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Computer vision algorithms for measurement and inspection of external screw threads

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ABSTRACT

The current methods of measuring screw threads are either time consuming or expensive. In addition, no single measurement method is available and capable of accurately measuring all screw thread features while significantly reducing the measurement time. This paper introduces a vision system for automatic measurement and inspection of most types of screw threads. Many image processing and computer vision algorithms have been developed to analyze the captured images of screw threads and perform the measurement and inspection processes. Most of the common screw thread features (18 features) could be measured by the introduced vision system. The system has been calibrated for both imperial and metric units and was verified by measuring a standard ISO metric thread plug gage and comparing the results of the measurements with the standard values. The results showed that the maximum difference between the standard and measured values was ±5.4 μm, which provide a good accuracy for measurement.

1. Introduction

Screw threads probably are among the most important of all machine elements. Threaded pipe joints are commonly used in various industries such as petroleum, transport, and mining [1]. According to the statistics, the threaded connections generally account for 15% of the total mechanical parts in each machinery and equipment. The frequency of using screw thread is so high in the industrial production so that it also plays an important role to do real-time high-precision measurement and to improve the quality of accessories [2].

Due to the basic design of a screw thread, which involves helical geometry, screw thread technology is complex [3]. Methods of measuring threads are as varied as the threads themselves. These methods include coordinate measuring machines (CMM), profile projectors, laser measurements, measuring microscopes, 3-wire units, screw thread micrometers and V-groove micrometers. On the other hand, methods of thread inspection range from lasers to fixed and variable limit gauging.

There are about 30 separate geometrical features and dimensional characteristics in the design and construction of screw threads [4]. The most rigorous standard in the United States inspects 11 major thread characteristics [5]. In addition, recent researches [6,7] explored the effect of thread dimensional nonconformity on fastener performance and it was reported that dimensional nonconformity of 150% out of tolerance for pitch diameter yielded a 4% reduction in tensile strength. Therefore, the measurement and inspection of screw threads are very important to ensure the required degree of accuracy and conformity [8].

Due to the importance of measuring screw thread features, research in the field of measuring screw thread is still underway. For example, Laczik [9] introduced a derivation of geometrical features of the screw surfaces with the exact mathematical forms. Fujun et al. [10] presented a method, which used optical techniques and image processing techniques to measure the physical dimension of tube thread and give further analysis. Zhang and Zhang [11] introduced an online contact measuring system that can automatically detect large screw threads by using the neotype gauge head of threads. They used spectrum analysis to analyze the dynamic error and to obtain the data of the functional diameter. They reported that the neotype gauge head of thread is capable to get the error and the relative changes of the functional diameter of the screw thread. Tong et al. [12] introduced a system for automatic measurement of screw thread parameter based on the theory of laser measurement. The inspection and estimation of the screw thread contour were done using position sensitive device

Abbreviations: EPA, edge pixels arrangement; MISTVision, Screw Thread Measurement and Inspection by Vision; IPE, Inversion Pixels Extraction; CRPE, Crest and Root Pixels Extraction; CRPG, Crest and Root Pixels Grouping; CRGC, Crest and Root Groups Classification; CRDC, Crest and Root Data Calculation; STPC, Screw Thread Features Calculation; *pd*, perpendicular distance.

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(PSD) to measure the coordinate data of the screw thread contour and using precise raster to measure the axial displacement of the precision worktable. Gadelmawla [13] developed a non-contact measurement system using a measurescope, personal computer and developed software, for measuring and inspecting most of the common types of screw threads. Kosarev and Sugrobova introduced a method to inspect the quality of the profile of an internal screw thread produced by means of plastic deformation of metal is determined [14].

The current methods of measuring screw threads are either time consuming or expensive. In addition, no single measurement method is available and capable of accurately measuring all screw features while significantly reducing the measurement time. Therefore, the aim of this work is to develop a non contact measuring system, based on the computer vision techniques, for measuring and inspecting the most common features of external screw threads.

2. Implemented vision system

A vision system consists of two main parts, hardware and a developed software, has been used. The hardware is used to capture images for screw threads to be measured and the software is used to analyze the captured images and perform the measurement and inspection processes.

2.1. System setup

As shown in Fig. 1, the hardware consists of three items. The first item is the backlighting table, which is a lighting box with diffusing surface at its front, and it is used to produce a back lighting for the screw thread to be measured. The second item is a CCD color video camera and a set of lenses with different focal lengths. The camera is carried by a camera holder and it is connected to a PC computer through a USB connection. Capturing software is provided with the CCD camera to acquire images with different resolutions up to 4.2 Mp (2048 $*$ 2048 pixels).

The developed software, named MISTVision (Measurement and Inspection of Screw Threads by Vision), 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 and inspect screw thread features from captured images. Fig. 2 shows the main interface of the *MISTVision* software.

2.2. Capturing images

Before capturing images for screw threads to be measured, the vision system was adjusted to capture images that satisfy the following criteria:

1. The screw thread to be measured is set on the backlighting table so that its axis appears horizontally in the captured image.
2. The CDD camera is adjusted so that the image of the screw thread appears as maximum as possible in the capturing software window.
3. At least, three complete threads should appear in the captured image for both the upper and lower profiles of the screw thread.
4. The left and right sides of the captured image should be opened, i.e., there is no background at the left or right sides of the image.
5. The size of the captured images will affect the accuracy of measurement, as it will be discussed in Section 5.3; therefore, the vision system was adjusted to capture images of size 2048 $*$ 2048 pixels to obtain good accuracy (5 μm/pixel).

3. The developed algorithms

Several image processing and computer vision algorithms have been developed and applied to the captured image to perform the measurement and inspection processes. Fig. 3 shows the procedures of applying these algorithms and the following sections explain them.

3.1. Image processing algorithms

The aim of the image processing algorithms is to extract the coordinates of the pixels that constitute the upper and lower profiles of the screw threads. These coordinates will be utilized by developed computer vision algorithms to measure the screw thread features. Five image processing algorithms were used: image segmentation, edge pixels detection, edge pixels thinning, edge pixels labeling, and edge pixels arrangement (EPA). The first four algorithms were explained in a previous work [15] while the EPA algorithm is explained here.

3.1.1. Edge pixels arrangement

The pixels stored in the UpperEdgePixels and LowerEdgePixels arrays are usually not arranged due to the scanning process discussed in the edge detection algorithm. To deal with the extracted pixels easily, these pixels should be arranged sequentially according to their positions in the thread profiles. Therefore, the Edge Pixel Arrangement (EPA) algorithm is designed to perform this process. This algorithm works as follows:

1. Search all pixels in the UpperEdgePixels array to find the pixel that has the minimum x coordinate and mark it as the first pixel in the array.
2. Measure all distances between the first pixel and the remaining pixels in the UpperEdgePixels array to find the pixel that has the minimum distance and mark it as the second pixel in the UpperEdgePixels.
3. Repeat step 2 by measuring the distances between the second pixel and all remaining pixels in the UpperEdgePixels array to find third pixel.
4. Repeat step 3 to arrange all remaining pixels in the UpperEdgePixels according to their minimum distances from the previous pixel.

The result of the EPA algorithm is a list of pixels arranged sequentially from left to right. The two lists shown in the left side of Fig. 4 shows the extracted pixels of the upper and lower profiles after applying the EPA algorithm.

3.2. Computer vision algorithms

Six computer vision algorithms were developed to calculate the screw thread features (18 features) and one algorithm was developed to inspect the screw threads. Once the coordinates of the upper and lower profiles are arranged sequentially by the EPL algorithm, the computer vision algorithms are applied to perform the measurement and inspection processes as discussed in the following subsections.

3.2.1. Inversion Pixels Extraction

For screw thread profiles, the inversion pixels are the pixels at which the profile changes its direction as shown in Fig. 5. For any pixel in the screw thread profile, the direction of the profile can be calculated by subtracting the y coordinate of that pixel from the y coordinates of both the previous and next pixels. If the two values have the same sign (positive or negative), then the pixel is considered an inversion pixel. The inversion pixels are useful to

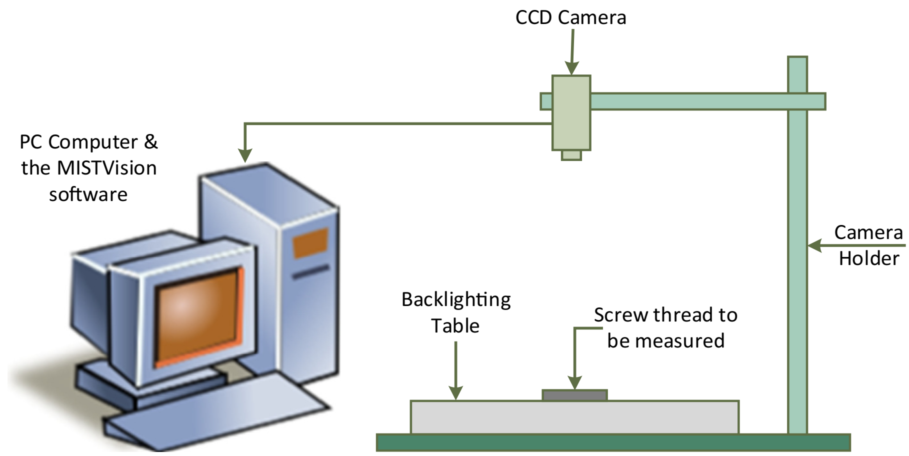


Fig. 1. Layout of the implemented vision system.

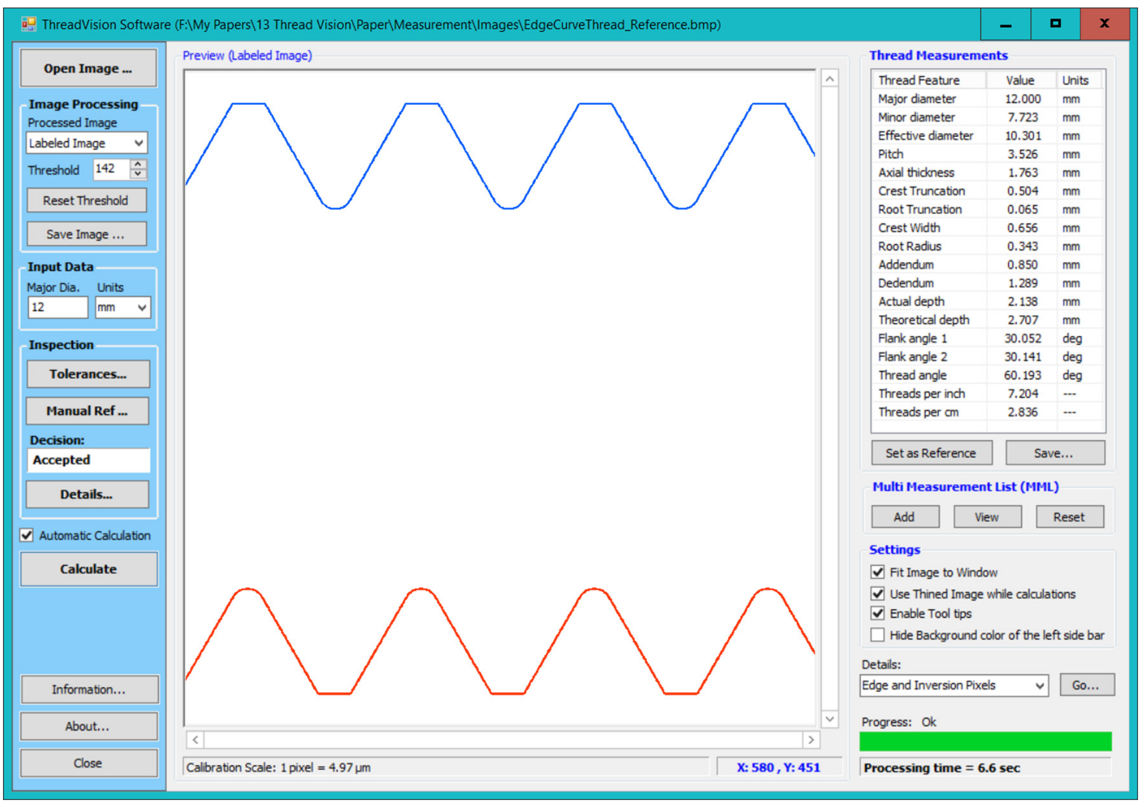


Fig. 2. Main interface of the MISTVision software.

calculate the crest and root lines of the screw threads; therefore, the Inversion Pixels Extraction (IPE) algorithm has been developed to extract all inversion pixels from the edge pixels of the upper and lower profiles. For example, the IPE algorithm extracts the inversion pixels of the upper profile as follows:

1. Find the first two successive pixels which have different y coordinates, for example y_n, y_{n+1}.
2. Using the image coordinate system shown in Fig. 5, the initial direction (Dir_{Init}) of the profile can be calculated between these two pixels as follows:
   If $y_{n+1} < y_n$ then Dir_{Init} = Up, otherwise, Dir_{Init} = Down.
3. Consider the initial direction (Dir_{Init}) is the previous direction (Dir_{Prev}) for the next pixels, i.e., $Dir_{Prev} = Dir_{Init}$.
4. Loop through all remaining pixels in the *UpperEdgePixels* array and do the following for each pixel. Consider *i* the pixel number of the current pixel.
   a. Calculate the next direction (Dir_{Next}) of the profile by comparing the *y* coordinate of the next pixel (y_{i+1}) with the *y* coordinate of the current pixel (y_i) as follows:
      – If $y_{i+1} < y_i$ then Dir_{Next} = Up
      – Else If $y_{i+1} > y_i$ then Dir_{Next} = Down
      – Otherwise, skip.

   b. If Dir_{Prev} and Dir_{Next} are the same then skip, otherwise, do the following:
   – If Dir_{Next} = Down, then mark the current pixel as crest inversion pixel.

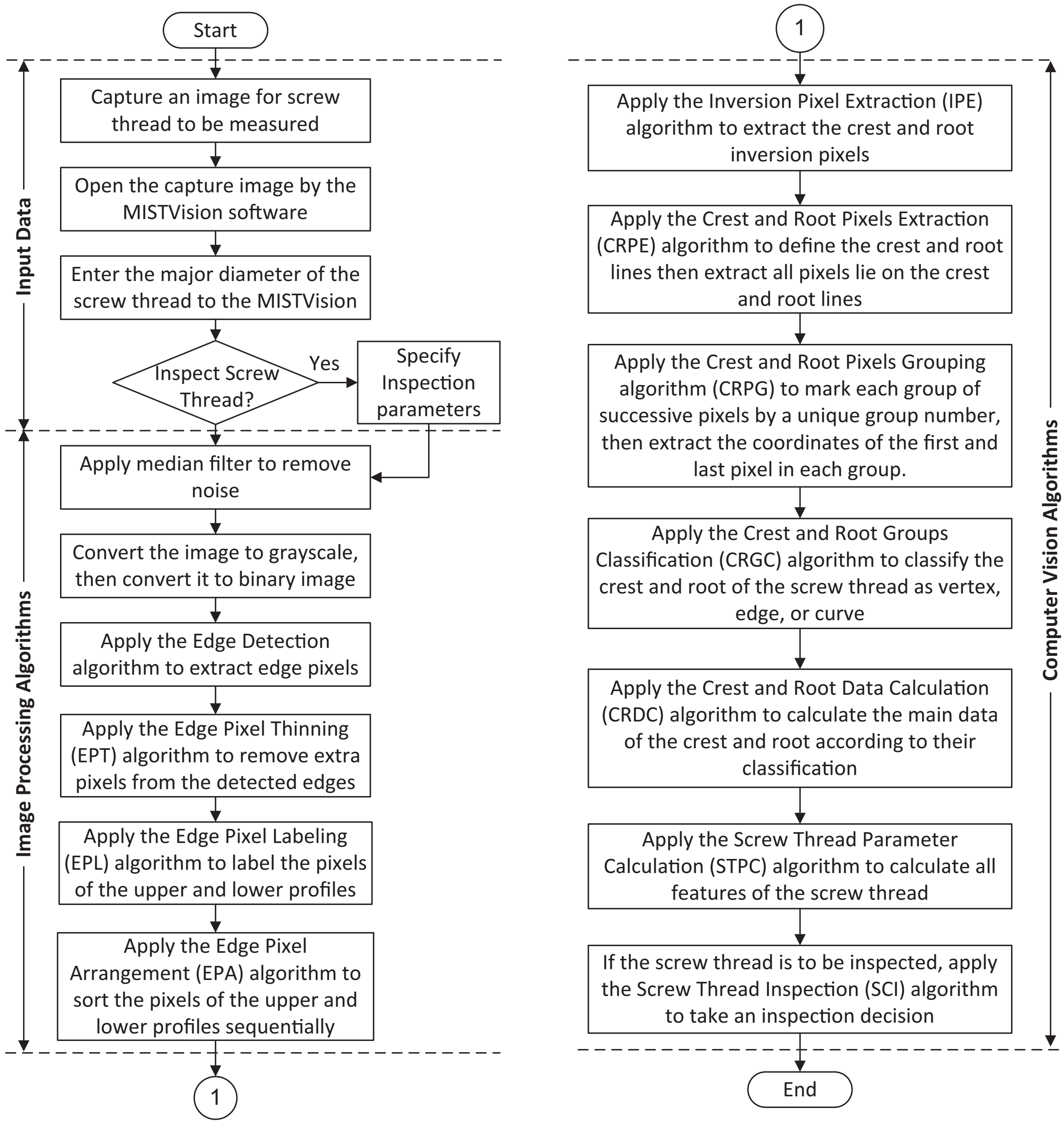


Fig. 3. Procedures of the measurement and inspection process by MISTVision software.

– If Dir_{Next} = Up, then mark the current pixel as root inversion pixel.
– Set Dir_{Prev} = Dir_{Next} then loop to the next pixel.

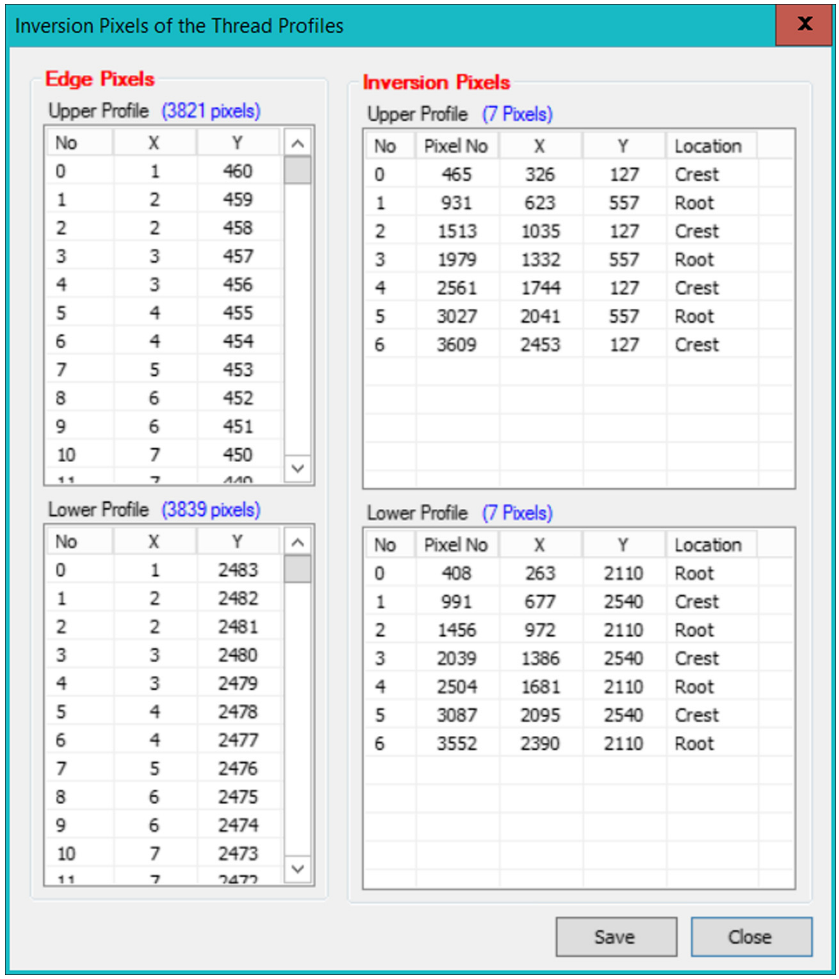
The IPE algorithm uses the same procedures to extract the inversion pixels of the lower profile with one exception in step 4. b. For the lower profile, if Dir_{Next} = Down, then the current pixel is marked as root inversion pixel instead of crest inversion pixel. Similarly, if Dir_{Next} = Up, then the current pixel is marked as crest inversion pixel instead of root inversion pixel. The two lists shown in the right side of Fig. 4 shows the inversion pixels extracted by the IPE algorithm for the upper and lower profiles.

3.2.2. Crest and Root Pixels Extraction

The Crest and Root Pixels Extraction (CRPE) algorithm has been developed to extract all pixels lie on the crest and root lines of the screw thread profiles. Based on the geometry of the screw thread profile shown in Fig. 6, the crest lines are the two lines pass through the crest inversion pixels of the upper and lower profiles. Similarly, the root lines are the two lines pass through the root inversion pixels of the upper and lower profiles.

By referring to Fig. 4, the upper right list represents the crest and root inversion pixels of the upper profile. From this list, the crest line of the upper profile can be defined as the line connects between the first crest inversion pixel (pixel 465) and the last crest inversion pixel (pixel 3609). Similarly, the root line of the upper profile can be defined as the line connects between the first root inversion pixel (pixel 931) and the last root inversion pixel (pixel 3027). Similarly, the crest and root lines of the lower profiler can be defined. Table 1 shows the extracted data for the crest and root lines of the upper and lower profiles.

Any pixel can be classified as crest/root pixel if the perpendicular distance (pd) between the pixel and the crest/root line is nearly equal to zero, i.e. $1 > pd > -1$. For example, the CRPE algorithm extracts the crest pixels of the upper profile by calculating pd between each pixel in the *UpperEdgePixels* array and the crest line of the upper profile. All pixels satisfy the condition of $1 > pd > -1$ are marked as crest pixel for the upper profile. The value of pd can be calculated using Eq. (1):



Inversion Pixels of the Thread Profiles

Edge Pixels

Upper Profile (3821 pixels)

No	X	Y
0	1	460
1	2	459
2	2	458
3	3	457
4	3	456
5	4	455
6	4	454
7	5	453
8	6	452
9	6	451
10	7	450

Lower Profile (3839 pixels)

No	X	Y
0	1	2483
1	2	2482
2	2	2481
3	3	2480
4	3	2479
5	4	2478
6	4	2477
7	5	2476
8	6	2475
9	6	2474
10	7	2473

Inversion Pixels

Upper Profile (7 Pixels)

No	Pixel No	X	Y	Location
0	465	326	127	Crest
1	931	623	557	Root
2	1513	1035	127	Crest
3	1979	1332	557	Root
4	2561	1744	127	Crest
5	3027	2041	557	Root
6	3609	2453	127	Crest

Lower Profile (7 Pixels)

No	Pixel No	X	Y	Location
0	408	263	2110	Root
1	991	677	2540	Crest
2	1456	972	2110	Root
3	2039	1386	2540	Crest
4	2504	1681	2110	Root
5	3087	2095	2540	Crest
6	3552	2390	2110	Root

Save Close

Fig. 4. Extracted coordinates of the edge pixels (left lists) and Inversion pixels (right lists) for the upper and lower profiles.

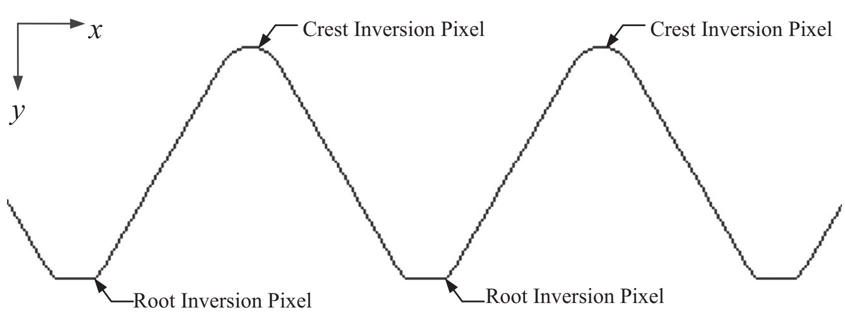


Fig. 5. Inversion pixels at the crest and root of the upper profile (enlarged image).

$$Pd = \frac{(x_2 - x_1)(y_1 - y_3) - (x_1 - x_3)(y_2 - y_1)}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}} \qquad (1)$$

where pd is the perpendicular distance, x_1, y_1 are the coordinates of the first pixel (p_1) of the crest line and x_2, y_2 are the coordinates of the last pixel (p_2), x_3, y_3 are the coordinates of the pixel at which pd is calculated (p_3).

For Cartesian coordinates, negative values of pd means that the pixel p_3 lies to the left of the crest line (looking from the first pixel to the second pixel), positive values means that the pixel p_3 lies to the right of the crest line, and zero values means that the pixel p_3 lies on the crest line. For the image coordinates shown in Fig. 5, the opposite is true, i.e., negative values of pd means that the pixel p_3 lies to the right of the crest line and positive values means that the pixel p_3 lies to the left.

The crest and root pixels of the upper profile can be extracted by applying the following steps:

1. For each pixel in the upper profile, calculate pd between the pixel and the crest line.
2. If $pd < 1$ and $pd > -1$, then mark the pixel as crest pixel.
3. For each pixel in the upper profile, calculate pd between the pixel and the root line.
4. If $pd < 1$ and $pd > -1$, then mark the pixel as root pixel.

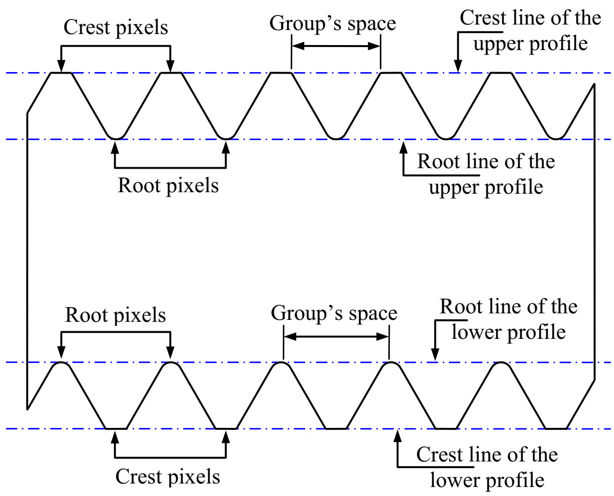


Fig. 6. Using crest and root lines to extract crest and root pixels.

The crest and root pixels of the lower profile can be extracted by the same way. Fig. 7 shows the extracted crest and root pixels for the upper and lower profiles. The number of crest pixels for the upper and lower profiles is greater than the number of root pixels because the crest of the investigated thread (Fig. 2) is a straight edge while the root is a curve.

3.2.3. Crest and Root Pixels Grouping

The aim of the Crest and Root Pixels Grouping (CRPG) algorithm is to extract useful information about the screw thread from the crest and root pixels extracted by the CRPE algorithm. This can be done by applying the following two steps:

1. Assigning each group of successive pixels a unique group number.
2. Extracting useful information from the identified groups.

3.2.3.1. Assigning each group of successive pixels a unique group number. In this step, each pixel is assigned a unique group number based on the distance between the pixel and the next pixel. As shown in Fig. 7, the distance between each two successive pixels in the same group will be equal to 1 pixel and should not be greater than 1.414 ($\sqrt{2}$). The space between each two groups of pixels is represented by the distance between the last pixel in one group and the first pixel in the next group. This space will always be greater than 2 pixels. Considering this, the CRPG algorithm can group the crest pixels of the upper profile, for example, as follows:

1. Consider the first pixel is the current pixel and assign it a group number of 1.
2. Calculate the distance between the current pixel and the next pixel.
3. If the calculated distance is less than or equal to 2 pixels, then assign the same group number to the next pixel, otherwise, increase the group number by 1 and assign the new group number to the next pixel.
4. Move to the next pixel and consider it the current pixel.
5. Repeat steps 2–4 for all crest pixels of the upper profile.

The root pixels of the upper profile as well as the crest and root pixels of the lower profile can be assigned a unique group number using the same way. As shown in the last column of each list in Fig. 7, each pixel is assigned a unique group number by this algorithm.

3.2.3.2. Extracting useful information from the identified groups. After assigning each pixel a unique group number, each group of successive pixels can be considered as a short line. Therefore, useful information such as the start, the end, and the length of each short line can be calculated from each group as shown in Fig. 8. For each group, the coordinates of the start point are the coordinates the first pixel in the group. Similarly, the coordinates of the end point are the coordinates of the last pixel in the group. The length of each short line is the distance between the start and the end points of each group.

3.2.4. Crest and Root Groups Classification

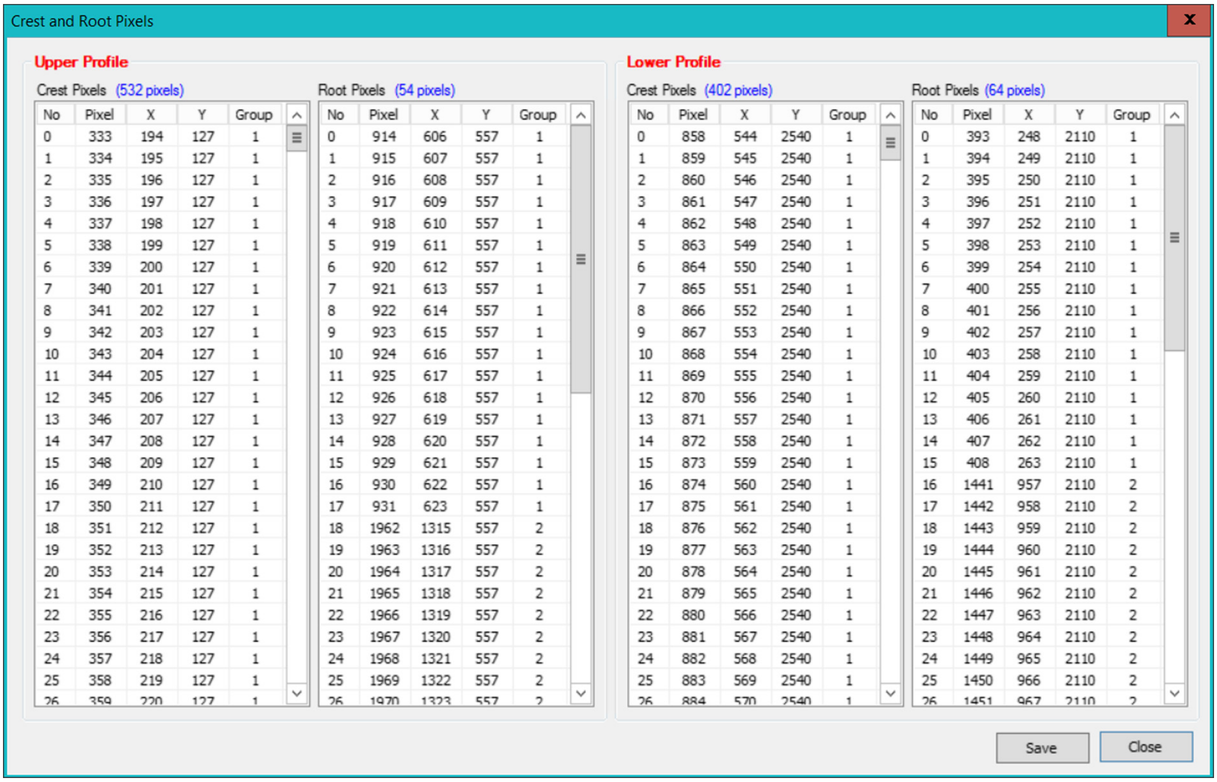
Based on the screw thread type, the root and crest can be classified as vertex, edge, or curve. As a result, the shape of the screw threads can be classified into the five groups shown in Figs. 9 and 10a. Based on this classification, the Crest and Root Groups Classification (CRGC) algorithm uses the information extracted by the CRPG algorithm to classify the crest and root of the screw thread. By referring to Fig. 9, the CRGC algorithm can classify the crest and root of the upper profile, for example, as follows:

1. Assume a flank line fl_1 connects the end pixel of a root group (R_e) and the start pixel of the next crest group (C_s).
2. For all pixels lie between the two pixels (R_e, C_s), use Eq. (1) to calculate the minimum perpendicular distance (pd_{min}) and the maximum perpendicular distance (pd_{max}) between each pixel and the flank line fl_1.
3. For the four cases shown in Fig. 9, use the calculated values of pd_{min} and pd_{max} to classify the crest and root shape as shown in Table 2. It should be noticed here that the calculated values shown in the table are based on the image coordinate system, not Cartesian coordinate system.
4. As shown in Fig. 10, use the lengths of the crest and root groups (C_s, C_e/R_s, R_e), which were calculated by the CRPG algorithm, to distinguish between vertex and edge shapes. If the group length is less than 2 pixels, then classify the crest/root as vertex, otherwise, classify the crest/root as edge.

After applying the CRGC algorithm, the crest and root of the screw thread are classified as shown in the upper section in Fig. 11.

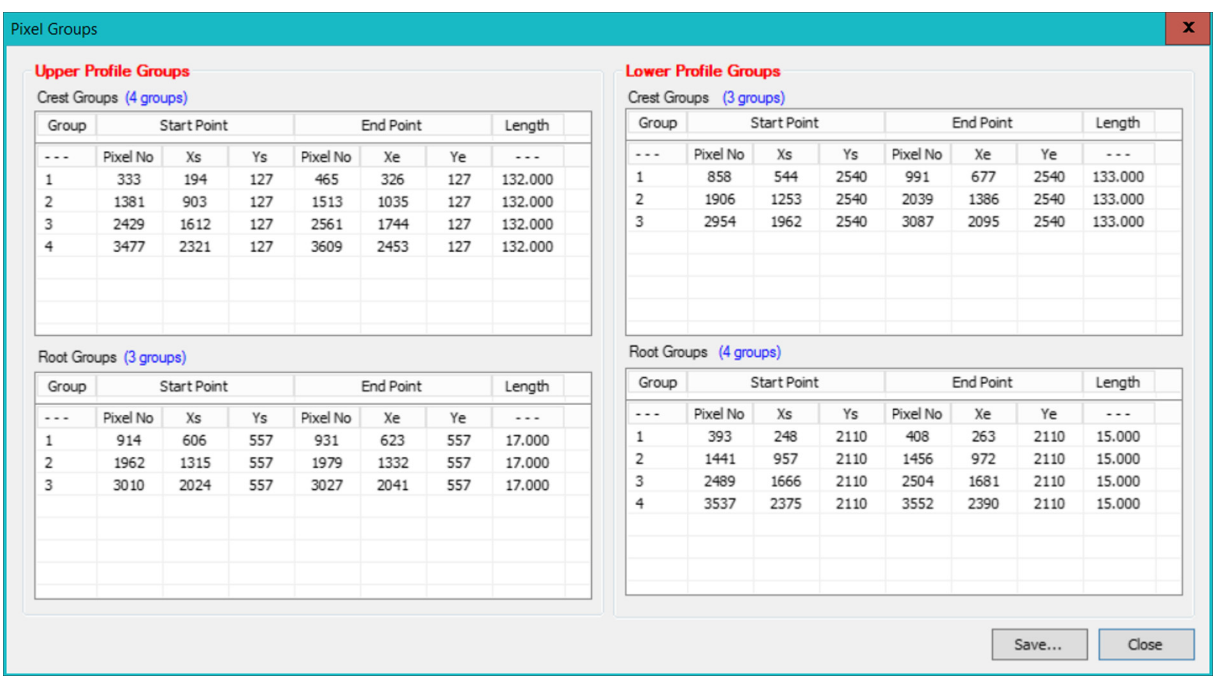
Table 1
Extracted data for the crest and root lines of the upper and lower profiles.

Profile	Line type	First pixel			Last pixel		
		Pixel no.	X1	Y1	Pixel no.	X2	Y2
Upper	Crest line	465	326	127	3609	2453	127
	Root line	931	623	557	3027	2041	557
Lower	Crest line	991	677	2540	3087	2095	2540
	Root line	408	263	2110	2552	2390	2110



No	Pixel	X	Y	Group	No	Pixel	X	Y	Group	No	Pixel	X	Y	Group	No	Pixel	X	Y	Group
0	333	194	127	1	0	914	606	557	1	0	858	544	2540	1	0	393	248	2110	1
1	334	195	127	1	1	915	607	557	1	1	859	545	2540	1	1	394	249	2110	1
2	335	196	127	1	2	916	608	557	1	2	860	546	2540	1	2	395	250	2110	1
3	336	197	127	1	3	917	609	557	1	3	861	547	2540	1	3	396	251	2110	1
4	337	198	127	1	4	918	610	557	1	4	862	548	2540	1	4	397	252	2110	1
5	338	199	127	1	5	919	611	557	1	5	863	549	2540	1	5	398	253	2110	1
6	339	200	127	1	6	920	612	557	1	6	864	550	2540	1	6	399	254	2110	1
7	340	201	127	1	7	921	613	557	1	7	865	551	2540	1	7	400	255	2110	1
8	341	202	127	1	8	922	614	557	1	8	866	552	2540	1	8	401	256	2110	1
9	342	203	127	1	9	923	615	557	1	9	867	553	2540	1	9	402	257	2110	1
10	343	204	127	1	10	924	616	557	1	10	868	554	2540	1	10	403	258	2110	1
11	344	205	127	1	11	925	617	557	1	11	869	555	2540	1	11	404	259	2110	1
12	345	206	127	1	12	926	618	557	1	12	870	556	2540	1	12	405	260	2110	1
13	346	207	127	1	13	927	619	557	1	13	871	557	2540	1	13	406	261	2110	1
14	347	208	127	1	14	928	620	557	1	14	872	558	2540	1	14	407	262	2110	1
15	348	209	127	1	15	929	621	557	1	15	873	559	2540	1	15	408	263	2110	1
16	349	210	127	1	16	930	622	557	1	16	874	560	2540	1	16	1441	957	2110	2
17	350	211	127	1	17	931	623	557	1	17	875	561	2540	1	17	1442	958	2110	2
18	351	212	127	1	18	1962	1315	557	2	18	876	562	2540	1	18	1443	959	2110	2
19	352	213	127	1	19	1963	1316	557	2	19	877	563	2540	1	19	1444	960	2110	2
20	353	214	127	1	20	1964	1317	557	2	20	878	564	2540	1	20	1445	961	2110	2
21	354	215	127	1	21	1965	1318	557	2	21	879	565	2540	1	21	1446	962	2110	2
22	355	216	127	1	22	1966	1319	557	2	22	880	566	2540	1	22	1447	963	2110	2
23	356	217	127	1	23	1967	1320	557	2	23	881	567	2540	1	23	1448	964	2110	2
24	357	218	127	1	24	1968	1321	557	2	24	882	568	2540	1	24	1449	965	2110	2
25	358	219	127	1	25	1969	1322	557	2	25	883	569	2540	1	25	1450	966	2110	2

Fig. 7. Extracted crest and root pixels for the upper and lower profiles.



Upper Profile Groups – Crest Groups (4 groups)

Group	Start Point			End Point			Length
---	Pixel No	Xs	Ys	Pixel No	Xe	Ye	---
1	333	194	127	465	326	127	132.000
2	1381	903	127	1513	1035	127	132.000
3	2429	1612	127	2561	1744	127	132.000
4	3477	2321	127	3609	2453	127	132.000

Upper Profile Groups – Root Groups (3 groups)

Group	Start Point			End Point			Length
---	Pixel No	Xs	Ys	Pixel No	Xe	Ye	---
1	914	606	557	931	623	557	17.000
2	1962	1315	557	1979	1332	557	17.000
3	3010	2024	557	3027	2041	557	17.000

Lower Profile Groups – Crest Groups (3 groups)

Group	Start Point			End Point			Length
---	Pixel No	Xs	Ys	Pixel No	Xe	Ye	---
1	858	544	2540	991	677	2540	133.000
2	1906	1253	2540	2039	1386	2540	133.000
3	2954	1962	2540	3087	2095	2540	133.000

Lower Profile Groups – Root Groups (4 groups)

Group	Start Point			End Point			Length
---	Pixel No	Xs	Ys	Pixel No	Xe	Ye	---
1	393	248	2110	408	263	2110	15.000
2	1441	957	2110	1456	972	2110	15.000
3	2489	1666	2110	2504	1681	2110	15.000
4	3537	2375	2110	3552	2390	2110	15.000

Fig. 8. Results of the Crest and Root Pixels Grouping (CRPG) algorithm.

3.2.5. Crest and Root Data Calculation (CRDC)

After classifying the crest and root of the screw thread, the Crest and Root Data Calculation (CRDC) algorithm is used to calculate the main data of the screw thread. This data include the crest/root width for straight features and the crest/root radius for curved features. By referring to Fig. 9, the CRDC algorithm calculates the main data of the screw thread as follows:

1. If the crest/root is classified as a vertex, the start and end pixels will be the same and their coordinates can be extracted from the pixel groups shown in Fig. 8. Accordingly, the coordinates of the middle pixel will be the same as the first and end pixels.
2. If the crest/root is classified as an edge, the start and end pixels will be different and their coordinates can be extracted

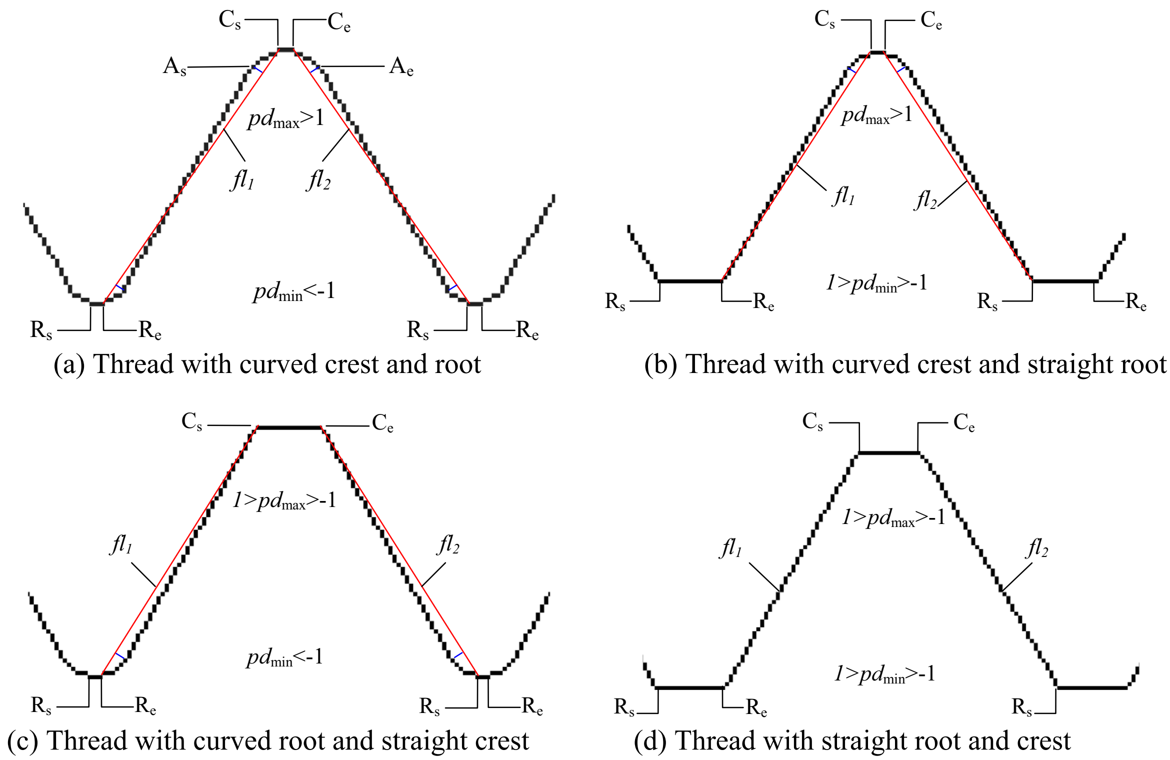


Fig. 9. Classification of crest and root as straight and curve (magnified images) (C_s: Crest start, C_e: Crest end, R_s: Root start, R_e: Root end, A_s: Arc start, A_e: Arc end, pd_{min}: Minimum perpendicular distance, pd_{max}: Maximum perpendicular distance).

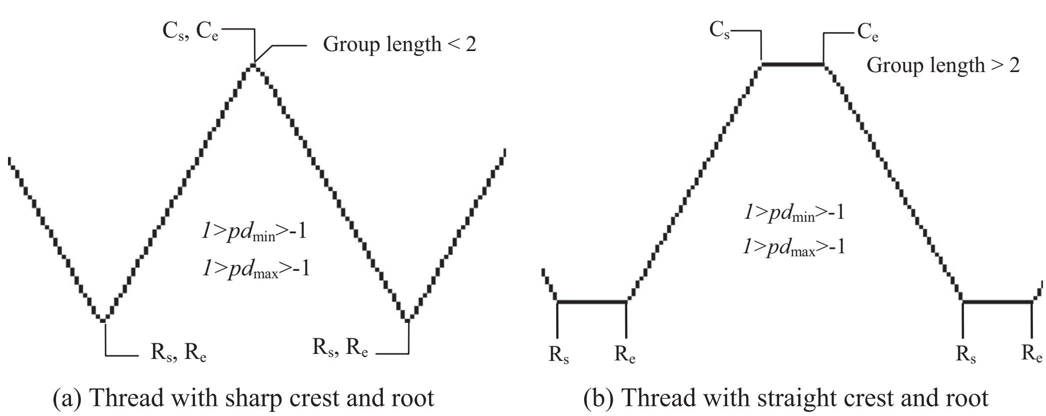


Fig. 10. Classification of screw threads having straight and vertex crests and roots.

Table 2
Classification of the crest and root shapes according to the minimum and maximum distances between flank pixels and the flank line.

Thread type	pd_{min}	pd_{max}	Crest	Root
(a)	$pd_{min} < -1$	$pd_{max} > 1$	Curve	Curve
(b)	$1 > pd_{min} > -1$	$pd_{max} > 1$	Curve	Vertex/edge
(c)	$pd_{min} < -1$	$1 > pd_{max} > -1$	Vertex/edge	Curve
(d)	$1 > pd_{min} > -1$	$1 > pd_{max} > -1$	Vertex/edge	Vertex/edge

from the pixel groups shown in Fig. 8. The middle pixel is calculated as the point between the start and end pixels.

3. If the crest/root is classified as a curve, three points are required to identify the arc. As shown in Fig. 9a, the start and end points of the crest arc (A_s, A_e) can be defined as the two pixels which produce the maximum perpendicular distances (pd_{max}) from the two flank lines (fl_1, fl_2). The second point of the arc can be calculated as the middle point between the start and end pixels.

Once the three points of the arc are defined, the center and radius of the arc can be calculated. If (x_1,y_1), (x_2,y_2) and (x_3,y_3) are the coordinates of the start, middle, and end point of the arc, respectively, then the coordinates of the center point can be calculated using Eqs. (2) and (3) and the radius can be calculated using Eq. (4):

$$c_x = \frac{a(cc' + bb') - b(dd' + aa')}{2(ce - be')} \tag{2}$$

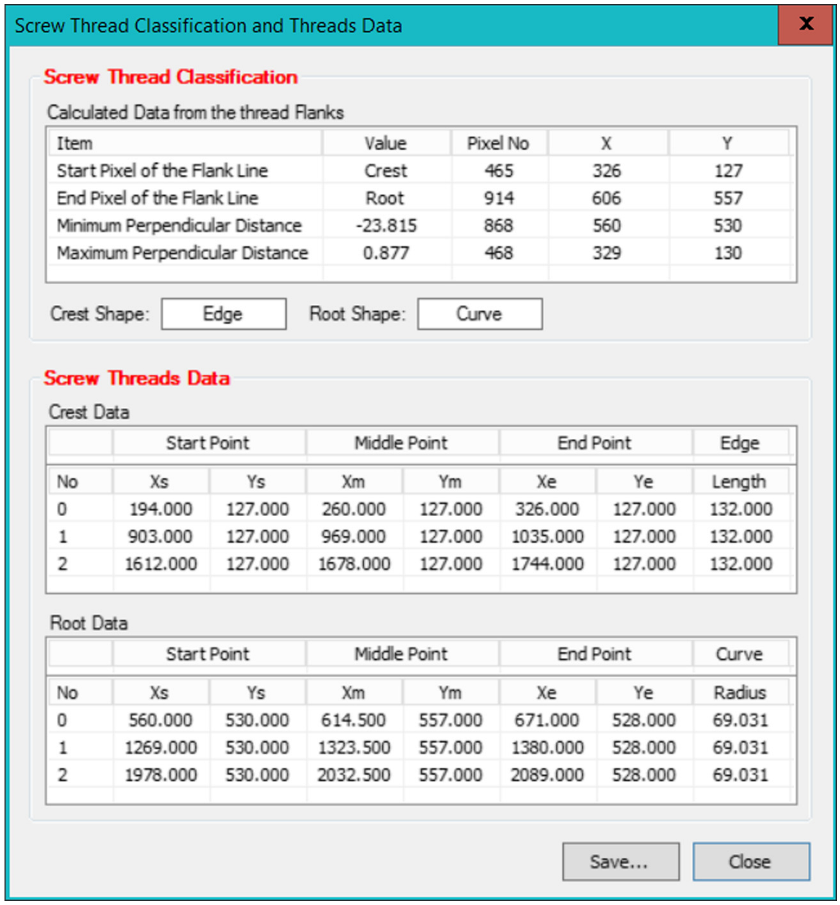


Fig. 11. Classification of the crest and root of the screw thread (upper section) and calculating the main data of the screw thread (lower section).

$$c_y = \frac{c(dd' + aa') - d(cc' + bb')}{2(ce - be')} \tag{3}$$

$$R = \sqrt{(x_i - c_x)^2 + (y_i - c_y)^2} \tag{4}$$

where

c_x and c_y are the x and y coordinates of the center point of the arc.
$a = y_3 - y_1,\ a' = y_3 + y_1$
$b = y_2 - y_1,\ b' = y_2 + y_1$
$c = x_2 - x_1,\ c' = x_2 + x_1$
$d = x_3 - x_1,\ d' = x_3 + x_1$
$e = y_3 - y_2,\ e' = x_3 - x_2$
x_i and y_i are the x and y coordinates of the start point of the arc.

After applying the CRDC algorithm, the main data of the screw thread is calculated as shown in the lower section in Fig. 11.

3.2.6. Screw Thread Features Calculation

The Screw Thread Features Calculation (STFC) algorithm is used to calculate the screw thread features based on the main data extracted by the CRDC algorithm. The main important features are calculated as follows.

3.2.6.1. Calculation of the major and minor diameters. By referring to Fig. 6, the major diameter can be calculated by calculating the perpendicular distance (*pd*) between any pixel in the crest pixel groups of the upper profile and the crest line of the lower profile. To obtain accurate measurements, three calculations are performed for three pixels in different groups, then the average of the three calculations is taken as the major diameter. Similarly, the minor diameter can be calculated by calculating *pd* between any pixel in the root pixel groups of the upper profile and the root line of the lower profile.

3.2.6.2. Calculation of the theoretical depth and crest truncation. By referring to Fig. 12, the theoretical depth (h_1) of the screw thread can be calculated as follows:

1. If P_1 and P_2 are the two end points of the flank line fl_1 and P_3 and P_4 are two end points of the flank line fl_2, then the intersection point (P_5) of the two flank lines can be calculated using Eqs. (5) and (6).

$$x_{\text{int}} = P1_x + r * (P2_x - P1_x) \tag{5}$$

$$y_{\text{int}} = P1_y + r * (P2_y - P1_y) \tag{6}$$

where

x_{int} is the x coordinate of the intersection point,
y_{int} is the y coordinate of the intersection point,

$$r = \frac{(P1_y - P3_y)(P4_x - P3_x) - (P1_x - P3_x)(P4_y - P3_y)}{(P2_x - P1_x)(P4_y - P3_y) - (P2_y - P1_y)(P4_x - P3_x)} \tag{7}$$

If the denominator in Eq. (7) is equal to zero, then the two lines are parallel.

2. Similarly, the intersection points P_6 and P_7 can be calculated between the two flank lines fl_3 and $fl4$ and the two flank lines fl_2 and fl_3 respectively.
3. The theoretical depth (h_1) can be calculated as the perpendicular distance between the point P_7 and the line connecting P_5 and P_6. This distance can be calculated using Eq. (1).
4. The crest truncation (h_2) can be calculated as the perpendicular distance between any pixel in the crest groups of the upper profile and the line connecting P_5 and P_6. Eq. (1) is also used to calculate this perpendicular distance.

3.2.6.3. Calculation of the pitch and effective diameter. By referring to Fig. 12, the pitch can be calculated as the distance between P_5 and P_6. The effective diameter line is defined as the line which divides the screw thread so that the widths of the threads and the widths of the spaces are equal on a perfect thread. According to this definition, the distance h_3 is equal to half of the theoretical depth, i.e. $h_3 = 0.5h_1$. Hence, the effective diameter ($D_{effective}$) of the screw thread can be calculated as follows:

$$D_{effective} = D_{major} - 2(h_3 - h_2),$$
$$D_{effective} = D_{major} - 2(0.5h_1 - h_2) \tag{8}$$

where D_{major} is the major diameter, h_1 is the theoretical depth, h_2 is the crest truncation.

3.2.6.4. Calculation of the axial thickness. By referring to Fig. 12, the axial thickness (T_e) is the width of the screw thread measured at the effective line. To calculate the axial thickness, the effective diameter line should be defined by any two end points, for example, P_8 and P_9. Based on the screw thread geometry, the effective diameter line is parallel to the line P_5 P_6 and far from it with a distance equal to h_3. Therefore, the two end points (P_8 and P_9) of the effective diameter line can be calculated as follows:

$$P_8 \cdot x = P_5 \cdot x + h_3 * \mathrm{Cos}(\theta) \tag{9}$$
$$P_8 \cdot y = P_5 \cdot y + h_3 * \mathrm{Sin}(\theta) \tag{10}$$
$$P_9 \cdot x = P_6 \cdot x + h_3 * \mathrm{Cos}(\theta) \tag{11}$$
$$P_9 \cdot y = P_6 \cdot y + h_3 * \mathrm{Sin}(\theta) \tag{12}$$

where $P_8{\cdot}x$ and $P_8{\cdot}y$ are the x and y coordinates of P_8, $P_9{\cdot}x$ and $P_9{\cdot}y$ are the x and y coordinates of P_9, h_3 equal to the half of the theoretical depth, θ is the angle of inclination of the line P_5 P_6. For horizontal lines, θ is equal to zero.

After defining the effective diameter line, the axial thickness can be calculated as follows:

1. Use Eqs. (7)–(9) to calculate the intersection point (P_{10}) between the effective diameter line and the flank line fl_1.
2. Similarly, calculate the intersection point (P_{11}) between the effective diameter line and the flank line fl_2.
3. Calculate the axial thickness as the distance between P_{10} and P_{11}.

3.2.6.5. Calculation of the other features of the screw thread. The rest of the screw thread features can be calculated using similar ways according to the basic geometry shown in Fig. 13. For example, the Addendum (10) can be calculated from the upper profile as the perpendicular distance between any pixel in the crest groups and the effective diameter line. Similarly, the Dedendum (11) can be calculated as the perpendicular distance between any pixel in the root groups and the effective diameter line. Also, the actual depth (12) can be calculated as the perpendicular distance between any pixel on the upper profile crest groups and the root line of the upper profile.

4. Work procedures

To perform the measurement or inspection processes, the screw thread to be measured is set on the backlighting table then an image is captured and saved to a BMP file using the capturing software provided with the CCD camera. The captured image is then opened by the *MISTVision* software to perform the measurement and inspection processes as shown in the following sub-sections.

4.1. Measurement of screw threads

By referring to the main interface shown in Fig. 2, if the Automatic calculation check box is checked, the measurement process is performed automatically after opening the captured image of the screw thread to be measured. Otherwise, the user should click the Calculate button. The calculated features of the screw thread appear in the Thread Measurement section. If the system is calibrated, as it will be discussed in Section 5, the thread features will be calculated in millimeters or inches. Otherwise, it will be calculated in pixels. The calculated features can be saved to a text file and it can be used as a reference data for the inspection process as it will be discussed in the next section.

4.2. Multi measurement process

In metrology, usually one measurement is not enough to give accurate results; therefore, the *MISTVision* software can store up to five measurements for the same screw thread in order to calculate the average values of the screw thread features. These measurements are stored to a list called Multi Measurement List

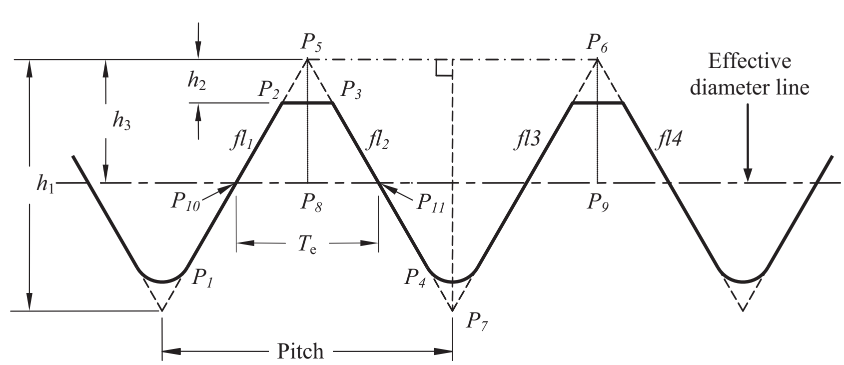
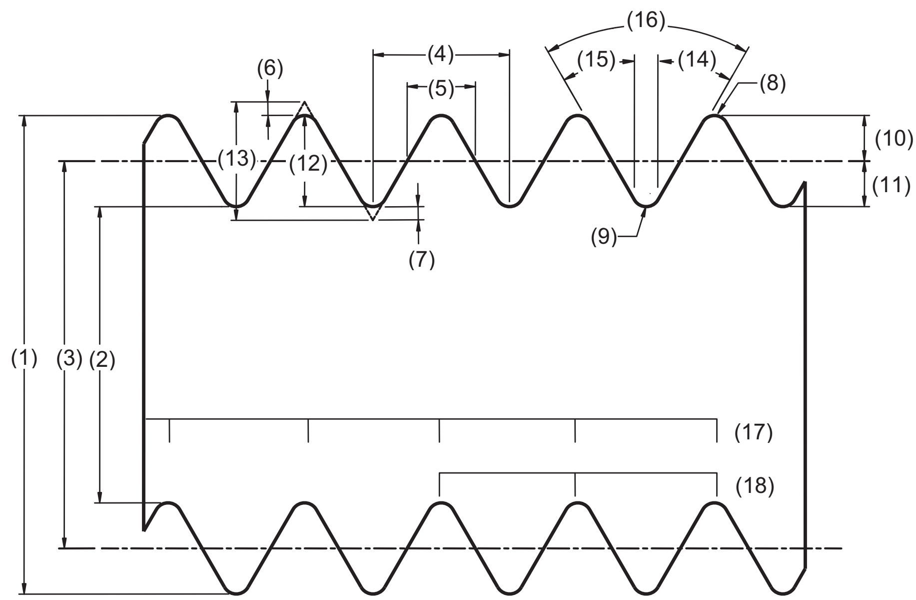


Fig. 12. Calculating the effective diameter and other thread features.



(1)	Major diameter	(7)	Root Truncation	(13)	Theoretical depth
(2)	Minor diameter	(8)	Crest width/Radius	(14)	Flank angle 1
(3)	Effective diameter	(9)	Root width/Radius	(15)	Flank angle 2
(4)	Pitch	(10)	Addendum	(16)	Thread angle
(5)	Axial thickness	(11)	Dedendum	(17)	No of threads per inch
(6)	Crest Truncation	(12)	Actual depth	(18)	No of threads per cm.

Fig. 13. Thread features that can be measured by the MISTVision software.

(*MML*) and each measurement can be obtained from a different image for the same screw thread. Fig. 14 shows the *MML* for three measurements obtained from three different images for the same screw thread and the average value for each screw thread parameter. The *MML* could be saved to a file for further usage.

4.3. Inspection of the screw threads

The inspection process is performed by comparing the measured features of the screw thread to be inspected with the features of a standard screw thread within specified tolerances. In the main interface of the MISTVision software (Fig. 2), the Inspection section deals with this process. The inspection process is performed using the following four steps:

1. *Entering the features for the reference screw thread:*

The standard features for the reference screw thread can be entered to the *MISTVision* software by two methods. In the first method, the standard screw thread is measured by the vision system and the calculated features are stored as reference values by clicking the *Set as Reference* button in the Thread measurement section. One reference screw thread could be used to check many screw threads. In the second method, the reference values are set manually by clicking the *Manual Ref.* button.

2. *Selecting the screw thread features to be inspected:*

This can be done through the Inspection Tolerances dialog box shown in Fig. 15, which can be displayed by clicking the *Tolerances* button. The features to be inspected should be checked and their allowable tolerances are assigned. Each parameter can be assigned unique tolerance values (lower and upper). Alternatively, the same tolerance value can be applied to all thread items by entering the required value in the text box *Value for all thread items* then clicking the *Assign* button.

3. *Measuring the screw thread to be inspected*

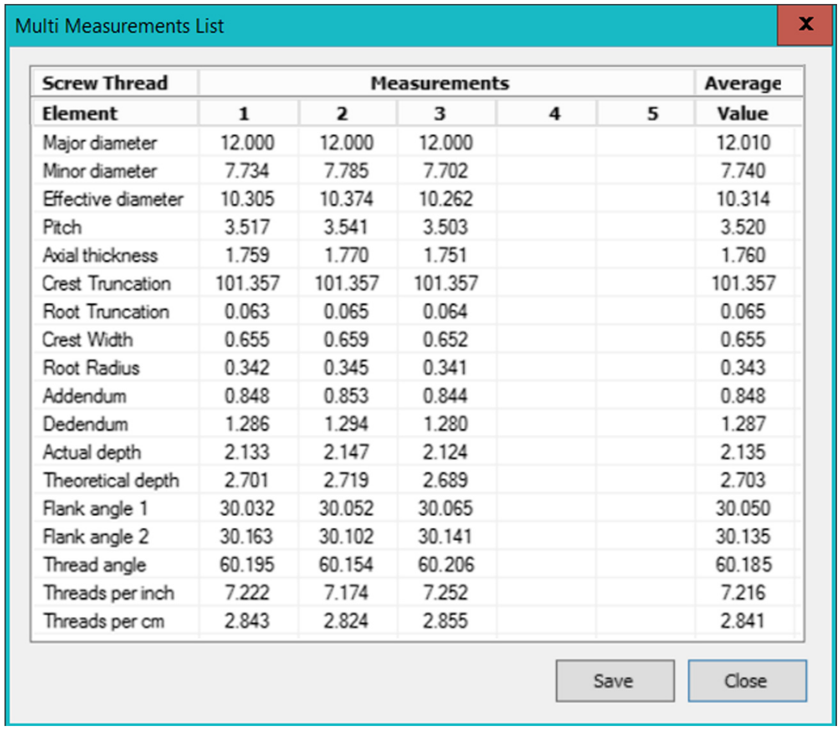
The screw thread to be inspected is measured by the vision system, then the calculated features are compared with the standard screw thread features according to the tolerances given through the inspection tolerance dialog box.

4. *Taking an inspection decision*

The inspection decision is displayed automatically in the Inspection section (Fig. 2). The decision will be "Accepted" if all inspected features of the screw thread to be inspected meet the corresponding features of the standard screw thread 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. 16), which can be displayed by clicking the Details button in Fig. 2.

5. System verification

This section explains the calibration and the accuracy of the employed vision system. In addition, the verification of the system accuracy is explained.



Screw Thread Element	Measurements 1	2	3	4	5	Average Value
Major diameter	12.000	12.000	12.000			12.010
Minor diameter	7.734	7.785	7.702			7.740
Effective diameter	10.305	10.374	10.262			10.314
Pitch	3.517	3.541	3.503			3.520
Axial thickness	1.759	1.770	1.751			1.760
Crest Truncation	101.357	101.357	101.357			101.357
Root Truncation	0.063	0.065	0.064			0.065
Crest Width	0.655	0.659	0.652			0.655
Root Radius	0.342	0.345	0.341			0.343
Addendum	0.848	0.853	0.844			0.848
Dedendum	1.286	1.294	1.280			1.287
Actual depth	2.133	2.147	2.124			2.135
Theoretical depth	2.701	2.719	2.689			2.703
Flank angle 1	30.032	30.052	30.065			30.050
Flank angle 2	30.163	30.102	30.141			30.135
Thread angle	60.195	60.154	60.206			60.185
Threads per inch	7.222	7.174	7.252			7.216
Threads per cm	2.843	2.824	2.855			2.841

Fig. 14. The Multi Measurement List (MML).

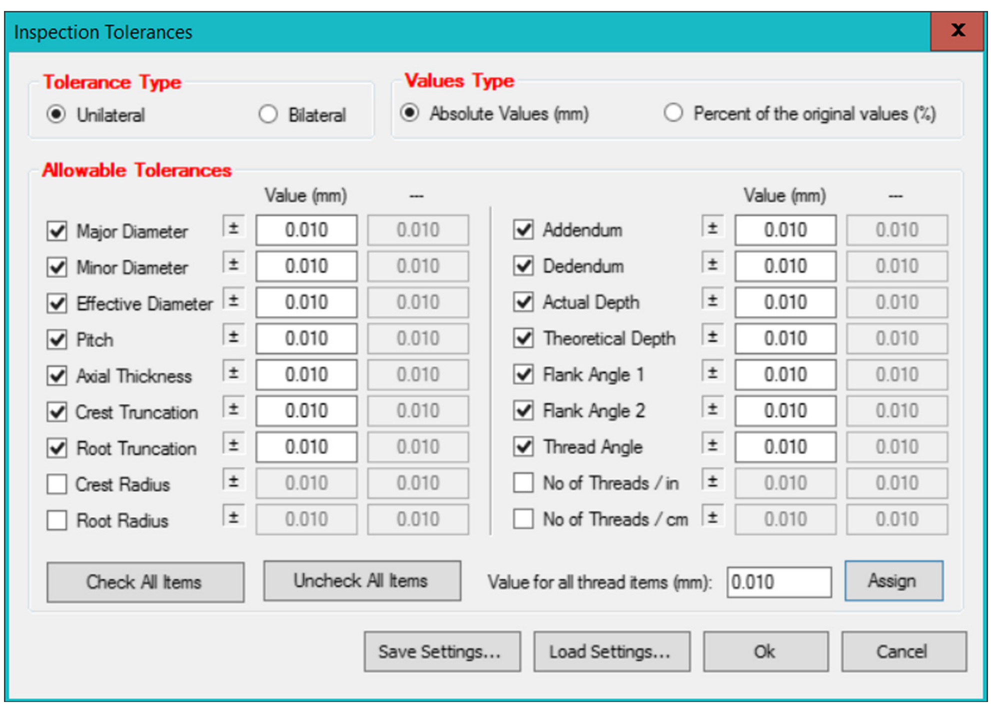
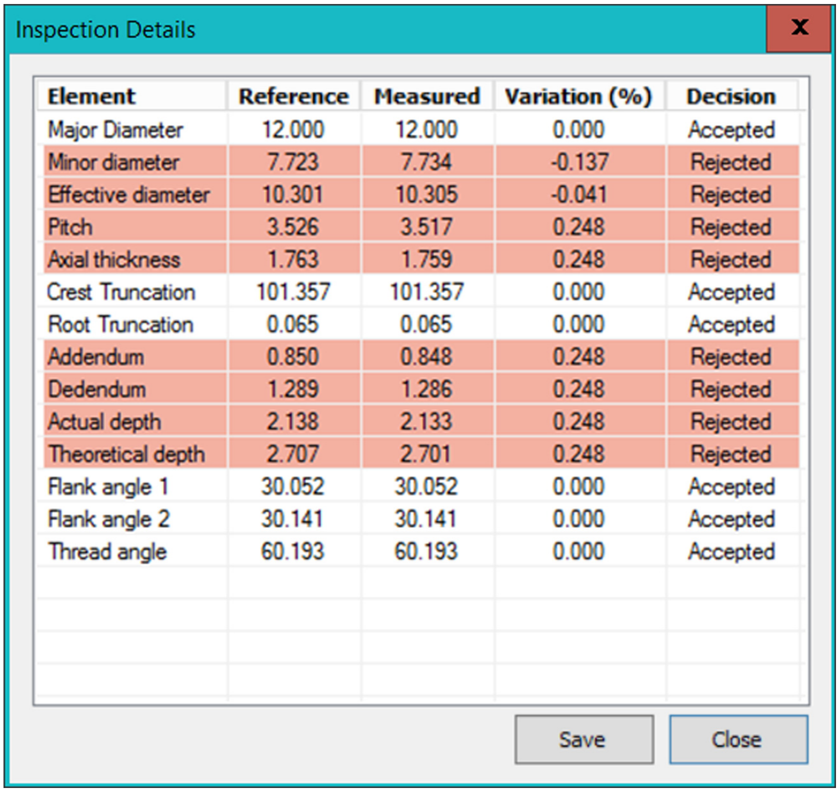


Fig. 15. Inspection tolerance dialog box.

5.1. System calibration

The units of the captured images are pixels. To calibrate the proposed vision system for actual units (i.e. millimeter or inches), the pixel size in y direction is calculated according to the major diameter of the screw thread to be measured as follows:

1. The major diameter (D_{major}) of the screw thread to be measured or inspected should be entered by the user to the MISCVision software through the Input Data section in the main interface (Fig. 2). Also, the units of measurements should be selected from the Units combo box. If the major diameter is specified, the system will be calibrated automatically and the



Inspection Details

Element	Reference	Measured	Variation (%)	Decision
Major Diameter	12.000	12.000	0.000	Accepted
Minor diameter	7.723	7.734	-0.137	Rejected
Effective diameter	10.301	10.305	-0.041	Rejected
Pitch	3.526	3.517	0.248	Rejected
Axial thickness	1.763	1.759	0.248	Rejected
Crest Truncation	101.357	101.357	0.000	Accepted
Root Truncation	0.065	0.065	0.000	Accepted
Addendum	0.850	0.848	0.248	Rejected
Dedendum	1.289	1.286	0.248	Rejected
Actual depth	2.138	2.133	0.248	Rejected
Theoretical depth	2.707	2.701	0.248	Rejected
Flank angle 1	30.052	30.052	0.000	Accepted
Flank angle 2	30.141	30.141	0.000	Accepted
Thread angle	60.193	60.193	0.000	Accepted

Save Close

Fig. 16. The inspection details dialog box.

measurements will be calculated in actual units, otherwise, it will be calculated in image pixels.

2. The MISCVision software searches the edge pixels of the upper and lower profiles for the opened image to find the two pixels having the minimum and maximum y coordinates (Y_{min}, Y_{max}) then it calculates the maximum diameter of the screw thread in y direction (D_{max}) as follows:

$$D_{max} = Y_{max} - Y_{min} \quad (13)$$

3. A calibration factor (CF) is calculated as follows:

$$CF = D_{major}/D_{max} \quad (14)$$

4. All thread features are multiplied by the calibration factor (CF) except the flank and thread angles and the number of threads per inch or centimeter.

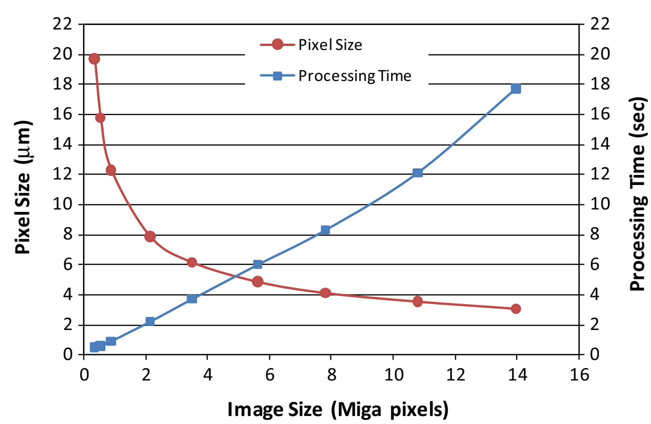


Fig. 17. Relationship between the captured image size and both processing time and pixel size for thread M10 (major diameter = 10 mm).

5.2. System accuracy

The accuracy of the employed vision system can be affected by two factors (1) the size of the measured screw thread and (2) the size of the captured image. For the first factor, increasing the size of the measured screw thread increases the pixel size, i.e. decreases the accuracy of measurement. For the second factor, increasing the size of the captured image decreases the pixel size, i.e. increases the accuracy of measurement and increases the processing time. Fig. 17 shows the relationship between the size of the captured image and both of the pixel size and the processing time for thread type M10. From the figure, it can be seen that images with size of 4.2 Mp (2048 ∗ 2048 pixels) can produce a resolution of 5 µm/pixel for screw threads of 10 mm major diameter in a reasonable processing time (6.6 s).

5.3. System verification

To verify the proposed vision system, an ISO metric thread plug gage (M16 coarse) with nominal major diameter equals to 16 mm and a pitch equals to 2 mm was measured by the proposed vision system. The measurement process was performed three times using the MML feature, offered by the proposed software, and the averages of the measurements were recorded. The features of the ISO metric thread plug gage were calculated according to its basic geometry. Table 3 shows a comparison between the values of the thread features for both the standard thread plug gauge and the measured features by the developed system. The differences between the standard and measured features are listed in µm. It can be noticed that the maximum difference between the standard and measured values was ±5.4 µm.

Table 3
Comparison between the values of the thread features for both the standard thread plug gauge and the features measured by the vision system.

No	Thread feature	Measurements			Difference	
		Standard specimen	Measured specimen	Units	Value	Units
1	Major diameter	16.0000	16.001	mm	−1.00	μm
2	Minor diameter	13.8340	13.837	mm	−3.0	μm
3	Effective diameter	14.7000	14.6979	mm	2.1	μm
4	Pitch	2.0000	2.003	mm	−3.0	μm
5	Axial thickness	1.0006	1.0003	mm	0.3	μm
6	Crest truncation	0.2165	0.2171	mm	−0.6	μm
7	Root truncation	0.4330	0.4342	mm	−1.2	μm
8	Crest width	0.2500	0.2523	mm	−2.3	μm
9	Root width	0.5000	0.5054	mm	−5.4	μm
10	Addendum	0.6500	0.6516	mm	−1.6	μm
11	Dedendum	0.4330	0.4344	mm	−1.4	μm
12	Actual depth	1.0830	1.086	mm	−3.0	μm
13	Theoretical depth	1.7325	1.7373	mm	−4.8	μm
14	Flank angle 1	30.0000	29.9752	degree	0.025	degree
15	Flank angle 2	30.0000	29.9884	degree	0.012	degree
16	Thread angle	60.0000	59.9636	degree	0.036	degree
17	No of threads per inch	12.7000	12.6810	–	0.019	–
18	No of threads per centimeter	5.0000	4.99251	–	0.0075	–

6. Conclusions

A vision system has been utilized, as a new non-contact measurement system, for measurement and inspection of various types of screw threads. Six computer vision algorithms have been developed to analyze the captured images and perform the measurement and inspection processes from the captured images. The proposed vision system is capable of identifying most of the thread types automatically and calculating the most common screw thread features (18 features), which cannot be achieved by any other measuring system. The software is capable of inspecting screw threads based on reference values and specified tolerances for selected features. The system has been calibrated for both imperial and metric units and was verified by measuring a standard ISO metric thread plug gage and comparing the results with the standard values. The results showed that the maximum difference between the standard and measured values was ±5.4 μm, which provide a good accuracy.

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