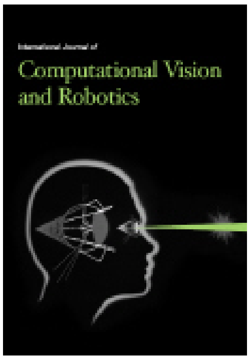


International Journal of Computational Vision and Robotics

ISSN online: 1752-914X - ISSN print: 1752-9131
https://www.inderscience.com/ijcvr

Automated inspection of spur gears using machine vision approach

Ketaki Joshi, Bhushan Patil

DOI: 10.1504/IJCVR.2022.10044716

Article History:

Received:	12 December 2020
Accepted:	05 December 2021
Published online:	30 November 2022

Automated inspection of spur gears using machine vision approach

Ketaki Joshi* and Bhushan Patil

Fr. Conceicao Rodrigues College of Engineering,
Affiliated to: University of Mumbai, India
Fr. Agnel Ashram, Bandstand, Bandra (W),
Mumbai, Maharashtra 400050, India
Email: ketaki.joshi@fragnel.edu.in
Email: bhushan.patil@fragnel.edu.in
*Corresponding author

Abstract: The paper presents a machine-vision-based system for automated inspection of standard spur gears. Image processing algorithms are used for the measurement of important gear dimensions such as radii of addendum circle, dedendum circle and pitch circle, module, number of teeth, pressure angle, tooth thickness, circular pitch, radial run-out and tooth alignment error. Deviations from theoretical values according to gear standards are computed and a decision is made regarding acceptance/rejection. The performance of machine vision inspection system is evaluated in terms of its accuracy and precision. Accuracy is based on deviation of machine vision values from those obtained using traditional metrology instruments and gear standards. Precision is measured using partial gauge R&R study. The results obtained for gear images taken by different operators using different imaging devices are repeatable, reproducible and in good agreement with the true values. The results indicate that the machine vision approach is accurate and precise.

Keywords: machine vision; inspection; spur gear; image processing; accuracy; precision; gauge R&R.

Reference to this paper should be made as follows: Joshi, K. and Patil, B. (2023) 'Automated inspection of spur gears using machine vision approach', *Int. J. Computational Vision and Robotics*, Vol. 13, No. 1, pp.38–51.

Biographical notes: Ketaki Joshi has received her PhD (Science and Technology) in Mechanical Engineering from the University of Mumbai. She is presently working as an Assistant Professor in Mechanical Engineering at the Fr. Conceicao Rodrigues College of Engineering, affiliated to University of Mumbai. Her area of research is machine vision and its applications in manufacturing industry.

Bhushan Patil received his PhD (Technology) in Production Engineering from the Veermata Jijabai Technological Institute (VJTI), University of Mumbai. He is currently working as a Professor, the Head of the Department (Mechanical Engineering) and Dean (Research and Development) at the Fr. Conceicao Rodrigues College of Engineering, affiliated to University of Mumbai. His areas of research interests include machine vision, minimum quantity lubrication, and ERP systems.

1 Introduction

Gear drives are a vital power transmission mode in manufacturing, automobiles, aerospace, and many other industries. Designers and manufacturers must meet ever-increasing demands for their power transmission capability, noise emission control, compactness, and useful life. Measurement of all critical parameters is crucial for inspection and quality control of gears (Goch, 2003). For inspection of standard spur gears, individual and composite errors are measured and ensured to be within the tolerance ranges specified by gear standards (Maitra, 1994). Traditional instruments being mechanical prove to be tedious, making 100% inspection difficult. Numerically controlled gear measuring instruments (GMIs) and coordinate measuring machines (CMM) are versatile in inspecting complex object geometries but costlier. Machine vision technology has the potential to provide an industry solution to carry out 100% non-contact automated inspection of manufactured gears using image processing algorithms. Its potential in gear metrology was realised towards the end of the last century as it provided a non-contact method for measuring all significant dimensions of gears. However, camera resolution, sensitivity to ambient light, noise in image capture were major concerns for acceptance of these systems for industrial use. Advancements in camera technology and image processing techniques can make the approach applicable in industrial metrology. Researchers have used the machine vision approach for various purposes such as gear sorting, gear inspection based on major dimensions, defects detection, and gear tooth profile measurement. However, it can be realised that the precision required by gear metrology standards is at the micron level. Achieving this level of precision is challenging using image processing because of limitations in image quality, details captured due to limited camera resolution and noise present during image acquisition. Therefore, there is necessary to assess the accuracy and precision of the machine vision system to be acceptable by the industry.

This paper presents the machine vision algorithms used to measure critical parameters of standard spur gears followed by the computation of individual errors for inspection purposes. The deviation in important dimensions, circular pitch, radial runout and tooth alignment error are compared with the tolerance ranges specified by gear standards for deciding upon acceptance/rejection of the gear. The system's accuracy is calculated by comparing the results obtained for gears under consideration using the machine vision approach with those obtained using the traditional approach. The precision is measured using partial gauge R&R method, which computes the repeatability and reproducibility of the results obtained by processing images captured by different operators and devices.

2 Literature survey

The images of spur gear are captured using an image acquisition device and further processed in the computer using various image pre-processing and processing techniques to extract the gear parameter values of interest. The first step is image pre-processing and edge detection. Images acquired are first pre-processed by conversion from RGB to greyscale image, binarisation using thresholding technique and image segmentation to extract gear tooth profile (Gadelmawla, 2009, 2011; Chen and Li, 2010; Mavi and Kaur, 2012; Huang et al., 2016). Researchers have used various edge detection algorithms to extract the gear tooth profile, which are mainly based on comparing image pixel values with the neighbouring pixels and labelling them as foreground or background. It is generally followed by edge thinning to improve the measurement accuracy by removing two consecutive pixels having the same pixel values (Gadelmawla, 2011; Huang et al., 2016; Wang et al., 2015). Then the morphological operations can be carried out to fill the image (Wang et al., 2015). The next step is to extract the spur gear centre using the centre of gravity of the gear tooth profile image (Huang et al., 2016). Then the outer and root diameters are calculated by positioning those circles using various approaches. Gadelmawla (2011) detected outermost and innermost pixels and then used the distance formula to measure diameters. Huang et al. (2016) used a similar approach after transforming polar coordinates into rectangular coordinates. Ge et al. (2017) located the outermost circle based on a convex polygon encompassing the image and then found the equation of the circle for that polygon. The next step is to extract the number of teeth in the spur gear image, in which researchers have used various approaches. Erosion and extraction of connected components to measure the number of teeth is a commonly used method (Mavi and Kaur, 2012; Wang et al., 2015; Tao et al., 2019; Moru and Borro, 2020). Wu et al. (2015) calculated the number of teeth based on peak distances from the centre. Gadelmawla (2009, 2011) computed the number of teeth based on the distance between consecutive gear tooth profile pixels. Then other parameters such as module, base circle, pitch circle diameter, pressure angle are calculated using equations and values of the number of teeth, addendum and root circle diameters extracted earlier (Mavi and Kaur, 2012). For measuring pitch and tooth thickness deviation, Ge et al. (2017) located pitch circle based on the standard equation, found points on the gear tooth profile intersecting the pitch circle and calculated tooth thickness and circular pitch using distance formula for these pixels. Some researchers also used template matching and areas of extracted gear teeth using image erosion for identifying gear tooth defects (Wang et al., 2015; Chen et al., 2012; Chauhan et al., 2016). Robinson et al. (1995) investigated the measurement accuracy using a low-cost CCD camera and identified the possible sources of error. Many other researchers have identified few or all of the critical gear parameters using machine vision data (Du et al., 2011; Jin et al., 2011; Ding et al., 2016; Wu et al., 2019). Kamal et al. (2018) and Yu et al. (2019) have worked on surface defects of spur gears using vision data. Jalili et al. (2013) have evaluated the accuracy and repeatability of the machine vision system compared to CMM. Ali et al. (2013, 2014a, 2014b) have used vision data to accurately and precisely measure gear profile. Recent researches also indicate that 3D optical data can be used effectively in gear inspection (Urbas et al., 2021). Many other researchers have also contributed to gear measurement using vision data (Xiangwei, 2004; Faluvegi and Cristea, 2011; Liu et al., 2016).

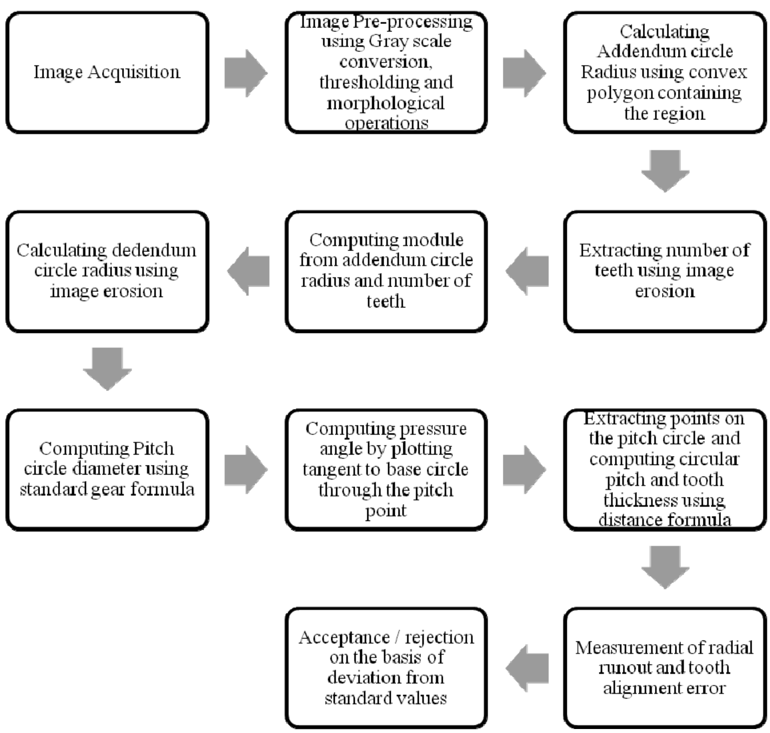
From the literature surveyed, it is evident that machine vision can provide an industry-ready solution for the inspection of spur gears. Challenges include image quality, details captured due to limited resolution, noise during image acquisition. Hence their lies a future scope of devising image acquisition, pre-processing and processing approach capable of measuring essential dimensions of spur gear up to micron level and developing a robust, precise and accurate measurement system that the industry can accept.

The present paper aims to develop an image-based spur gear inspection system capable of capturing all critical dimensions (quality characteristics) of a standard spur gear, calculating individual gear errors and comparing them with the tolerance ranges as suggested gear standards (Maitra, 1994). The system can be used for deciding for acceptance or rejection of a spur gear based on its conformance to specifications. All major dimensions of a standard spur gear are extracted from its image captured using an image acquisition device (camera) and compared with the actual values measured using traditional measuring instruments. Once the machine vision-based inspection system results are validated, the individual errors are checked to be in the tolerance ranges suggested as per the gear standards. If the errors are within the tolerance range, then the spur gear can be certified for its quality; else is to be rejected. The system developed is checked for accuracy and precision using percent error analysis and partial gauge R&R study.

3 Extraction of important spur gear parameters and inspection using machine vision

The methodology adopted for extraction of various important dimensions, measurement of individual errors and decision regarding acceptance/rejection is as indicated in Figure 1.

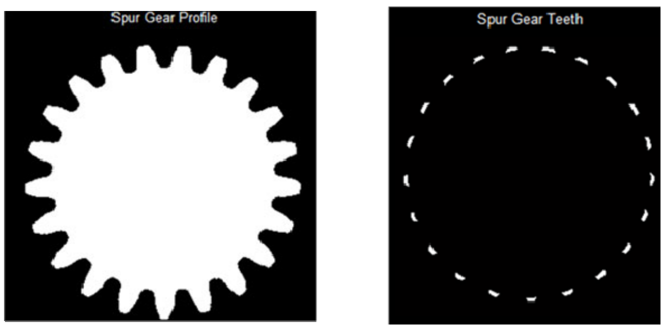
Figure 1 Methodology for inspection of spur gear using machine vision (see online version for colours)



The RGB image captured by camera is acquired in MATLAB and pre-processed using standard pre-processing functions including conversion to greyscale, conversion to B/W image using thresholding, cleaning the image by morphological opening and filling of holes to extract the gear teeth contour. Then addendum circle radius is computed by using pixels on the smallest convex polygon containing the region and calculating their average distance from the centroid using distance formula. The value obtained in pixels is converted into millimetre scale using proper conversion ratio obtained through image calibration.

For measuring the number of teeth, the image is eroded using structuring elements, measuring properties of the eroded region, setting its pixel values to zero for subtracting it from the original image and subsequently counting the connected components as shown in Figure 2.

Figure 2 (a) Spur gear profile (b) Number of teeth extracted from the image



(a) (b)

The module is measured from the addendum circle radius and the number of teeth using equation (1) given below and selecting the nearest standard module.

$$Module = \frac{2 * Addendum\ circle\ radius}{(Number\ of\ teeth + 2)} \quad (1)$$

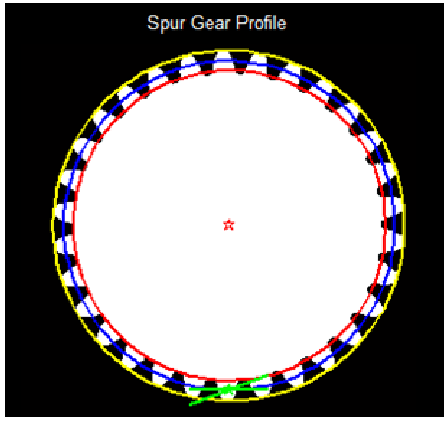
For dedendum circle radius, spur gear image is eroded until the number of teeth extracted from the newly eroded image becomes less than the number extracted earlier. Once the dedendum circle position is finalised, the radius is calculated using convex polygon properties similar to the procedure mentioned for addendum circle radius. Pitch circle radius is calculated from dedendum circle radius and number of teeth using standard formula given in equation (2) below.

$$Pitch\ circle\ radius = \frac{Dedendum\ circle\ radius * Number\ of\ teeth}{(Number\ of\ teeth + 2)} \quad (2)$$

The base circle is positioned by locating fillets at the base circle and adding fillet radius to dedendum circle radius for calculation of base circle radius. Then, the pressure angle is calculated by marking a point on the pitch circle, plotting the tangent to the base circle passing through this pitch point as indicated by green lines in Figure 3. The included angle between this tangent and horizontal is the pressure angle determined using $\tan^{-1}$ of the tangent slope.

The position of various important circles is also shown in Figure 3. The yellow circle indicates addendum circle, blue circle indicates pitch circle and red circle indicates base circle.

Figure 3 Important circles and pressure angle measurement (see online version for colours)



Points on the pitch circle are also extracted using image erosion and for each labelled element (tooth), its extreme points are obtained using the distance formula. Furthermore, tooth thickness is calculated by considering the average distance between two consecutive points on each tooth. The circular pitch is obtained by considering the average distance between a point on a tooth and the corresponding point on the adjacent tooth. The values obtained in pixel scale are converted into millimetre scale using conversion ratio. The values obtained in pixel scale are converted into millimetre scale using conversion ratio.

Radial runout is calculated based on the gear tooth profile's eccentricity from the gear's axis. For measuring tooth alignment error, the side view of the gear is captured and pre-processed to get the B/W image. Then lines in the image are detected using Hough transform and the slope of the longest line is calculated as tooth alignment error. The value obtained in pixel scale is converted into millimetre scale.

Table 1 Standard Spur gear formula used for calculation of deviations

Module	$m = \frac{2R_a}{(T+2)}$
Dedendum circle radius	$R_d = \frac{T-2}{T+2} * R_a$
Pitch circle radius	$R_p = \frac{T}{T+2} * R_a$
Base circle radius	$R_p = R_p * \cos\phi$
Tooth thickness	$W = mT \sin\left(\frac{90}{T}\right)$
Circular pitch	$p = \pi m$

Note: $*R_a$ – addendum circle radius, ϕ – pressure angle, T – number of teeth.

For validating the results, values obtained using machine vision are compared with those obtained using traditional metrology instruments such as micrometre, gear tooth calliper and corresponding values based on the standard spur gear formulae mentioned in Table 1. Upon validation, the system is used for making a decision regarding acceptance or rejection based on individual errors. Machine vision-based values are compared with the standard values obtained using the formulae given in Table 1 to compute the deviations.

The deviations in tooth thickness, circular pitch, radial runout and tooth alignment are compared against the tolerance ranges specified in gear standards (Maitra, 1994) for spur gears.

4 Precision and accuracy of the machine vision system developed for inspection of spur gears

Any measurement system developed should be checked for its accuracy and precision. In the present paper, accuracy of the system is checked based the % error in measurement whereas precision is checked based on its repeatability and reproducibility. Accuracy of the measurement system is obtained by calculating % error in measurement using the formula (3) given below.

$$\%\ Error = \frac{Machine\ vision\ value - Actual\ value}{Actual\ value} \times 100 \tag{3}$$

The precision of the measurement system is measured in terms of repeatability and reproducibility. Repeatability refers to variation between the measurements made by a single appraiser on the same part, which can be attributed to the instrument. Reproducibility refers to variation between the measurements made by different appraisers on the same part, which can be attributed to appraisers. Gauge R&R refers to the total measurement error obtained using variance due to repeatability and reproducibility. The variation is also present in the true dimensions of different parts being measured by the measurement system. For the measurement system to effectively captures this variation, the part-to-part variation should be large enough compared to R&R.

Table 2 Equations for measuring repeatability and reproducibility of the system

Average range	$\overline{R} = \dfrac{\sum_{i=1}^{m}\sum_{j=1}^{n} R_{ij}}{mn}$
Range of average	$\overline{R}_{\bar{x}} = Range\left(\overline{x_1}, \overline{x_2}, ..., \overline{x_m}\right)$
Repeatability	$\hat{\sigma}_{repeat} = \dfrac{R}{d_2^*(r, mn)}$
Reproducibility	$\hat{\sigma}_{repro} = \sqrt{\left(\dfrac{\overline{R}_{\bar{x}}}{d_2^*(m, 1)}\right)^2 - \dfrac{\hat{\sigma}_{repeat}}{mn}}$
Combined variability from R&R	$\hat{\sigma}_{R\&R} = \sqrt{\hat{\sigma}_{repeat}^2 + \hat{\sigma}_{repro}^2}$
Variability due to parts (process sigma not specified)	$\hat{\sigma}_{parts} = \dfrac{\overline{R}_{\bar{x}_j}}{d_2^*(n, 1)}$
Total variability	$\hat{\sigma}_{Total} = \sqrt{\hat{\sigma}_{repeat}^2 + \hat{\sigma}_{repro}^2 + \hat{\sigma}_{parts}^2}$

Note: *r = number of trials, m = number of parts, n = number of operators.

A partial gauge R&R study is carried out for measuring precision of the machine vision-based measurement system developed for inspecting spur gears, using the equations given in Table 2. Three spur gears of similar size (addendum circle diameters ranging from 46 to 50 mm) are chosen, making the number of parts used for the study equal to 3. The computerised inspection procedure provides the same results every time a particular image of spur gear is processed, ideally making its repeatability 100%. However, the system output depends on the image quality, different images of a particular gear taken by an appraiser would bring in repeatability error. Hence three operators using three different imaging devices (camera) with resolutions 12 MP, 6 MP and 4 MP respectively are used for the study, making the number of appraisers equal to 3. Every operator takes three images of each gear making number of trials equal to 3. The image sets are then processed using the system developed and results are used to measure the system's accuracy and precision.

5 Results and discussion

Table 3 presents the values of pitch circle radii obtained for different treatment conditions and is used for calculating appraiser bias, consistency and resolution of the system.

Figure 4 Charts showing results of partial gauge R&R for pitch circle radius (see online version for colours)

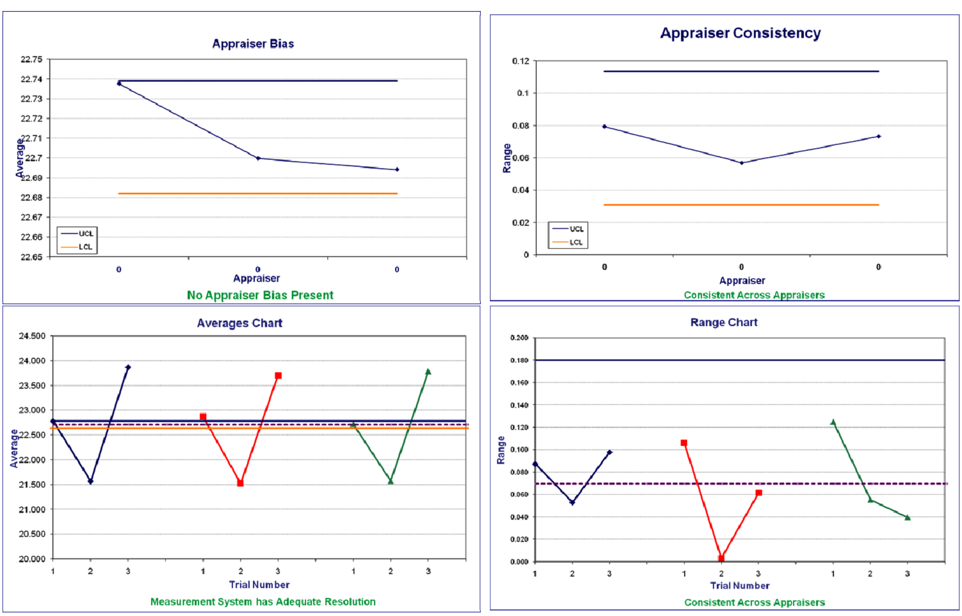


Figure 4 shows the absence of appraiser bias, consistency in the results, and adequate system resolution for the given range of parts.

Variability due to gauge R&R as given in Table 4, being less than 10%, the system is accepted for measurement of pitch circle radius. A similar study is carried out for other important radius values and the variability due R&R is found to be within 10%. Hence, it is concluded that the system developed for inspecting spur gears can measure all important radii with considerable precision.

Table 3 Datasheet for R&R of pitch circle radius

Appraiser (A):					
Trial\sample	*1*	*2*	*3*	*Average*	
1	22.8371	21.5737	23.8017	22.74	
2	22.7497	21.5939	23.8996	22.75	
3	22.7498	21.541	23.8918	22.73	
Average	22.78	21.57	23.86	*Xbar(A)*	22.74
Range	0.09	0.05	0.10	*Rbar(A)*	0.08
Appraiser (B):					
Trial\sample	*1*	*2*	*3*	*Average*	
1	22.8758	21.5225	23.6926	22.70	
2	22.813	21.522	23.7477	22.69	
3	22.9193	21.5194	23.6861	22.71	
Average	22.87	21.52	23.71	*Xbar(B)*	22.70
Range	0.11	0.00	0.06	*Rbar(B)*	0.06
Appraiser (C):					
Trial\sample	*1*	*2*	*3*	*Average*	
1	22.6635	21.5874	23.7644	22.67	
2	22.7885	21.5974	23.804	22.73	
3	22.7128	21.5421	23.7876	22.68	
Average	22.72	21.58	23.79	*Xbar(C)*	22.69
Range	0.13	0.06	0.04	*Rbar(C)*	0.07
Part average	22.79	21.56	23.79	$X_{doublebar}$	22.71
				$R_{doublebar}$	0.07
				R_p	2.23
				R_o	0.04

Table 4 Result of partial gauge R&R for pitch circle radius

Variation head	*% of total variation*
Repeatability (equipment variation)	3.5
Reproducibility (appraiser variation)	1.6
Variability due to gauge R&R	3.8
Variability due to parts	99.9

The study of partial gauge R&R for circular pitch revealed the presence of likely appraiser bias as given in Figure 5. A similar bias was found to be present in the case of tooth thickness. Irrespective of the presence of likely appraiser bias, the variability due to gauge R&R for tooth thickness was 9.6% and for the circular pitch was 5.8%, as given in Table 5. It is concluded that the presence of likely bias can be attributed to the difference in the camera resolution and small value of dimensions under consideration. The camera with high resolution provides better accuracy. Despite the bias present due to camera resolution, the machine vision system developed can measure the deviations with considerable precision.

Figure 5 Charts showing results of partial gauge R&R for circular pitch (see online version for colours)

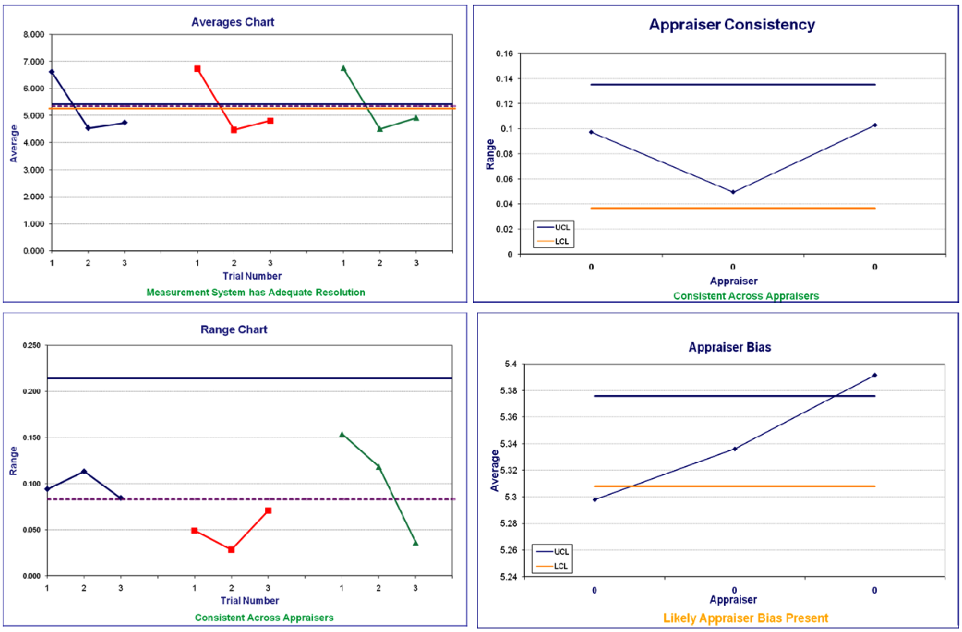


Table 5 Gauge R&R results for tooth thickness and circular pitch

Variation head	*% of total variation*	
	Tooth thickness	*Circular pitch*
Repeatability (equipment variation)	4.5	4.2
Reproducibility (appraiser variation)	8.5	4.0
Variability due to gauge R&R	9.6	5.8
Variability due to parts	99.5	9.8

Accuracy of the system is checked by comparing the values obtained using machine vision with those obtained using traditional metrology instruments such as micrometre, gear tooth calliper and all other related values based on the standard gear formulae. Table 6 shows percent measurement error for all the three gears based on the best results obtained by the images captured by operator 1 having the camera with the highest resolution. A maximum error of 6.37% is obtained in the measurement of the circular pitch. All measurement errors being less than 7%, the system can be considered accurate for the size range of spur gears used in the study.

After confirming the system's accuracy and precision, it can be used for deciding on acceptance or rejection of the gear based on conformance to quality. Figure 5 shows the images of the spur gears under inspection after the pre-processing step with the extracted gear tooth profile.

Table 6 Percent error in measurement of important gear parameter values using machine vision

		Dedendum circle radius	*Pitch circle radius*	*Base circle radius*	*Tooth thickness*	*Circular pitch*	*Number of teeth*	*Module*	*Pressure angle*
Gear 1	MV	20.6621	22.8371	21.4599	2.8333	6.6836	21	2	20
	TA	20.6522	22.8261	21.4495	3	6.2832	21	2	20
	% error	0.05	0.05	0.05	5.56	6.37	0	0	0
Gear 2	MV	20.0554	21.541	20.242	1.6925	4.4894	29	1.5	20
	TA	20.0323	21.5161	20.2185	1.8	4.7124	29	1.5	20
	% error	0.12	0.12	0.12	5.97	4.73	0	0	0
Gear 3	MV	22.299	23.8918	22.451	2.2151	4.6959	30	1.5	20
	TA	22.1375	23.7188	22.2883	2.3551	4.7124	30	1.5	20
	% error	0.35	0.35	0.35	3.94	1.44	0	0	0

Note: *MV – machine vision value, TA – value obtained using traditional approach.

Figure 6 Images of spur gears under inspection using machine vision system

Gear 1 Gear 2 Gear 3

Gear 1, shown in Figure 6, has thinner teeth and hence has a deviation in tooth thickness and circular pitch outside the range according to the gear standards. Gear 2 has a slight radial runout and has uneven tooth thickness, resulting in a deviation in average tooth thickness outside the range specified by gear standards. Hence, both the gears are rejected by the machine vision inspection system developed. Gear 3 is a standard spur gear with all the deviations in tooth thickness, circular pitch, radial runout and tooth alignment error well within the expected standard range. Hence, the gear is accepted by the system. In this manner, the system can inspect the spur gears for different individual errors and decisions regarding acceptance or rejection based on the deviations according to gear standards.

Computational cost of the algorithm developed in MATLAB is measured in terms of memory and time required for processing the code. The program was run on a desktop with 8 GB RAM multiple times and the average time and memory utilisation was noted. It was found that the average time required to execute the algorithm was 40.75 seconds and memory utilisation was increased by 0.8 GB or 10.25% while running the program. Therefore it can be concluded that the algorithm developed in effective in terms of the computational cost.

6 Conclusions

The paper presented a machine vision approach for extracting important dimensions of a standard spur gear such as radii of addendum circle, dedendum circle, pitch circle, base circle, module, number of teeth, pressure angle, tooth thickness and circular pitch using image processing and feature extraction algorithms in MATLAB. Deviations in different dimensions from standard values and tooth alignment error and radial runout were calculated, followed by acceptance/rejection based on deviations according to IS standards for standard spur gears. The precision of the system was evaluated using a partial gauge R&R study. Three gears and three image acquisition devices (cameras) with different resolutions were selected for analysis. Three images of each gear were captured with each camera. All the 27 images were processed for extracting critical dimensions using image processing and feature extraction algorithms. The partial gauge R&R study indicated that variability due to gauge R&R was within 10%, with negligible or no appraiser bias for important dimensions, indicating repeatability and reproducibility of results. Images captured with a high-resolution camera provided the best results compared with values captured using traditional metrology instruments and standard spur gear formulae. Machine vision values were in good agreement with those obtained using the conventional approach with a maximum error of 6.37%.

The research work can be furthered by integrating this machine vision system with the production line for 100% automated inspection of spur gears. Algorithms can also be developed for computing composite errors using machine vision.

References

Ali, M.H., Kurokawa, S. and Uesugi, K. (2013) 'Vision based measurement system for gear profile', in *2013 International Conference on Informatics, Electronics and Vision (ICIEV)*, IEEE, pp.1–6.

Ali, M.H., Kurokawa, S. and Uesugi, K. (2014aa) 'Application of machine vision in improving safety and reliability for gear profile measurement', *Machine Vision and Applications*, Vol. 25, No. 6, pp.1549–1559.

Ali, M.H., Kurokawa, S. and Uesugi, K. (2014b) 'Camera based precision measurement in improving measurement accuracy', *Measurement*, March, Vol. 49, pp.138–147.

Chauhan, R., Mehan, V. and Mait, M. (2016) 'Identify defects in plastic gears using local binary pattern and morphological operations', *International Journal of Engineering Science*, Vol. 6, No. 3, pp.3062–3065.

Chen, J.Z., Wang, G.T., Chen, J.Q. and Yin, X.L. (2012) 'Automatic inspection system of small plastic gears based on machine vision', in *Key Engineering Materials*, Vol. 522, pp.628–633, Trans Tech Publications Ltd.

Chen, M. and Li, Y. (2010) 'The study of gear Parameter Measurement method based on machine vision', in *2010 International Conference on Intelligent Control and Information Processing*, IEEE, pp.248–251.

Ding, J., Zhang, Y., Zhuang, J. and Pan, R. (2016) 'A method of plastic gear inspection based on machine vision', in *2nd International Conference on Advances in Mechanical Engineering and Industrial Informatics*.

Du, H., Jin, W., Zhang, X. and Hu, J. (2011) 'A method of dimension measurement for spur gear based on machine vision', in *2011 International Conference on Multimedia and Signal Processing*, IEEE, Vol. 1, pp.243–246.

Faluvegi, E. and Cristea, L. (2011) 'Control operation and analysis of the spur gears profile', *Hungarian Journal of Industry and Chemistry*, Vol. 39, No. 2, pp.169–172.

Gadelmawla, E.S. (2009) 'Development of computer vision algorithms for measurement and inspection of spur gears (Dept. M)', *MEJ. Mansoura Engineering Journal*, Vol. 34, No. 1, pp.27–38.

Gadelmawla, E.S. (2011) 'Computer vision algorithms for measurement and inspection of spur gears', *Measurement*, Vol. 44, No. 9, pp.1669–1678.

Ge, D.Y., Yao, X.F., Lian, Z.T., Wang, H.Z. and Tao, T. (2017) 'Applications of computer vision in measuring total cumulative pitch deviation of a gear', *Tehnički vjesnik*, Vol. 24, No. 1, pp.71–78.

Goch, G. (2003) 'Gear metrology', *CIRP Annals-Manufacturing Technology*, Vol. 52, No. 2, pp.659–695.

Huang, Y., Gu, J., Wang, S., Xiao, H. and Yuan, K. (2016) 'Vision based embedded tiny spur gear inspection and measurement system', in *2016 IEEE International Conference on Mechatronics and Automation*, IEEE, pp.1679–1684.

Jalili, M., Dehgan, H. and Nourani, E. (2013) 'A cheap visual inspection system for measuring dimensions of brass gear', *International Journal of Computer and Electrical Engineering*, Vol. 5, No. 2, p.150.

Jin, W.Y., Du, H.R., Zhang, X. and Hu, J.P. (2011) 'Development on inspection system for gear's dimension based on machine vision', in *Advanced Materials Research*, Vol. 317, pp.925–930, Trans Tech Publications Ltd.

Kamal, I.M., Sutrisnowati, R.A., Bae, H. and Lim, T. (2018) 'Gear classification for defect detection in vision Inspection system using deep convolutional neural networks', *ICIC Express Letters Part B: Applications ICIC International*, Vol. 9, No. 12.

Liu, R., Zhong, D., Lyu, H. and Han, J. (2016) 'A bevel gear quality inspection system based on multi-camera vision technology', *Sensors*, Vol. 16, No. 9, p.1364.

Maitra, G.M. (1994) *Handbook of Gear Design*, 1 June, Tata McGraw-Hill Education, UK.

Mavi, A. and Kaur, M. (2012) 'Identify defects in gears using digital image processing', *International Journal of Engineering Research and Development ISSN*, June, Vol. 1, No. 6, pp.49–55, ISSN: 2278-067X.

Moru, D.K. and Borro, D. (2020) 'A machine vision algorithm for quality control inspection of gears', *The International Journal of Advanced Manufacturing Technology*, Vol. 106, No. 1, pp.105–123.

Robinson, M.J., Oakley, J.P. and Cunningham, M.J. (1995) 'The accuracy of image analysis methods in spur gear metrology', *Measurement Science and Technology*, Vol. 6, No. 7, p.860.

Tao, J., Luo, Z. and Liu, Q. (2019) 'Defect detection of small modulus gear based on machine vision', in *Tenth International Symposium on Precision Engineering Measurements and Instrumentation*, Vol. 11053, p.1105340, International Society for Optics and Photonics.

Urbas, U., Zorko, D., Černe, B., Tavčar, J. and Vukašinović, N. (2021) 'A method for enhanced polymer spur gear inspection based on 3D optical metrology', *Measurement*, February, Vol. 169, p.108584.

Wang, W., Guan, F., Ma, S. and Li, J. (2015) 'Measurement system of gear parameters based on machine vision', *Measurement and Control*, Vol. 48, No. 8, pp.242–248.

Wu, W., Wang, X., Huang, G. and Xu, D. (2015) 'Automatic gear sorting system based on monocular vision', *Digital Communications and Networks*, Vol. 1, No. 4, pp.284–291.

Wu, Y., Ge, D., Gao, X., Wen, X., Xu, Z., Zhu, Q. and Yao, X. (2019) 'Detection of gear tooth number and common normal length change based on computer vision', in *2019 International Conference on Artificial Intelligence and Advanced Manufacturing (AIAM)*, IEEE, pp.618–621.

Xiangwei, C.F.I.E.N. (2004) 'Research on measuring system for gear parameters based on CCD', *Tool Engineering*, Vol. 38, No. 5, pp.44–46.

Yu, L., Wang, Z. and Duan, Z. (2019) 'Detecting gear surface defects using background-weakening method and convolutional neural network', *Journal of Sensors*, Vol. 2019, pp.1–13, DOI: 10.1155/2019/3140980.