2023 IEEE Symposium Series on Computational Intelligence (SSCI)
Mexico City, Mexico. December 5-8, 2023

Low-Cost Automated Visual Screw Inspection System

Yiran LI
School of Computer Science
University of Nottingham Ningbo China
Ningbo, China
yiran.li@nottingham.edu.cn

Jiayi LI
School of Computer Science
University of Nottingham Ningbo China
Ningbo, China
0009-0009-7887-9784

Xiaoying YANG
School of Computer Science
University of Nottingham Ningbo China
Ningbo, China
xiaoying.yang@nottingham.edu.cn

Cheng'ao LI
School of Aerospace Engineering
University of Nottingham Ningbo China
Ningbo, China
ssycl4@nottingham.edu.cn

Xihan XIONG
Deparment of Computing
Imperial College London
London, UK
xihan.xiong20@imperial.ac.uk

Yutong FANG
Teaching Research Center
Ningbo Open University
Ningbo, China
fangyt@nbou.cn

Shusheng DING
Business School
Ningbo University
Ningbo, China
dingshusheng@nbu.edu.cn

Tianxiang CUI
School of Computer Science
University of Nottingham Ningbo China
Ningbo, China
tianxiang.cui@nottingham.edu.cn

***Abstract*—Despite the significant achievements in the development of automation technologies, the application of autonomous robots to improve the production efficiency of small-scale industries has been largely ignored. While there has been excellent progress in industrial image processing systems implementation, most of the work has focused on a unique aspect of specific objects rather than introducing a general inspection system. Thus, this paper discusses the critical industrial topic of quality control, which develops rapidly through the use of autonomous systems. Given the high cost of implementing automated systems, this paper presents an affordable low-budget solution for the visual inspection system. This method of inspecting screw dimensions consists of four visual inspection parts and a special mechanical supporting structure. The designed system was able to check the overall screw dimensions, including screw head diameter, screw head driven type, screw length, screw thread length, and screw head thickness. It could also separate the qualified screws from the unqualified ones after the inspection process. The accuracy of most inspection cases is 100%, meaning the error ranges within 0.1mm, which meets all the non-negotiable requirements and most of the target requirements. The visual inspection parts can be further enhanced by building a template matching library that includes different angles of the screw head or by using Hough Transform to identify the defect types of the screw thread.**

***Index Terms*—Computer-assisted visual inspection, Automated quality control, Industrial computer vision, Low-cost**

I. Introduction

Automation technologies, including artificial intelligence and autonomous machines, have been a hit in the industry and daily life. According to research in 2017 [1], at least 30% composed work of 60% professions will be completely automated by modern technologies. It's also worth noticing that the Return on Investment (ROI) is quite high when a machine replaces human labour under certain circumstances including low technical complexity, little human judgment, and high dealing volume. Pushed by the trend, more and more manufacturing industries have been seeking affordable robotic automation such as inspection machines to improve production efficiency and reduce costs. Inspection machines are generally used for quality control, which plays a vital role in manufacturing industries. Many instances indicated the importance of quality control. A study by Ford Motor Co. exposed that the most common cause of warranty repairs was the fasteners problem especially threaded fasteners [2]. Screws are known as one of the most common threaded fasteners, which are widely used in almost every scene of human life. Therefore, screws are chosen as the representatives in this article to illustrate the quality control process. The traditional way of inspecting defective screws is via human observation, which is neither efficient nor reliable. Meanwhile, modern methods like inspection machines are usually expensive according to market research and thus are mainly used by large factories [3]. To fill the gap for the need of small-scale manufacturers, this article desires to propose and evaluate a screw defect inspection machine, utilizing detection algorithms in the computer vision area, and supporting mechanical methods, with a relatively low cost and proper capacity. The following objectives are set for this work:

Non-negotiable Requirements:

- The maximum cost for the whole system must not exceed 2000 CNY;
- The minimum Inspection speed is 2pcs/min;

- The precisions of detection error range of entire screws' length and thread length are within 1mm;
- The precisions of detection error range of screws' head thickness and outer diameter are within 0.5mm;

Target Requirements:

- The precision of detection error range of entire screws' length, thread length, head thickness and outer diameter is within 0.1mm;
- The Inspection accuracy rate of detecting the cross groove on the screws' head length is higher than 90%.

II. Literature Review

The following review of literature will start with a discussion of quality control, through choices of inspection systems, to general feature extraction solutions in the computer vision area.

A. Quality Control

Quality control presents problems that go beyond manual operation, discusses general and specific solutions, and concludes that automated inspection machines are desirable for today's and tomorrow's companies. The word reliability was first created by Samuel T. Coleridge in 1816 [4]. Almost two hundred years later, a scientific journal named Quality Engineering [5] was first published, emphasising quality control and quality assurance management in reliability analysis. More and more researchers and companies have heeded the call to action for quality control. In a general view, the quality assurance strategy in manufacturing has developed from inspecting parts of products (operator quality control) to monitoring the whole manufacturing system quality (total quality management) [6]. Nevertheless, all these quality controls are practised with manual inspection. Even when evolution already collaborates with the use of scientific calculation of probabilities; there are still mistakes happening.

B. Part Inspection Technologies

The mainstream technologies for part inspection include electromagnetic, visual, radiography, and ultrasonic ways [7]. They have different characteristics for different aspects of a part. Electromagnetic, as a Non-Destructive Testing (NDT) method, can detect surface or near-surface defects fast and accurately. This detection method is mainly used in inspecting the final product surface or maintenance, or raw materials [8]. Visual inspection technique refers to the technology that captures the object image with enclosed structures and examines it in real-time view, which is cost-effective and often used as a primary inspection method [9]. Radiography, as a widely used and reliable NDT method, stresses more advantages when applied to inspecting thickness variations and visible defects [10]. Ultrasonic testing is also a widely used NDT method [11] to detect internal discontinuities after welding or forgings in various materials. With the dimension parameters of a part as the primary inspection decision, the electromagnetic method and ultrasonic method were not suitable choices. Another considerable factor is the cost when comparing visual inspection and radiography inspection. The price of a single radiography machine without the corresponding inspection system is around 10k CNY, whereas the cost of an industrial camera is around 1k CNY. Latorella, K.A., and Drury, C.G. [12] also indicated that visual inspection is the least expensive and quickest method for examining both product condition and its parts. Therefore, the visual inspection technique is optimal to measure the dimensions of the screw.

C. Visual Inspection Technologies

The use of optical inspection technology dates back thousands of years, presumably beginning with the born of a human being with vision. Modern visual inspection technology operates with a camera and a computer vision algorithm. Throughout the years, computer vision-assisted examination has gradually become accessible as the first examination step and the most common NDT technique. An overarching approach to a visual inspection system usually involves two necessary steps, extracting characters of the object, and analyzing the object's dimensions. Several modern pattern recognition methods for screws have been developed since 2008 [13], despite their common problems including but not limited to these points:

- Most research only focused on one aspect of screw features, screw thread dimensions or screw head features.
- Where research had an impressive visual system and perfect results, its mechanical structure would typically have been a sophisticated frame or had a high requirement for the mechanical structure for real application. However, when research presents an accessible structure, the structure may interface with the inspection process.
- The cost of the whole system seems to be a taboo topic. Articles rarely mention it.

As stated above, no close equivalent of the whole screw inspection machine design with low-cost limitations has been found in the literature, which confirms the validity of this article. The following sections will be based on this knowledge to develop a low-cost automated screw inspection system, which can inspect features from both the screw head and screw thread in two 2D viewpoints based on a simple mechanical structure design.

III. Proposed Methodology

A variety of visual inspection methods with different emphasis have been suggested to address the problem of screw defect inspection. These methods include the combination of eigenspace and template matching to detect the defect of rotating screw heads [14], a composite of multiple algorithms to obtain screw thread features [15], line detection to find screw threads [13], Bayesian super-resolution method to increase image quality for further inspection [16]. Among them, the line detection method by Hough Transform (HT) and the template matching method attract interest in this article. However, the proposed system cannot meet the speed requirement when using both circular Hough transform (CHT) for circle detection and HT for line detection. Since the CHT method was integrated with the standard circular detection function in the computer vision library of choice, a straightforward workaround instead of HT has been decided as the measurement of the thread length. Therefore, the combination of the Circular Hough Transform, the template matching, and the direct approach jointly contributed to the proposed screw dimension inspection.

Assuming that the lighting condition is suitable for the object detection process, for example, in the images of screw thread-like profiles, the contrast between object and background is distinct. Thereby, the methodology focused explicitly on the approaches used in visual detection and measurement, the assistant control system, and the mechanical structure design. In this paper, an M2*6 screw has been chosen as a sample to demonstrate the relevant methodologies and experimental results. An overview of how the system works is shown in Fig. 1.

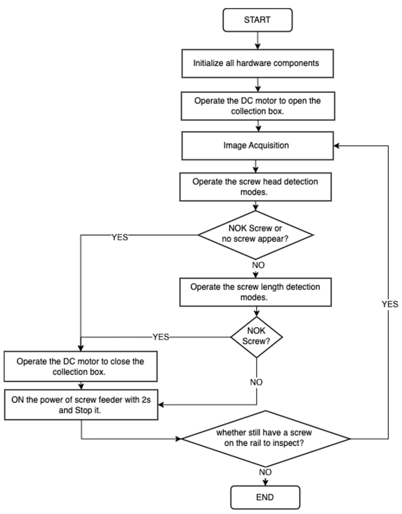

Fig. 1. The outline of the structure of the whole system. (Noted that the NOK screw means that the screw is disqualified.)

A. Detection of Screw Head Outline by CHT

The idea of detecting the head of the screw would follow the strategy shown in Fig. 2: Circular Hough transform (CHT) method to detect the diameter of screw heads can be regarded as a primary method for circle detection. It is known that the regular expression of a line ($y = kx + b$) in the Cartesian axes can transform to a polar form ($\rho = xcos(\theta) + ysin(\theta)$) based on its distance and angle from the origin. Then, the line could be parameterized as a point (ρ, θ) in 2D space (accumulator). Moreover, the operation principle of CHT is also based on the geometry properties of a circle. The expression equation for a circle is $(x-a)^2 + (y-b)^2 = r^2$ at the parameterized axes, with a point position (a, b, r) corresponding to the point (x, y) at the Cartesian axes. With the use of CHT, an example of screw head detection is shown in Fig. 3.

B. Detection of Cross Section by Template Matching

The method used to detect the cross-section of the screw head was named as template matching method. Fundamentally,

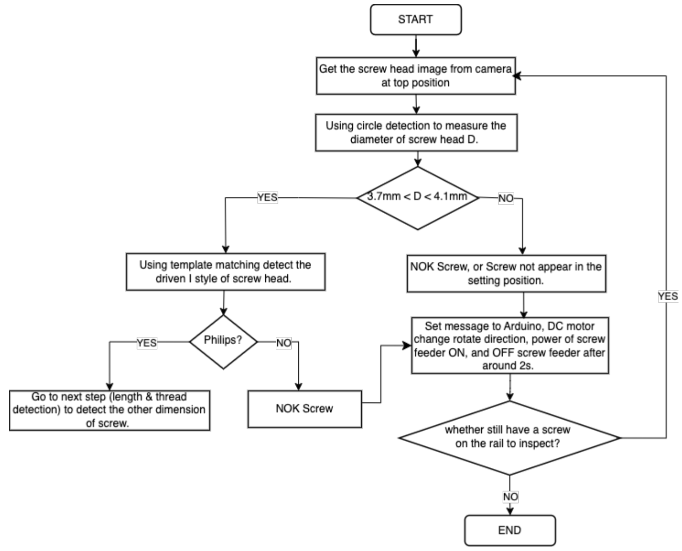

Fig. 2. The flowchart of the purpose of catching the screw head.

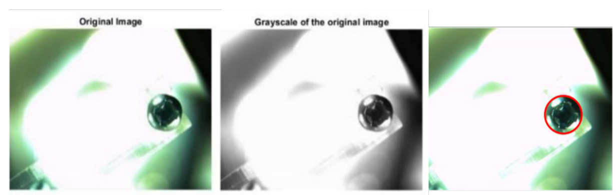

Fig. 3. An example of screw head detection.

the idea of template matching is using an image as a template to try to find the most similar part in the searched image through the formula of square error with six forms.

Firstly, the similarity between the reference image and the template image could be measured by:

$$\begin{aligned}D(i,j) &= \sum_{m=1}^{M}\sum_{n=1}^{N}\Big[S^{ij}(m,n) - T(m,n)\Big]^2 \\ &= \sum_{m=1}^{M}\sum_{n=1}^{N}\Big[S^{ij}(m,n)\Big]^2 - 2\sum_{m=1}^{M}\sum_{n=1}^{N} S^{ij}(m,n) \times T(m,n) \\ &+ \sum_{m=1}^{M}\sum_{n=1}^{N}[T(m,n)]^2\end{aligned}$$

It could be found that the first term of the expanded form represents the energy of the global image and the third term of the expanded form refers to the power of the template image. The critical condition is the second one, which connects the relationship between the global image and the template image with the change of i, j. The maximum value would be obtained when these two images match. For convenience in the further classification process, the formula has been normalized to obtain a correlation coefficient of template matching:

$$R(i,j) = \frac{\sum_{m=1}^{M}\sum_{n=1}^{N} S^{ij}(m,n) \times T(m,n)}{\sqrt{\sum_{m=1}^{M}\sum_{n=1}^{N}[S^{ij}(m,n)]^2}\sqrt{\sum_{m=1}^{M}\sum_{n=1}^{N}[T(m,n)]^2}}$$

Based on the correlation coefficient formula, the decision threshold can be set in the program. The flowchart of the template matches the working principle as shown in Fig. 4.

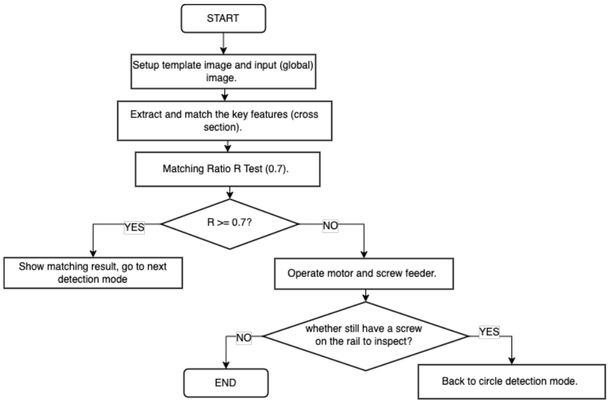

Fig. 4. The flowchart of template matching working principle.

C. Detection of the Rest of A Screw

The idea of detecting the whole screws' length, screws' head thickness, and screws' thread length were captured as in Fig. 5.

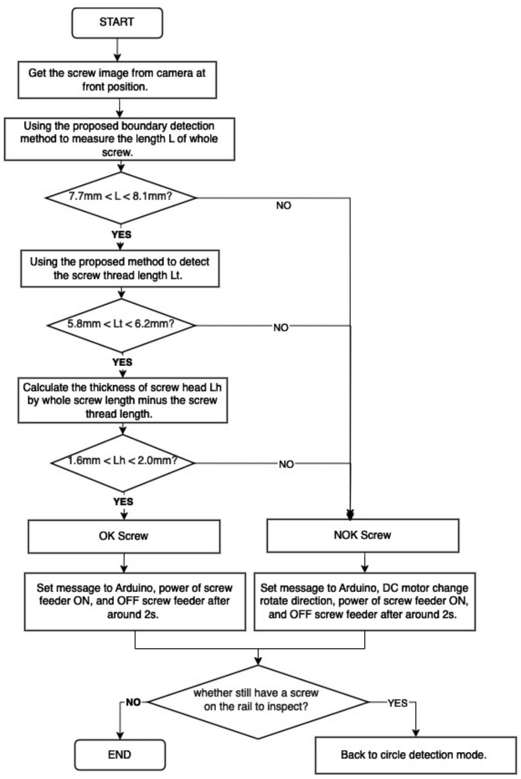

Fig. 5. The control strategy of identifying the rest length of the screw.

Based on a series of experiments, it was found that a high-contrast image of screws can be obtained by using two light sources with different placements and an acrylic rail to hold the screw. Silhouette images could then be extracted from the real screw image through the edge detection technique, to detect the thread of the screw from its particular boundaries shape. Fig. 6 demonstrates the experimental results with the images of a processed screw silhouette to measure its whole length, which shows the specific value on the pop-up window.

For the thread length, the main idea here was transforming

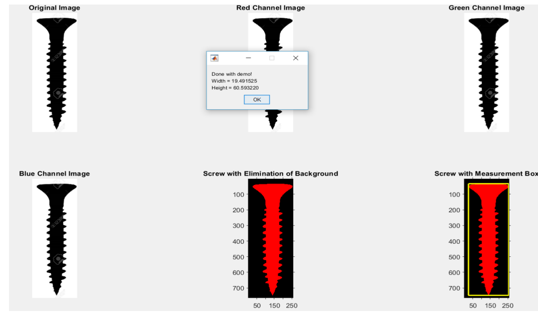

Fig. 6. The results with the calculated height of the screw with a silhouette.

the measurement of the length of the screw thread to the slope value which exists in the screw shape. If the whole screw length and the screw head diameter were a certain value, the slope of the screw would be in a certain range assuming it has a proper screw thread. The data of each point was calculated based on both calculation of screw thread features and digital vernier calliper measurement, where Pitch [P] = 0.75mm, Height of fundamental triangle [H] = 0.65mm, Thread pitch diameter [D2] = 1.53mm, Thread minor diameter [D1] = 1.26mm, Head Diameter = 3.88mm (Fig. 7). Based on these values, the ideal slope value is around 0.93. Moreover, considering the individual difference between screws and obvious errors during the detection process, the allowable slope range was 0.0929 ± 0.01. Fig. 8 displays one of the test results of this method with a silhouette image.

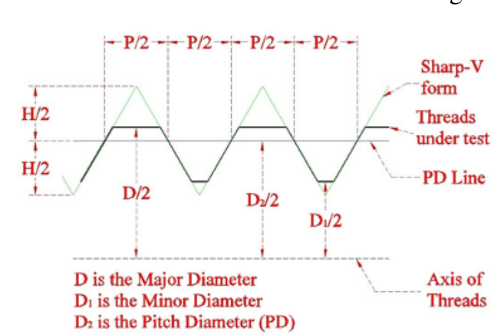

Fig. 7. The sketch map of screw thread. [1]

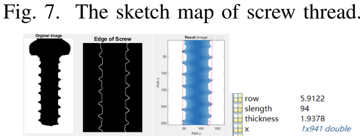

Fig. 8. The test result with a screw silhouette image.

A second method of detecting the screw length was demonstrated by Fig. 9, which used iterations in addition to the similar logic flow as the first method.

IV. Results and Discussion

The vision system was implemented on an Intel Core i7 7th generation machine with program language in Matlab. The chosen cameras are USB 2.0-based 3-megapixel industrial cameras used to capture the figure of screws. The light source

[1]Source: https://commons.wikimedia.org/wiki/File:ThreadProfileDiameters.jpg

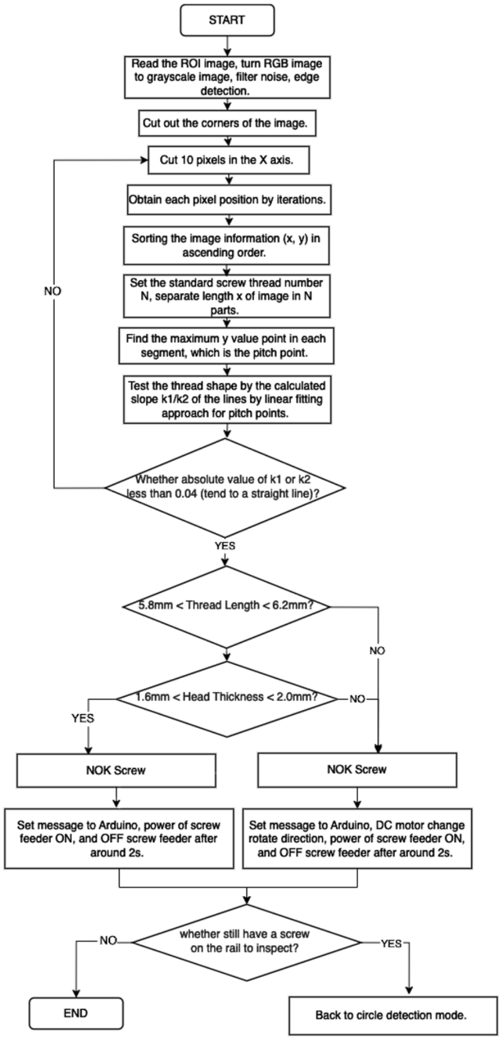

Fig. 9. The flowchart of the screw thread detection.

includes a ring LED light source with a diameter of 60mm and three flexible LED small bulbs as additional light sources. The field of view of the top position camera is 22.5mm*16.9mm with a working distance of 20mm, and the field of view of the camera at the front position is 18.3mm*13.7mm with a working distance of 10mm. The final mechanical structure is shown in Fig. 10.

The overall operation time is 25.9s based on the performance time test for each inspection mode and screw feeder operation. More specifically, the running time of the whole program would cost 14s (detection of the screw head) + 8.7s (the detection of the rest parts in the screw) + 2.2s (screw feeder operation) + 1s (the rest operation) = 25.9s. Note that the time was less than 25.9s for unqualified screws as there was no need to finish the image detection process. The inspection speed is 2 pcs/min, while the real minimum inspection speed in this case is 2.32 pcs/min. Hence, the design satisfied the non-negotiable requirements.

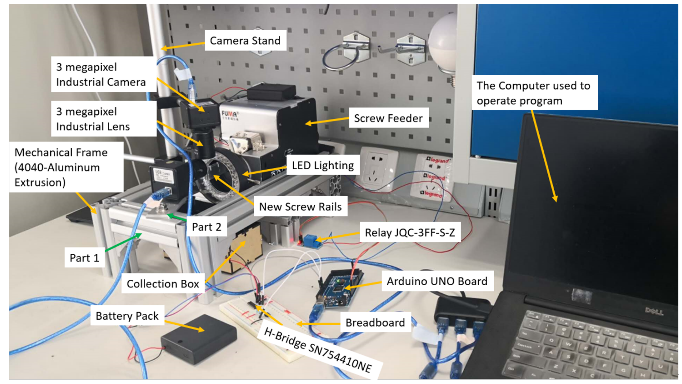

Fig. 10. The complete view of the entire system structure.

The above-designed model and the calculations would yield the following results. The accepted size is measured by the digital vernier caliper, while the experimental dimension is referred to the measurement obtained by the vision system with the explained methods. It is also noted that the range of error bars shown in the below figures was based on the calculation of instrument uncertainty as $\pm 0.0029mm$. Table I includes the experimental result data and comparisons of screw head diameter dimension, where D was an abbreviation for Diameter in the tables. The result perfectly met the non-negotiable requirements defined earlier.

TABLE I
THE COMPARISONS OF SCREW HEAD DIAMETER

Screw No.	Accepted D (mm)	Experimental D (Pixels)	Experimental D (mm)	Error (mm)	Error %
1	3.92	155.3823	3.88	0.04	0.90%
2	3.97	156.9617	3.92	0.05	1.16%
3	3.81	148.6846	3.72	0.09	2.44%
4	3.91	153.6961	3.84	0.07	1.73%
5	3.88	151.0735	3.78	0.10	2.66%
6	3.95	154.1729	3.85	0.10	2.42%
7	3.89	152.8301	3.82	0.07	1.78%
8	3.87	152.0781	3.80	0.07	1.76%
9	3.85	151.5716	3.79	0.06	1.58%
10	3.98	157.1617	3.93	0.05	1.28%

For the detection of cross-section on screw heads, the test results are shown in Fig. 11. The accurate inspection rate judged by the percentage of correct object detection numbers was around 75%.

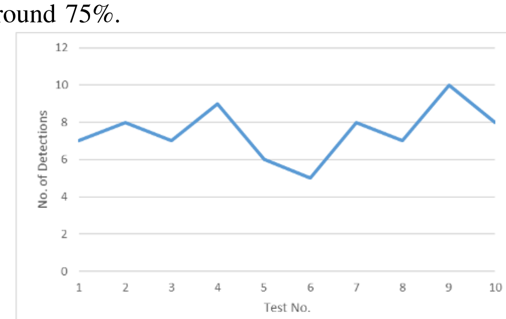

Fig. 11. The No. of detection when each test with the number of screws as 10.

For the inspection of the entire screw length, the proposed approach for measuring the entire screw length worked well, which has not only achieved the error range within 1mm in the non-negotiable requirements but also met the error range within 0.1mm in the target requirements (Table II).

TABLE II
THE COMPARISONS OF ENTIRE SCREW LENGTH

Screw No.	Accepted L (mm)	Experimental L (Pixels)	Experimental L (mm)	Error (mm)	Error %
1	7.85	875.9673	7.82	0.03	0.37%
2	7.86	877.1032	7.83	0.03	0.37%
3	7.88	878.6867	7.85	0.03	0.44%
4	7.90	883.4985	7.89	0.01	0.15%
5	7.80	871.3715	7.78	0.02	0.26%
6	7.88	874.5828	7.81	0.07	0.90%
7	7.80	871.0548	7.78	0.02	0.29%
8	7.90	883.6471	7.89	0.01	0.13%
9	7.86	873.9621	7.80	0.06	0.72%
10	7.81	871.1419	7.78	0.03	0.41%

For the length detection, both mentioned methods have been tried. The results are shown in Tab. III, which shows that the performance of the second approach is better than the first one, which had an error range within 0.1mm (met both the non-negotiable requirement and target requirement). Hence, the second method has been used in the final operation.

TABLE III
THE COMPARISONS BETWEEN THE TWO SCREW THREAD DETECTION METHODS

Screw No.	Accepted Screw Slope	Experimental Screw Slope	Error %	Accepted Thread Length (mm)	Experimental Thread Length (Pixels)	Experimental Thread Length (mm)	Error (mm)	Error %
1	0.0929	0.1047	12.75%	6.18	689.8059	6.16	0.02	0.34%
2	0.0929	0.1086	16.87%	6.14	685.9090	6.12	0.02	0.26%
3	0.0929	0.0968	4.22%	6.16	686.5784	6.13	0.03	0.48%
4	0.0929	0.1043	12.26%	6.10	676.4983	6.04	0.06	0.98%
5	0.0929	0.1028	10.67%	6.12	682.0392	6.09	0.03	0.50%
6	0.0929	0.1076	15.80%	6.07	671.8994	6.00	0.07	1.17%
7	0.0929	0.1036	11.54%	6.11	672.8167	6.01	0.10	1.68%
8	0.0929	0.1024	10.26%	5.98	663.2037	5.92	0.06	0.98%
9	0.0929	0.0994	7.03%	6.21	689.1352	6.15	0.06	0.92%
10	0.0929	0.1101	18.50%	6.10	673.3213	6.01	0.09	1.45%

Based on the measured screw whole length and screw thread length, the screw head thickness could be calculated as in Table IV. The error range was also within 0.1mm, which had achieved the corresponding non-negotiable requirement.

TABLE IV
THE COMPARISONS OF SCREW HEAD THICKNESS

Screw No.	Accepted T (mm)	Experimental T (Pixels)	Experimental T (mm)	Error (mm)	Error %
1	1.67	186.1614	1.66	0.01	0.47%
2	1.72	191.1942	1.71	0.01	0.75%
3	1.72	192.1183	1.72	0.00	0.27%
4	1.80	209.0002	1.87	0.07	3.67%
5	1.68	189.3323	1.69	0.01	0.62%
6	1.81	202.6834	1.81	0.00	0.02%
7	1.69	198.2381	1.77	0.08	4.73%
8	1.92	220.4434	1.97	0.05	2.51%
9	1.65	184.8169	1.65	0.00	0.01%
10	1.71	197.8206	1.77	0.06	3.29%

V. CONCLUSION

To conclude, this paper focused on building an accessible low-cost automated screw inspection system based on visual detection. It was found that the overall screw dimension can be detected, measured and inspected via the circle detection method, template matching method, and proposed feature extraction approach in the computer vision area, and that separation of different screws could be realized by the Arduino Control system. The conclusions acquired from this article are summarized as follows:

- The proposed screw inspection machine exhibits a stable, low-cost frame to support the operation of the whole system.
- The proposed visual inspection system shows a straightforward, clearer logical approach, which can reach a percentage error range within 5%.
- The results data indicate that the performance of the whole system can achieve all of the non-negotiable requirements and most of the target requirements.

The present results suggested that the proposed screw inspection machine exhibits allowable feasibility, suitable capacity, acceptable accuracy, and lower cost than the market inspection machines. The preliminary experiments with the proposed visual system, however, also clearly indicated the limitations of this system, such as the semi-complete cross-section detection mode. Further research is recommended to optimize the visual detection algorithm and the entire structure to enhance the achievements.

AKNOWLEDGEMENT

This Project is Supported by the Ningbo Natural Science Foundation (Project ID 2023J194).

REFERENCES

[1] J. Manyika, S. Lund, M. Chui, J. Bughin, J. Woetzel, P. Batra, R. Ko, and S. Sanghvi, "Jobs lost, jobs gained: Workforce transitions in a time of automation," *McKinsey Global Institute*, vol. 150, no. 1, pp. 1–148, 2017.

[2] D. Stienstra, "Introduction to design for (cost effective) assembly and manufacturing," *Department of Mechanical Engineering, Rose-Hulman Institute of Technology, Terre Haute, USA*, 2016.

[3] A. Akundi and M. Reyna, "A machine vision based automated quality control system for product dimensional analysis," *Procedia Computer Science*, 2021.

[4] S. T. Coleridge, J. Engell, and W. J. Bate, *Biographia literaria, or, Biographical sketches of my literary life and opinions*. Princeton University Press, 1984.

[5] M. Dekker, *Quality Engineering*. American Society for Quality, 2007.

[6] A. V. Feigenbaum, *Total Quality Control, 3rd ed.* McGraw-Hill, 1991.

[7] "Inspection technologies many modalities. more confidence. better decisions. ge measurement & control," 2012.

[8] B. Gupta and B. Ducharne, "Comparison of electromagnetic inspection methods for creep-degraded high chromium ferritic steels," *NDT & E International*, 2021.

[9] J. M. Rožanec, P. Zajec, and E. Trajkova, "Towards a comprehensive visual quality inspection for industry 4.0*," *IFAC-PapersOnLine*, 2022.

[10] Y. Zhao, S. Liu, and X. Li, "Radiographic inspection of submerged arc welding using semantic segmentation," *2021 IEEE Sensors*, 2021.

[11] F. Honarvar and A. Varvani-Farahani, "A review of ultrasonic testing applications in additive manufacturing: Defect evaluation, material characterization, and process control," *Ultrasonics*, 2020.

[12] K. A. Latorella and C. G. Drury, "A framework for human reliability in aircraft inspection," in *Proceedings of the Seventh FAA Meeting on Human Factors Issues in Aircraft Maintenance and Inspection. Federal Aviation Administration, Washington, DC*, 1992.

[13] S. R. Cruz-Ramirez, Y. Mae, T. Takubo, and T. Arai, "Detection of screws on metal-ceiling structures for dismantling tasks in buildings," in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2008, pp. 4123–4129.

[14] H. Ukida, "Visual defect inspection of rotating screw heads," in *SICE Annual Conference 2007*. IEEE, 2007, pp. 1478–1483.

[15] E. Gadelmawla, "Computer vision algorithms for measurement and inspection of external screw threads," *Measurement*, vol. 100, pp. 36–49, 2017.

[16] A. Deshpande, P. Patavardhan, and D. Rao, "Super resolution based low cost vision system," in *2015 IEEE International Conference on Computational Intelligence and Computing Research (ICCIC)*. IEEE, 2015, pp. 1–6.