Development of Computer Vision Algorithms for Measurement and Inspection of Spur Gears

Abstract:
Gears are one of the most common mechanisms for transmitting power and motion. Error in gears causes two main problems, increased acoustic noise in operation and increased wear, both of which are sufficiently troublesome to cause concern. Therefore, precision measurement of gears plays a vital role in gear measurement and inspection. The current methods of gear measurement are either time-consuming or expensive. In addition, no single measurement method is available and capable of accurately measuring all gear parameters while significantly reducing the measurement time. The aim of this paper is to utilize the computer vision technology to develop a non-contact and rapid measurement system capable of measuring and inspecting most of spur gear parameters with an appropriate accuracy. The vision system has been established in the metrology lab and it is used to capture images for gears to be measured or inspected. A software (named GearVision) has been especially developed in-house using Microsoft Visual C++ to analyze the captured images and to perform the measurement and inspection processes. The introduced vision system has been calibrated for both metric and pixel units. After calibration, the system was verified by measuring two sample gears and comparing the calculated parameters with the actual values of gear parameters. The maximum variations between the calculated parameters and the actual values were ±0.101 mm for a spur gear with 156 mm outside diameter. This variation can be decreased by measuring small gears.

Keywords: Spur gears, Computer vision, Image processing, Measurements.

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1. Introduction

Gears are one of the most common mechanisms for transmitting power and motion. For most of the modern industrial and transport applications, gears are important and are frequently used as fundamental components [1]. Error in the manufacture of gears causes two main problems, increased acoustic noise in operation and increased wear, both of which are sufficiently troublesome to cause concern [2].

For closer control over the accuracy of gears manufacture, precision measurement of gears plays a vital role. Spur gears have the majority among all types of gears in use; therefore automating the measurement process of spur gears becomes a persisting target.

The deviation of an actual tooth from the design profile, the profile error, can be measured in a number of ways. The simplest way is to measure the tooth width at a number of pitches using an adapted caliper gauge [3]. Another method is to use gauging with a moving probe, with a displacement transducer attached, which traces the design profile. Many mechanical-probe gear inspection systems are available but these systems are not suitable for inspection of smaller gears. Some attempts have been made to develop smaller probes capable of measurement of small mechanical elements [4]. Alternatives are to use a coordinate measurement machine to measure the actual profile, or rolling the gear across a stationary probe [5-7]. Optical methods have also been employed to measure gear-tooth deformation [8], pitch errors and tooth profiles [9]. The use of laser-based system to measure the thickness, pitch, and tooth flank profile of spur gears was investigated by Younes et al [10, 11].

The current methods of spur gear measurement are either time consuming or expensive. In addition, no single measurement method is available and capable of accurately measuring all gear parameters while significantly reducing the measurement time. Therefore, the measurement and inspection of spur gears has been emphasized by many researchers.

Recently, vision systems have been widely used in many applications [12-15]. Computer vision systems have been developed for quality control and started to be used as an objective measurement and evaluation systems [16]. Robinson et al. [17] described the design of an involute spur gear inspection system in which measurements were made using a video camera and image analysis software. They investigated the possible measurement accuracy and the possible sources of error identified. They concluded that the measurement accuracy is comparable to that of current methods for tolerance inspection of spur gears. In addition, the low cost and ease of use made image analysis measurement systems an attractive alternative. Sung et al. [18] employs wavelet transform to detect the location of tooth defects in a gear system with high accuracy. They reported that utilizing this approach might improve the ability for fault detection of a gear transmission system, especially when the faulty gear rotates at an angular speed close to those of other gears.

The aim of this paper is to utilize computer vision to develop a non-contact measurement system capable of measuring most of spur gear parameters rapidly with a reasonable accuracy. This can facilitate and speed up the measurement and inspection processes of spur gears.

2. The Proposed System

Fig. 1 shows a photograph of the proposed vision system. It consists of two main parts, hardware and a developed software. The hardware consists of three items. The first item is the backlighting table (1), which is a lighting box with diffusing surface at its front, and it is used to produce a back lighting for the gear to be
measured (2). The second item is a CCD color video camera (3) and a set of lenses with different focal lengths. The camera is carried by a camera holder (4). The third item is a 24 bit per pixel (ELF VGA) frame grabber video card (5), which is installed inside the PC computer (6) and connected to the CCD camera. A capturing software (7) is provided with the frame grabber to acquire images and save it to files with various types of file formats.

The developed software (named GearVision) is fully written in-house using Microsoft Visual C++ as a 32-bit Windows application. It features many image processing and computer vision algorithms to measure spur gear parameters from captured images of the spur gears. Fig. 3 shows the main interface of the GearVision software.

To perform the measurement or inspection process, the gear to be measured is set on the backlighting table then an image is captured and saved to a BMP file using the capturing software. The captured image is then opened by the GearVision software and analyzed to perform the measurement and inspection processes.

3. The Developed Algorithms

To perform the measurement process, two data items are required to be entered from the user through the main interface of the GearVision software (Fig. 2). The first item is the value of the outer diameter \( D_0 \) of the gear to be measured and the second data is the pressure angle \( \phi \) of the gear. If the outer diameter is specified, the system will be calibrated automatically and the measurements will be performed in millimeter, otherwise, it will be performed in image pixels. If the pressure angle is specified, both base circle diameter \( D_b \) and base pitch \( P_b \) will be calculated.

Several image processing and computer vision algorithms (Gear algorithms) are applied to the captured image to perform the measurement process. Figure 3 shows a block diagram of these algorithms and the following sections explain them.
3.1 Image Processing Algorithms

The image processing algorithms shown in Figure 3 were discussed in details in a previous work [19]. In short, the process starts by opening the image of the gear to be measured. If the opened image is colored, then it will be converted into gray scale image. The gray image is converted into binary image based on a calculated threshold. After creating the binary image, an edge detection algorithm is applied to the binary image to extract the edge pixels, which represent the boundaries of the gear elements. A thinning algorithm is then applied to the edge pixels in order to remove extra pixels obtained by the edge detection algorithm. Fig. 4-a shows a sample gear image and Fig. 4-b shows the extracted edge pixels obtained by the edge detection algorithm after applying the thinning algorithm.

Next, a labeling algorithm is applied to the thinned image in order to mark each set of connected pixels by a unique label. As a result, the outer contour, which represents the profile of the gear teeth, can be distinguished from other contours such as the gear's hole or the internal slots. Once the outer contour is labeled, its pixels are extracted and a sorting algorithm is applied to sort the pixels sequentially according to the distances between each two successive pixels.

At this point, the coordinates of the pixels constituting the outer profile of the
pitch circle diameter ($D_p$) is correlated to the number of teeth and the diametral pitch while the module ($m$) is correlated to the pitch circle diameter and the number of teeth. In this situation, three computer vision algorithms were developed to calculate the outer diameter, the root diameter and the number of teeth of the gear to be measured, then other gear parameters are calculated using their equations based on these parameters.

3.2 The Outer Diameter Algorithm

The Outer diameter algorithm was developed to calculate the outer diameter ($D_p$) of the gear from the extracted edge pixels of the outer contour (teeth profile). The algorithm works as follows:

1. Search all edge pixels of the outer contour to find the following pixels:
   - The two pixels having the minimum and the maximum $x$ coordinates ($P_{x_{min}}, P_{x_{max}}$).
   - The two pixels having the minimum and the maximum $y$ coordinates ($P_{y_{min}}, P_{y_{max}}$).

2. Apply the least square circle method (discussed in details in [19]) to define a primary outer circle (POC) that fit the pixels ($P_{x_{min}}, P_{x_{max}}, P_{y_{min}}, P_{y_{max}}$) and to calculate its center ($POC_{cx}, POC_{cy}$) and radius ($POC_{r}$).

3. Search edge pixels again to extract all pixels lie (or nearly lie) on the POC (Fig. 4-c) and store their coordinates to an array called OutputPixels. This can be done as follows:
   - Calculate the distance ($d$) between the center of the POC ($POC_{cx}, POC_{cy}$) and each pixel ($x, y$) using equation (1).
     \[ d = \sqrt{(POC_{cx} - x)^2 + (POC_{cy} - y)^2} \] (1)
   - Extract all pixels having $d$'s equal to the radius of the POC within a tolerance of ±1 pixel as follows.
If \( d_i > POC_R - 1 \) AND \( d_i < POC_R + 1 \)  
Store the pixel \( P(x_i, y_i) \) to the \( \text{OuterPixels} \) array.

4. Apply the least square method on the \( \text{OuterPixels} \) array to define the actual outer circle \( (AOC) \) and to calculate its center \( (AOC_{cx}, AOC_{cy}) \) and radius \( (AOC_R) \).

5. Finally, the outer diameter \( (D_O) \) of the gear is calculated using equation (2).

\[
D_O = 2 \times AOC_R 
\]  

(2)

3.3 The Root Diameter Algorithm

The root diameter algorithm is used to calculate the root diameter \( (D_R) \) from the extracted edge pixels. This algorithm uses the center \( (AOC_{cx}, AOC_{cy}) \) of the AOC to calculate the root diameter as follows:

1. For all edge pixels of the outer contour (teeth profile), calculate the distance \( (d_i) \) between the center of the AOC and each pixel \( (x_i, y_i) \), then find the pixel that have the minimum distance \( (d_{min}) \).

2. Define a primary root circle \( (PRC) \) which its center is the center as the AOC and its radius \( (PRC_R) \) equal to the minimum distance \( (d_{min}) \).

3. Search edge pixels again to extract all pixels lie, or nearly lie, on the PRC (Fig. 4-d) and store them to an array called \( \text{RootPixels} \). This can be done by calculating the distance \( (d_i) \) between the center of the AOC \( (AOC_{cx}, AOC_{cy}) \) and
each pixel \((x_i, y_i)\), then extracting all pixels that satisfy the following criterion:

If \((d > PRC_R - 1 \text{ AND } d < PRC_R + 1)\)

Store the pixel \(P(x_i, y_i)\) to the RootPixels array.

4- Apply the least square method on the RootPixels array to define the actual root circle (ARC) and to calculate its radius (ARC_R).

5- Finally, the root diameter \(D_R\) of the gear is calculated using equation (3).

\[
D_R = 2 \times ARC_R
\]  \hspace{1cm} (3)

### 3.4 The Number of Teeth Algorithm

The number of teeth algorithm was developed to count the number of teeth \((N)\) from pixels extracted by the Outer Diameter algorithm, which stored to the OuterPixels array. If OPXi contains the \(x\) coordinates of the OuterPixels array and OPYi contains the \(y\) coordinates, then the following C code can be used to count the number of teeth.

```c
int N = 0; double dist = 0;
for (int i=0; i < NPoints-1; i++)
{
    dist = sqrt(pow(OPXi[i] - OPXi[i+1], 2) +
                pow(OPYi[i] - OPYi[i+1], 2));
    if (dist >= 5)
        N++;
}
```

Where: \(N\) is the number of teeth, NPoints is the number of pixels in the OuterPixels array, and dist is a variable stores the distance between each two successive pixels in the OuterPixels array.

The initial value of \(N\) is zero. When the distance between any two successive pixels in the OuterPixels array is greater than five the number of teeth is increased by one. The value of five was taken as an indication to the gap between the last pixel on a tooth and the first pixel on the next tooth. Usually, the distance between each two successive pixels on the same tooth does not exceed than 1.414 pixels \((\sqrt{2})\). Therefore, the value of five is safe enough to ensure that the gap between two teeth has been occurred.

### 3.4 Other Gear Parameters

The above three algorithms calculate the outer diameter, the root diameter and the number of teeth. Using these parameters, all other gear parameters can be calculated using their equations as follows:

#### 3.4.1 The Diametral Pitch

Having the outer diameter and the number of teeth, the diametral pitch \((P)\) can be calculated as follows:

\[
P = \frac{(N+2) \times D_o}{D}
\]  \hspace{1cm} (4)

#### 3.4.2 The Pitch Circle Diameter

Having the diametral pitch and the number of teeth, the pitch circle diameter \((D)\) can be calculated as follows:

\[
D = \frac{N \times P}{2}
\]  \hspace{1cm} (5)

#### 3.4.3 The Module

Having the pitch circle diameter \((D)\) and the number of teeth, the module \((m)\) can be calculated as follows:

\[
m = \frac{D}{N}
\]  \hspace{1cm} (6)

#### 3.4.4 The Circular Pitch

The circular pitch \((p)\) can be calculated as follows:

\[
p = \frac{\pi D}{N}
\]  \hspace{1cm} (7)

#### 3.4.5 The Addendum

Having the outer diameter \((D_o)\) and the pitch circle diameter \((D)\), the addendum \((a)\) can be calculated as follows:

\[
a = \frac{D_o - D}{2}
\]  \hspace{1cm} (8)

#### 3.4.6 The Dedendum

Having the root diameter \((D_R)\) and the pitch circle diameter \((D)\), the dedendum \((b)\) can be calculated as follows:

\[
b = \frac{D - D_R}{2}
\]  \hspace{1cm} (9)
3.4.7 The Clearance

Having the addendum \((a)\) and the dedendum \((b)\), the clearance \((c)\) can be calculated as follows:

\[
c = (b - a)
\] (10)

3.4.8 The Whole Depth

The whole depth \((h)\) can be calculated as follows:

\[
h = (a + b)
\] (11)

3.4.9 The Circular Tooth Thickness

The circular tooth thickness \((T_{circ})\) is calculated as follows:

\[
T_{circ} = \pi m / 2
\] (12)

3.4.10 The Chordal Tooth Thickness

The chordal tooth thickness \((T_{chord})\) is calculated as follows:

\[
T_{chord} = m \sin(90/N)
\] (13)

3.4.11 The Chordal Dedendum

The chordal dedendum \((b_{chord})\) is calculated as follows:

\[
b_{chord} = \frac{mN}{2} \left[ 1 + \frac{2}{N} \cos \left( \frac{90}{N} \right) \right]
\] (14)

3.4.12 The Base Circular Diameter

The base circular diameter \((D_b)\) is calculated as follows:

\[
D_b = D_0 \cos \phi
\] (15)

3.4.13 The Base Pitch

The base pitch \((P_b)\) is calculated as follows:

\[
P_b = \pi m \cos \phi
\] (16)

4. System Calibration

The system calibration is performed by calculating the pixel size in both \(x\) and \(y\) directions according to the actual size of the object to be measured as follows:

1. The user enters the outer diameter \((D_o)\) of the measured gear (in millimeter) to the GearVision software.

2. The software searches the edge pixels of the outer contour to find the two pixels having the minimum and the maximum \(x\) coordinates \((X_{min}, X_{max})\), then it calculates the maximum diameter of the gear in \(x\) direction \((D_{max,x})\) as follows:

\[
D_{max,x} = \text{Abs}(X_{max} - X_{min})
\]

3. A calibration factor in \(x\) direction \((CF_x)\) is calculated as follows:

\[
CF_x = D_o / D_{max,x}
\]

4. Similarly, a calibration factor in \(y\) direction \((CF_y)\) is calculated by applying step 2 to find the two pixels having the minimum and the maximum \(y\) coordinates. Then \(CF_y\) is calculated as follows:

\[
CF_y = D_o / D_{max,y}
\]

5. The final calibration factor \((CF)\) is calculated as follows:

\[
CF = \sqrt{CF_x \times CF_y}
\]

6. The calculated outer diameter and root diameter are multiplied by the calibration factor \((CF)\). All other gear parameters are automatically calibrated because they are directly or indirectly calculated from these two parameters.

5. Inspection of Spur Gears

The inspection process is performed by comparing the measurements of the gear to be inspected and the measurements of a standard gear within specified tolerances. The Inspection section in Fig. 2 deals with this process. The inspection process is performed as follows:

1. Entering the standard gear parameters:

The standard gear parameters can be entered to the GearVision software by two methods. In the first, the standard gear is measured by the vision system
and the calculated parameters are stored as reference values by clicking the Set as Reference button in the gear measurement section. One reference gear could be used to check many gears. In the second method, the reference values are set manually by clicking the Set Manual button.

2. Selecting the gear parameters to be inspected:

This can be done through the Inspection Tolerances dialog box shown in Fig. 5, which can be displayed by clicking the Tolerances button. The parameters to be inspected should be checked and their allowable tolerances are assigned. Each parameter can be assigned unique tolerance values (Lower and Upper) or the same tolerance values can be set for all parameters by clicking the Set All button in the main interface.

3. Measuring the gear to be inspected:

The gear to be inspected is measured by the vision system, then the calculated parameters are compared with the standard gear parameters according to the tolerances given through the inspection tolerance dialog box.

4. Taking an inspection decision:

The inspection decision is displayed automatically in the Inspection section. The decision will be "Accepted" if all inspected parameters for the measured gear meet the corresponding parameters of the standard gear within the specified tolerances. Otherwise, the decision will be "Rejected". The details of the comparison process can be displayed through the Inspection Details dialog box (Fig. 6), which can be displayed by clicking the Details button.

6. Verification and discussion

To verify the introduced system, two images were captured for two different gears, then the proposed algorithms were applied to each image to calculate the gear parameters. A comparison between the actual and the calculated values of each gear parameter as well as the variation between the two values are listed in Table 1. Positive variations mean that the calculated values are greater than the actual values and
vice versa. The actual values of gear parameters were obtained from the MITCalc software (Mechanical, Industrial and Technical Calculations), which is a software package for gear design and calculations [21].

As discussed earlier, \( D_b \), \( D_R \), and \( N \) are first calculated by the developed software, then other gear parameters are calculated based on these parameters. Therefore, only the variations of gear parameters based on these three parameters are affected, while the variations of other gear parameters are zero.

It can be seen that the variations between the actual and the calculated values for the second gear (Test gear 2) are greater than those of the first gear (Test gear 1). This refers to the fact that increasing the dimensions of the measured gear increases the pixel size for the captured images, which decreases the accuracy of the vision system. This makes the vision system more suitable for measuring small spur gears.

7. Conclusions

A vision system has been introduced as a new non-contact measurement system for measurement and inspection of spur gears from their captured images. A software has been developed in-house to analyze the captured images and perform the measurement and inspection processes using developed many image processing and computer vision algorithms.

The introduced vision system has been calibrated and verified by measuring two sample gears and comparing the calculated parameters with the actual values of gear parameters. The maximum variations between the calculated parameters and the actual values were ±0.101 mm for a spur gear with 156 mm outside diameter. The accuracy of the system is affected by the size of the gear to be measured. Hence, the variation between the calculated parameters and the actual values can be decreased by measuring small gears.

References

Nomenclature

\[ a \quad \text{Addendum} \]
\[ b \quad \text{Dedendum} \]
\[ C \quad \text{Clearance} \]
\[ D \quad \text{Pitch circle diameter} \]
\[ D_0 \quad \text{Base circle diameter} \]
\[ D_0 \quad \text{Outside diameter} \]
\[ D_R \quad \text{Root diameter} \]
\[ h_t \quad \text{Tooth depth} \]
\[ m \quad \text{Module} \]
\[ N \quad \text{Number of teeth} \]
\[ p \quad \text{Circular pitch} \]
\[ P \quad \text{Diametral pitch} \]
\[ P_0 \quad \text{Base pitch} \]
\[ T_{chord} \quad \text{Chordal tooth thickness} \]
\[ T_{circ} \quad \text{Circular tooth thickness} \]

Greek symbols

\[ \phi \quad \text{Pressure angle} \]

Abbreviations

\[ \text{POC} \quad \text{Primary outer circle} \]
\[ \text{POC}_{x,y} \quad x \text{ coordinate of the primary outer circle} \]
\[ \text{POC}_{y} \quad y \text{ coordinate of the primary outer circle} \]
\[ \text{POC}_R \quad \text{Radius of the primary outer circle} \]
\[ \text{AOC} \quad \text{Actual outer circle} \]
\[ \text{AOC}_{x,y} \quad x \text{ coordinate of the actual outer circle} \]
\[ \text{AOC}_{y} \quad y \text{ coordinate of the actual outer circle} \]
\[ \text{AOC}_R \quad \text{Radius of the actual outer circle} \]
\[ \text{PRC} \quad \text{Primary root circle} \]
\[ \text{POC}_R \quad \text{Radius of the primary root circle} \]
\[ \text{ARC} \quad \text{Actual root circle} \]
\[ \text{ARCR} \quad \text{Radius of the actual root circle} \]