
    x_{p3} &= x_{o2} - R_2 \\
    z_{p3} &= z_{o2}
\end{align*}
\]

where $(x_{p2}, z_{p2})$ is the position of the $P_2$, $(x_{p3}, z_{p3})$ is the position of the $P_3$, $(x_{o1}, z_{o1})$ is the position of the $O_1$, $(x_{o2}, z_{o2})$ is the position of the $O_2$, $R_1$ and $R_2$ are the radii of the fillets.

Then the width of a gap in a section is calculated as:

\[
L_i = x_{p3} - x_{p2}, \quad i = 1, 2, \ldots, n
\]

And the width of the gap is:

\[
L = \frac{1}{n} \sum_{i=1}^{n} L_i
\]

**Experiment and discussion**

**Experimental setup**

The measurement system employed in the verification experiment is shown in Figure 7. The high-precision mechanism and the support of the confocal sensor are fixed on the table, which the movement direction of the mechanism is defined as $X$ direction. The confocal sensor is fastened on the support, which the direction of the sensor is defined as $Z$ direction. A standard gap sample is mounted on the mechanism. The out flank of the sample is in the measurement range of the sensor, which the out flank is perpendicular to the $Z$ direction.
The resolution, repeatability and the range of the apparatus is enough to verify the edge identification method and the gap evaluation method. The measuring range of the confocal sensor is from 20 to 23 mm in Z direction, the measuring resolution in Z direction is less than 50 nm and the sampling frequency range from 1 to 6000 Hz. The bidirectional repeatability of the mechanism is $0.5 \mu m$, the moving range is 13 mm in X direction and the velocity can be control in 0.001–5 mm/s, which means that the measurement system could measure the gap less than 12 mm. The precision and the stable ability of the mechanism are important, which determines the upper limit of the measuring precision of the method.

The developed software is applied to control the high-precision mechanism and confocal sensor synchronously. The velocity of mechanism, sampling frequency and movement range can be set by the software. The gap evaluation method is also integrated in the software so that the measurement results of a gap could be obtained.

Several standard gap samples are manufactured to verify the proposed the definitions and methods, which is should in Figure 8.

**Figure 6.** The width of a gap in a section.

**Figure 7.** The experimental setup for verification.

**Figure 8.** The standard gap samples for verification.
The standard gap sample is manufactured precisely and its accuracy is controlled in ±1 μm. Three samples are applied for verification and their nominal width values of the steps are 30, 50 and 70 μm. The proposed measurement method is applied to evaluate these gaps and the results are compared to the nominal values.

**Experimental results**

Some experiments are carried out for verification. Firstly, three points of each sample are measured three times. Then measurement result of each time is recorded. The measured width of the gaps and the variations are calculated to evaluate the repeatability. The measurement time results of a sample are recorded and listed in Table 1. The measured width in Table 1 is the average of the three measured results. The variation is the difference of the maximum result and minimum result.

As shown in Table 1, the measured width of the gap is 29.12 μm by calculating the average of the measured data.

The measured result of each point of three samples are recorded and listed in Table 2 and the variations are calculated to evaluate the robust.

The measurement data is processed to draw the profile and the edge profile for analysis. The fitting profile of a measured edge is plot in Figure 9, which includes the measurement points of the profile, fitted profile, circle centre and the evaluation of the edge point. The actual edge profile used for identification is a part of a circle profile according to the Figure 9.

**The experimental results analysis**

**The measurement repeatability.** To exclude the effect of the installation of the sample, several measurement results of a measured point are compared. The

---

**Table 1.** The measurement results of a sample.

| Points | Nominal width | $L_1$ | $L_2$ | $L_3$ | Measured width | Variation |
|--------|---------------|-------|-------|-------|----------------|-----------|
| 1      | 30.00         | 31.97 | 31.57 | 30.90 | 31.48          | 1.07      |
| 2      | 30.00         | 27.05 | 28.94 | 28.36 | 28.12          | 1.89      |
| 3      | 30.00         | 28.01 | 27.02 | 28.24 | 27.76          | 1.22      |

The unit of the width is μm.

**Table 2.** The measurement results of three samples.

| Gaps   | Nominal width | $L_1$ | $L_2$ | $L_3$ | Measured width | Variation |
|--------|---------------|-------|-------|-------|----------------|-----------|
| 1      | 30.00         | 31.48 | 28.12 | 27.76 | 29.12          | 3.72      |
| 2      | 50.00         | 48.49 | 49.27 | 46.51 | 48.09          | 2.76      |
| 3      | 70.00         | 70.43 | 74.81 | 71.43 | 72.22          | 4.38      |

The unit of the width is μm.

---

Figure 9. The fitting profile of a measured edge.
The estimation of edge identification and gap width evaluation. The Figure 9 shows that the fitting of the edge is accord with the definition proposed in Section 2.1, when the assumption is admissible, which means that the edge identification method is feasible. The precision of the gap width could be calculated compared to the nominal value in Table 2, which shows that the precision is higher than $6_{\pm 2.5}^{\mu m}$.

The measurement efficiency. The position of the sensor in X direction should be adjusted roughly first before the measurement. Then the travel range of the mechanism could be controlled in 0.5 mm. When the velocity is set as 50 $\mu m/s$ and measuring times of a point is set as 3, the measuring time of a point is 30 s.

The drawbacks of the evaluation method. The discussion above shows that the repeatability, robust, precision and efficiency are acceptable for in-line measurement application in assembly. However, there are still some drawbacks which limit its application.

For some reason, the edge profile might be irregular as illustrated in Figure 10. It could not be approximately treated as a fillet. So it is unsuitable for the proposed method to find out the edge point.

The proposed method could only evaluate the width around outflank but the manual gauge could evaluate the gap width inside. This limitation is also existed in other optical measuring method such as vision measurement.

The geometrical error of a gap could much affect the measurement result as one section of the gap is evaluated in an installation. Multiple sections should be measured to minimise this effect and it could decrease the measuring efficiency and import installation error.

**Conclusions**

An edge identification method and a gap evaluation method are proposed for a confocal scanning based in-line gap measurement. The edge definition is firstly formulated based on fillet assumption. The shutter time feature is applied to find the edge profile and the edge definition is used to find the edge point. Then the width of a gap in one section is calculated by the position of two edge points. Some experiments for verification are carried out and the results show that: (1) the edge identification method could find out the edge point; (2) the gap evaluation method could be used for in-line measurement of narrow gap.

The experiment results also shows some limitations that should be undertaken in future work: (1) the precision of the method decreases as the edge of a gap is irregular; (2) the geometrical error of the gap could not be evaluated by the method; (3) the experiment is finished by the standard gap samples which has not been verified in engineering cases.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Project supported by CAEP Foundation (CX20200012).

**ORCID iD**

Qijian Zhao https://orcid.org/0000-0001-6787-6726

**References**

1. Minnetti E, Chiariotti P, Paone N, et al. A smartphone integrated hand-held gap and flush measurement system for in line quality control of car body assembly. Sensors 2020; 20(11): 1–17.
2. Yu B, Ke H, Shen E, et al. A review of blade tip clearance-measuring technologies for gas turbine engines. Meas Control 2020; 53(3-4): 339–357.
3. Ren TQ, Liu ZR, Xu XD, et al. Clearance measurement equipment for gas lubricated dynamic pressure bearing of gyro motor. Int J Precis Eng Manuf 2019; 20(12): 2051–2060.
4. JJG 62-2017. Feeler gauges. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2017.
5. Peng T, Jing Y, Kong J, et al. A Maglev gap measurement method based on machine vision. In: Asia-pacific conference on image processing, electronics and computers (IPEC), Dalian, China, 2020.
6. Vlaeyen M, Haitjema H and Dewulf W. Error compensation for laser line scanners. *Measurement* 2021; 175. DOI: 10.1016/j.measurement.2021.109085.

7. Svenman E, Christiansson AK and Runnemalm A. Experimental validation of an inductive probe for narrow gap measurement based on numerical modelling. *Measurement* 2019; 146: 396–402.

8. Svenman E and Christiansson AK. Investigation of effects from realistic influences on inductive gap measurement. *Measurement* 2019; 139(1): 127–133.

9. Gao Y, Qiao T, Zhang H, et al. A contactless measuring speed system of belt conveyor based on machine vision and machine learning. *Measurement* 2019; 146: 396–402.

10. Huang S, Jin W, Ye M, et al. A vision based method for automated measurement of circular fiber cross-sections. *Measurement* 2020; 162. DOI: 10.1016/j.measurement.2020.107913.

11. Gu H, Meng L, Lin Y, et al. The structure optimization of unmanned underwater vehicle’s wedge-ring joint based on the response surface method. In: *OCEANS 2016*, Shanghai, 2016. DOI: 10.1109/OCEANSAP.2016.748599.

12. Prause K, Thiele S, Herkommer AM, et al. Highly miniaturized endoscopic spatial confocal point distance sensor. *Opt Eng* 2020; 59: 1.

13. Denkena B and Biermann D. Cutting edge geometries. *CIRP Annals* 2014; 63: 631–653.

14. Groeger S, Segel F, Uhlmann E, et al. Definition of edges in correlation to abrasive flow machining as a finishing process. *Surf Topogr Metrology Properties* 2018; 6(3): 034001.

15. Burek J, Zylka L, Plodzien M, et al. The influence of the cutting edge shape on high performance cutting. *Aircr Eng Aerosp Technol* 2018; 90(1): 134–145.

16. Sharma A, Ranjan P and Balasubramaniam R. Investigation of effect of uncut chip thickness to edge radius ratio on nanoscale cutting behavior of single crystal copper: MD simulation approach. *J Micromach* 2021; 4(1): 6–17.

17. Lv D, Wang Y and Yu X. Effects of cutting edge radius on cutting force, tool wear, and life in milling of SUS-316L steel. *Int J Adv Manuf Technol* 2020; 111(9–10): 2833–2844.

18. Vopáť T, Podhorský Sahul M, et al. Cutting edge preparation of cutting tools using plasma discharges in electrolyte. *J Manuf Process* 2019; 46: 234–240.

19. Bernard SE, Selvaganesh R, Khoshick G, et al. A novel contact area based analysis to study the thermo-mechanical effect of cutting edge radius using numerical and multi-sensor experimental investigation in turning. *J Mater Process Technol* 2021; 293: 117085.

20. Arefin S, Zhang X, Neo DWK, et al. Effects of cutting edge radius in vibration assisted micro machining. *Int J Mech Sci* 2021; 208: 106673.

21. Luo B, Zhang K, Li Y, et al. Modelling of thrust force for worn drill bits characterised by cutting edge radius in drilling carbon fibre-reinforced plastic/Ti-6Al-4V alloy stacks. *Proc IMechE, Part B: J Engineering Manufacture* 2018; 232(11): 1960–1972.

22. Li Y, Cheng X, Zheng G, et al. Investigation on the size effect in micro end milling considering the cutting edge radius and the workpiece material. *Mech Sci* 2021; 12(1): 487–499.

23. Yang D, Xiao X and Liang X. Analytical modeling of residual stress in orthogonal cutting considering tool edge radius effect. *Int J Adv Manuf Technol* 2019; 103(5–8): 2965–2976.

24. Akbari M, Knapp W and Wegener K. Comparison of transparent objects metrology through diamond cutting edge radii measurements. *CIRP J Manuf Sci Technol* 2016; 13: 72–84.

25. Zhang K, Cai Y, Shimizu Y, et al. High-precision cutting edge radius measurement of single point diamond tools using an atomic force microscope and a reverse cutting edge artifact. *Appl Sci* 2020; 10(14): 4799.

26. Song S, Lu B, Zuo D, et al. A new cutting edge surface reconstruction method for hard whirling tools. *Measurement* 2020; 151: 107276.

27. Xuefeng Z, Hui L, Lin H, et al. Modeling and detection of the prepared tool edge radius. *Sci Prog* 2020; 103(3): 36850420957903.

28. Wu B, Zong W and Niu C. An in situ method to evaluate the waviness of rounded cutting edge of diamond tool. *Int J Adv Manuf Technol* 2020; 106(5–6): 1775–1785.