

Design and Development of an Image-Capturing System for the Non-Contact Estimation of Drilled Surface Roughness

Shilpa Karegoudra

Department of Computer Science and Engineering, GITAM School of Technology, GITAM University, Bengaluru, Karnataka, India
sakregou@gitam.in (corresponding author)

Vamsidhar Yendapalli

Department of Computer Science and Engineering, GITAM School of Technology, GITAM University, Bengaluru, Karnataka, India
vyendapa@gitam.edu

Received: 3 July 2025 | Revised: 28 July 2025 and 18 August 2025 | Accepted: 30 August 2025

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ABSTRACT

Accurate evaluation of surface roughness in drilled components is vital for quality assurance in manufacturing processes, particularly in high-precision industries such as aerospace and automotive. Traditional contact-based measurement techniques pose limitations when assessing the inner surfaces of drilled holes, especially blind holes. This study presents the design and development of a custom non-contact image-capturing system aimed at acquiring high-resolution images of drilled hole surfaces for subsequent texture-based roughness estimation. The proposed setup integrates a rotary stage, an X-Y positioning platform, and a height-adjustable, angle-controllable camera mount, along with a ring-based LED illumination unit to ensure uniform lighting within the hole interior. A series of controlled drilling trials were conducted on Aluminum 7075 (Al-7075) workpieces at varying spindle speeds and feed rates. Imaging experiments were carried out at multiple camera angles and vertical heights to identify the optimal configuration for maximum surface visibility. The best image clarity and observable depth (6.162 mm) were achieved at a 47° camera orientation and 21.5 cm height from the workpiece. This optimized setup lays the foundation for building a machine learning model for surface roughness prediction, which forms the next phase of this research. The study demonstrates the feasibility and effectiveness of a modular imaging platform for automated, non-contact inspection of drilled surfaces.

Keywords-image capturing setup; surface roughness; drilling; drilled surface; image acquisition; computer vision

I. INTRODUCTION

Surface roughness is a key parameter in determining the quality, performance, and longevity of machined components. In drilling applications, particularly in aerospace and automotive industries, the roughness of drilled holes directly affects fatigue resistance, joint strength, sealing performance, and dimensional accuracy. Ensuring high-quality surfaces in drilled holes is essential, especially where millions of fasteners are used in assemblies. Traditional surface roughness measurement techniques such as contact-type profilometers, although widely used, pose challenges when assessing the inner surfaces of blind holes. These instruments are limited by their inability to access confined geometries, risk damaging the surface, and require interrupting the manufacturing process.

To overcome these limitations, recent research has explored non-contact methods for surface roughness evaluation using

computer vision and image processing. Digital imaging approaches allow the capture and analysis of surface textures without physically touching the workpiece. Several studies have demonstrated the potential of these methods for machined surfaces. For example, authors in [1] used speckle image analysis and wavelet transforms to evaluate surface quality in electrical discharge machining. Similarly, authors in [2] employed Gray-Level Co-occurrence Matrix (GLCM) features to characterize brittle graphite surfaces. The surface detection system included a stereo microscope with CCD image acquisition and MATLAB image processing software. The stereo microscope was used to magnify the machined surface and acquire images. Nine graphite-machined workpieces were examined in this study. Authors in [3] proposed segmentation-based image analysis for helical gear surfaces, enabling localized roughness assessment.

Aluminum alloys, particularly Aluminum 7075 (Al-7075), are widely used in aerospace structures due to their high strength-to-weight ratio, corrosion resistance, and machinability. Al-7075 was selected in this study because of its mechanical strength and relevance to aerospace manufacturing.

Despite these advances, many existing systems are designed for flat or open surfaces, such as those produced by turning or milling. These setups often lack the flexibility required for capturing detailed images inside cylindrical or blind drilled holes, where lighting and angle constraints are significant. Furthermore, some studies, such as [4], addressed hole quality assessment using images but did not focus on capturing high-resolution internal surface textures. Lighting conditions, in particular, have been identified as a major challenge in image-based roughness analysis, with improper illumination leading to reflections, shadows, and loss of surface detail [5].

While neural networks and machine learning techniques have shown promise in predicting surface roughness from images [6], the reliability of these models depends heavily on the quality and consistency of the input data. Capturing meaningful and consistent images of drilled surfaces requires a dedicated imaging system capable of accommodating variable hole sizes, depths, and machining parameters such as feed rate and spindle speed.

This paper proposes a novel image-capturing system designed specifically for non-contact surface roughness estimation of drilled holes. The setup features a rotary base for workpiece rotation, an X-Y adjustable platform for precise positioning, and a height-adjustable camera mount with angular control. Additionally, the system incorporates a uniform LED illumination setup to address lighting challenges inside blind holes. The objective of this study is to develop and validate a flexible, cost-effective, and modular platform for acquiring high-quality images of drilled holes under varying machining conditions. The captured images serve as a custom dataset for future work involving machine learning-based surface roughness prediction.

II. PROPOSED SYSTEM ARCHITECTURE

A. Related Experimental Systems and Literature

In the proposed system, we are developing a setup similar to a Computer Numerical Control (CNC) machine to capture images without disturbing the workpiece. The chemical composition of the Al-7075 used as the workpiece includes 5.6–6.1% zinc, 2.1–2.5% magnesium, 1.2–1.6% copper, and less than 0.5% silicon, iron, manganese, titanium, chromium, and other metals.

Several experimental imaging systems have been reported for surface roughness evaluation. For example, a Basler CCD camera (PiA2400-12gm) equipped with a 45× optical zoom lens was used to capture images under white LED illumination. The camera, mounted on a height-adjustable table at a 90° angle to the specimen surface, was combined with diffused lighting to ensure homogeneous illumination. In another setup, a camera mounted on the chuck of an Electrical Discharge Machining (EDM) die-sinking machine was used to

automatically acquire a series of non-overlapping images of drilled holes at 752 × 480 pixels (approximately 2.6 μm/pixel) with a field of view of around 21.3 mm. The images were saved in lossless PNG format without modifications [7].

Lighting configurations have been shown to strongly influence image quality. A white ring lamp inclined at 50° enhanced surface texture visibility and reduced reflections from shiny surfaces, whereas improper illumination caused poorly defined edges and inaccurate measurements. To address this, studies applied LED lights from multiple directions to eliminate shadows and improve image clarity. In some cases, drilled holes were imaged parallel to the material surface with a fixed camera position, and the resulting images were analyzed using ANSYS software [8, 9].

Digital images have also been used for roughness measurement in milling operations, where the GLCM and Discrete Fourier Transform (DFT) were applied to analyze texture. In these experiments, milling was conducted at 3000 r/min, with a 1 mm depth of cut and a 0.15 mm feed rate. Various image processing techniques, such as preprocessing, background subtraction, noise filtering, grayscale conversion, binary image conversion, and intensity thresholding, have been reported in the literature [3]. Beyond image analysis, other studies investigated the effect of drilling parameters (cutting speed and feed rate) and material properties (reinforcement fraction and cutting tool type) on drilled surface roughness [10].

Machine learning approaches have further enhanced roughness evaluation. In one study, images of drill bits were captured before and after drilling, and wear was analyzed using MATLAB. The experiments, conducted on aluminum alloys with the Taguchi method, demonstrated the applicability of nondestructive image-based analysis [11]. Additional nondestructive techniques examined the influence of light sources and color models on surface texture [5, 12, 13]. Similarly, the integration of neural networks and statistical methods such as Analysis of Variance (ANOVA) has been employed to assess the effects of machining parameters on surface roughness. For instance, Ultrasonic-Assisted Turning (UAT) was tested on C40 carbon steel and 201 stainless steel, showing improvements in finish quality [14-16].

Finally, authors in [9] investigated drill tool wear in Al6061/SiCp composites using HSS, TiN-coated, and TiAlN-coated tools. High-resolution imaging combined with MATLAB processing enabled accurate wear measurement, and Taguchi OA9-based drilling experiments identified optimal parameters for minimizing tool wear.

B. Development of the Image Capturing Setup

The proposed image-capturing setup was designed in-house to enable non-contact visualization of the internal surfaces of drilled holes. The system consists of a rotary base to hold the workpiece, an X-Y adjustable platform to fine-tune positioning, and a camera mount with height and angular adjustment mechanisms. The frame was constructed using aluminum extrusions for modularity and stability. The experimental setup used for capturing images of drilled hole surfaces is illustrated in Figure 1. A high-resolution industrial camera (Logitech

C922) was used for image acquisition, mounted on a manually controlled vertical rail with a protractor-based angular scale to adjust the camera angle between 0° and 90°. To eliminate shadows and enhance feature visibility within blind holes, a custom ring-shaped LED illumination unit was designed and attached around the camera lens.

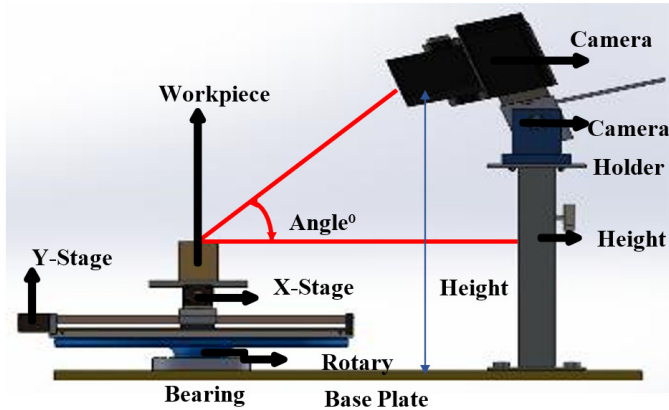


Fig. 1. Schematic of the custom-developed image-capturing system used for drilled hole surface analysis.

The system comprises a robust base plate fitted with a rotary bearing, enabling 360° rotation of the workpiece. An X-Y stage assembly is mounted above the bearing to facilitate precise lateral adjustments. The camera is affixed to a height gauge, which allows vertical movement along the Z-axis. Additionally, the camera can be inclined at controlled angles to effectively image the inner surfaces of blind holes. The system was interfaced with a laptop for image preview and capture. The captured image dataset will serve as the input for future image processing and surface roughness estimation using machine learning.

Effective illumination is essential for acquiring high-quality images, reducing shadow artifacts, and enhancing the accuracy of surface roughness analysis. In the proposed setup, the drilled hole—being a blind hole with a closed bottom—suffers from poor natural illumination due to the lack of through-light penetration. To overcome this limitation, a 12 V LED strip light was integrated into the imaging system. The light source is mounted around the workpiece using a custom-fabricated holder to ensure uniform, diffused lighting across the internal surfaces of the hole. This controlled illumination significantly improves image clarity and contrast, which is vital for accurate texture extraction and non-contact roughness estimation. Figure 2 illustrates the complete image-capturing setup with the illumination system in place.

C. Drilling of the Al-7075 Workpiece and Parameters

The proposed system involves drilling an Al-7075 aluminum alloy workpiece with specified diameters, followed by image acquisition using the custom-developed setup. The captured images are analyzed to estimate surface roughness through computer vision-based, non-contact techniques. The overall methodology, from drilling to roughness estimation, is outlined in the workflow diagram presented in Figure 3.

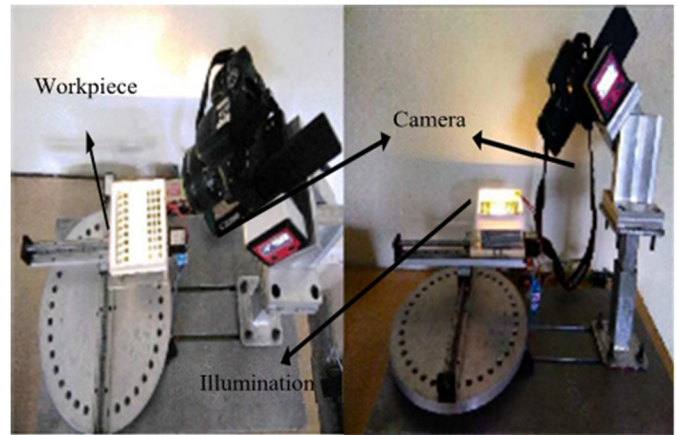
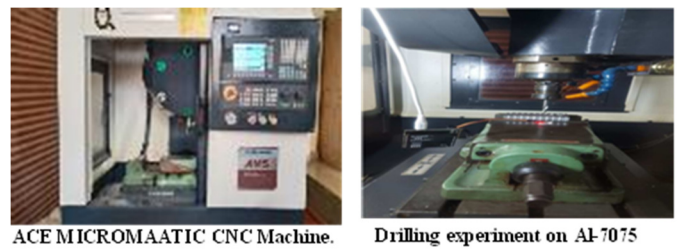


Fig. 2. Complete image-capturing setup with integrated LED illumination source for enhanced surface visibility.



ACE MICROMAATIC CNC Machine. Drilling experiment on Al-7075

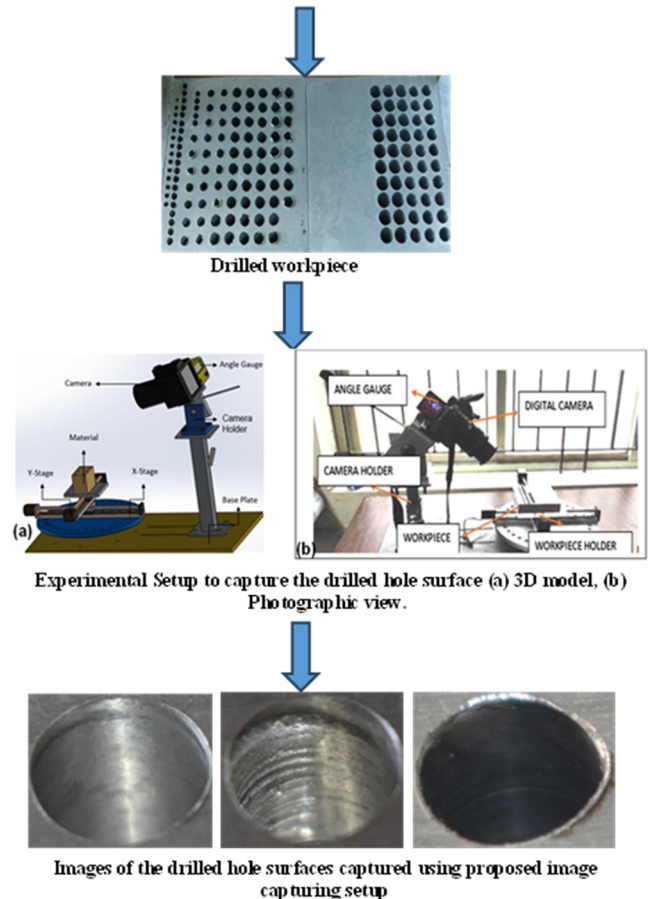


Fig. 3. Workflow of the proposed non-contact image-capturing system for surface roughness estimation.

D. Drilling Parameters and Experimental Layout

Experiments were conducted on an Al-7075 plate with dimensions of 102 × 102 × 25 mm using a carbide-tipped drill bit of 8 mm diameter. The machining was carried out on an ACE MICROMATIC CNC machine across a range of spindle speeds (2000–4000 r/min) and feed rates (25–150 mm/min). For each spindle speed, multiple feed rates were applied to assess their influence on hole quality. Figure 4 illustrates the drilling configuration used: (a) the designed hole pattern layout, and (b) the resulting machined workpiece with drilled holes.

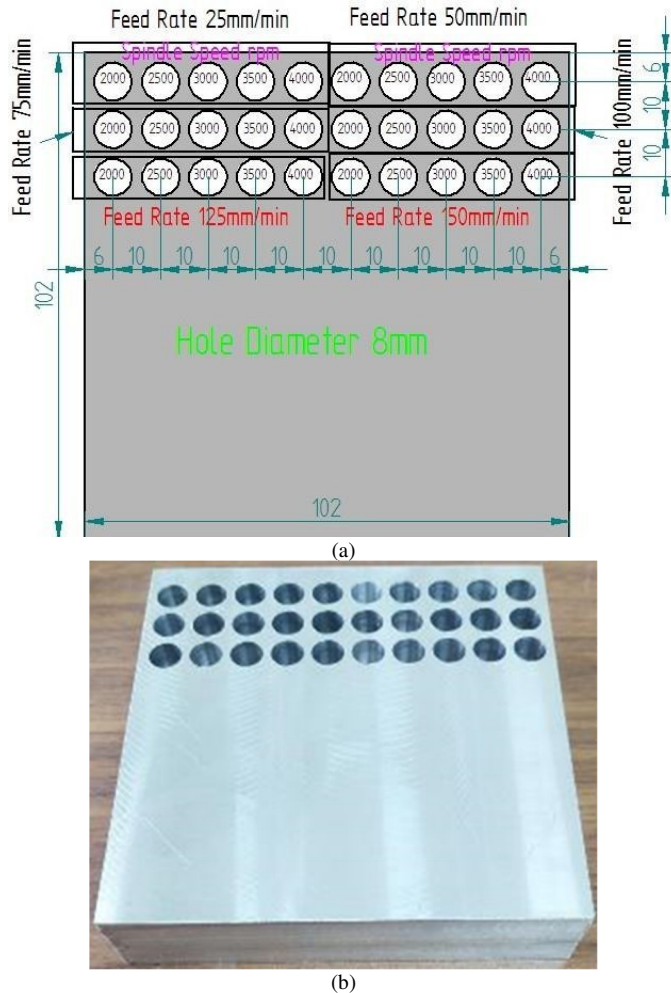


Fig. 4. Experimental setup for drilling the Al-7075 workpiece: (a) hole pattern design, (b) machined workpiece with drilled holes.

E. Image Acquisition with and without Illumination

Figure 5 presents comparative images of drilled holes captured with and without the integrated LED lighting system. Without illumination, images exhibited uneven contrast and shadow artifacts due to the cylindrical geometry and closed-bottom nature of the blind holes. When the LED ring light was activated, image clarity improved significantly, with uniform lighting across the internal surfaces. This highlights the importance of controlled illumination in non-contact image-based inspection systems.

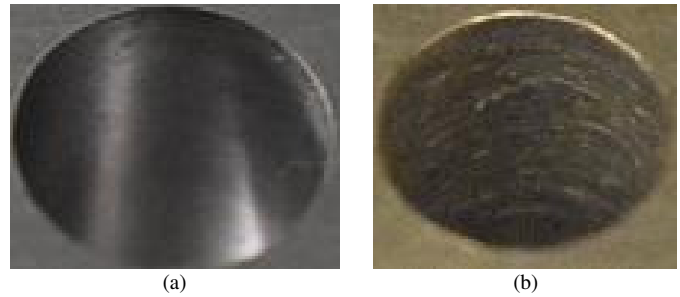


Fig. 5. Captured images of the drilled hole surface: (a) without illumination, (b) with LED illumination.

III. RESULTS AND DISCUSSION

A. Analysis of Hole Depth of the Drilled Surface

The experimental trials demonstrated that camera orientation plays a crucial role in capturing the internal surface of drilled holes. At shallow angles (below 35°), only the top edge of the hole was visible, and the observable depth was limited. As the angle increased toward 47°, the visible depth improved significantly, reaching a maximum of 6.162 mm. Beyond this orientation, further increases in angle reduced surface visibility due to shadowing and occlusion effects. The variation of captured depth with camera angle and vertical distance from the workpiece is illustrated in Figure 6.

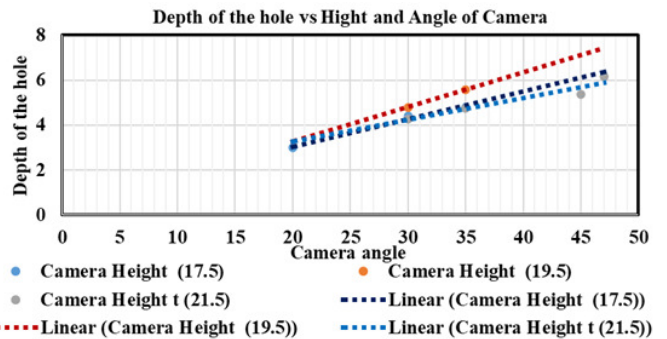


Fig. 6. Captured hole depth with respect to camera angle and vertical distance.

This result can be explained by the geometry of light reflection inside the hole. At lower angles, the line of sight restricts depth perception, whereas at excessively high angles, shadows dominate and distort the captured features. The optimal angle of 47° balances both effects, providing maximum clarity of internal textures. Similar challenges of illumination and reflections have been reported in earlier imaging studies [2, 8], although those studies were limited to flat or open surfaces. In contrast, this work extends these findings to blind hole imaging, which involves a significantly more complex geometry.

B. Influence of Vertical Distance on Observable Depth

The vertical distance between the camera and the workpiece strongly affects image quality. At distances less than 15 cm, image distortion and incomplete focus occurred due to the limited field of view. Conversely, distances greater than 25 cm resulted in reduced resolution and insufficient detail

capture. A height of 21.5 cm emerged as the optimal configuration, producing the clearest and deepest surface images when combined with the 47° camera orientation.

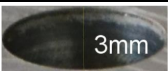
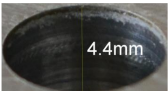

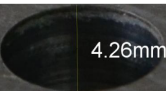
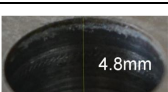
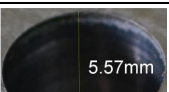
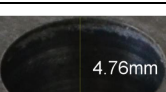
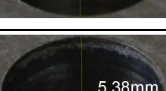
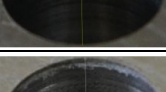
This balance between depth coverage and image resolution has not been adequately discussed in prior works on machined surface imaging, which typically focus on flat specimens. The present study establishes that both orientation and distance must be co-optimized for reliable hole surface imaging, providing a guideline for similar non-contact inspection setups in the future.

C. Feasibility of the Developed Imaging Setup

The results confirm that the developed modular setup successfully captures high-quality images of blind drilled holes, which are traditionally challenging for non-contact inspection. Unlike conventional systems designed for milling or turning surfaces [7], the present setup combines a rotary stage, adjustable camera mount, and controlled LED illumination to ensure reproducibility under varying machining conditions.

Table I summarizes the outcomes of the imaging trials, where successful captures correspond to the identified optimal configuration. This systematic evaluation validates the feasibility of the system for generating consistent datasets across different hole sizes, spindle speeds, and feed rates.

TABLE I. HOLE IMAGE CAPTURE SUCCESS AT DIFFERENT CAMERA ANGLES AND HEIGHTS

Sl. No.	Camera angle (°)	Camera height (cm)		
		17.5	19.5	21.5
1	20°		Not possible to capture the image	Not possible to capture the image
2	30°			
3	35°			
4	45°	Not possible to capture the image	Not possible to capture the image	
5	47°	Not possible to capture the image	Not possible to capture the image	

D. Implications for Roughness Prediction and Future Work

A key strength of the developed setup lies in its ability to produce a custom image dataset with consistent lighting and orientation, a critical requirement for training machine learning models. Previous studies [3, 5] have shown that neural network predictions of surface roughness are highly sensitive to image quality and noise. By optimizing imaging conditions, this work

ensures that the subsequent roughness prediction stage can rely on high-fidelity data.

While the present study focuses on the design and validation of the imaging system, it establishes the foundation for advanced analysis, including feature extraction (GLCM, wavelets, Local Binary Patterns (LBP)) and the development of predictive models. The system's modularity also allows adaptation to other geometries, making it broadly applicable for automated inspection in manufacturing.

IV. CONCLUSION

This study presents the design and development of a custom, non-contact image-capturing system tailored for the inspection of drilled hole surfaces. The system incorporates a rotary stage, an X-Y adjustable workpiece platform, a height- and angle-controllable camera mount, and a uniform LED illumination unit for enhanced visibility inside blind holes. Systematic imaging trials were conducted to examine the influence of camera orientation and vertical distance on surface visibility. The optimal configuration was identified as a 47° camera angle positioned 21.5 cm above the workpiece, enabling a maximum observable hole depth of 6.162 mm.

The developed setup consistently produced high-resolution imaging of internal surfaces under varying machining parameters, providing the input required for non-contact surface roughness estimation. These results validate the system's effectiveness and establish a reliable foundation for future work on machine learning-based roughness prediction. The next phase of research will focus on feature extraction and the development of predictive models trained on the captured image dataset, enabling automated surface quality assessment in manufacturing.

The novelty of this work lies in the development of a modular imaging system specifically designed for the challenging geometry of blind drilled holes, in contrast to most prior studies that focused on flat or open surfaces. The optimized configuration of camera angle and vertical distance provides new insights into maximizing internal surface visibility. Furthermore, the creation of a dedicated drilled-hole image dataset represents a unique contribution, laying the groundwork for future AI-driven surface roughness prediction. Collectively, these contributions establish the originality and practical significance of the proposed system for aerospace and automotive manufacturing applications.

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GITAM University, Bengaluru. He has around 24 years of academic experience, including two years in the IT industry. His research interests include Sustainable Software Models and the application of Artificial Intelligence in the domain of Agriculture. He can be contacted via email at: vyendapa@gitam.edu.

AUTHORS PROFILE

Shilpa Karegoudra holds a Master of Technology degree from Visvesvaraya Technological University, India, awarded in 2014. She received her Bachelor of Engineering from the same university in 2012. She is currently an Assistant Professor in the Department of Computer Science and Engineering at NMAM Institute of Technology, Nitte (Deemed to be University). Her research interests include Machine Learning, Deep Learning, Image Processing, and Natural Language Processing. She has published over eight papers in international journals and conferences. She is currently a Research Scholar at the GITAM School of Technology, GITAM University, Bengaluru. She can be contacted via email at: shilpa.m.k456@gmail.com or skaregou@gitam.in.

Dr. Vamsidhar Yendapalli received a Ph.D. degree in Computer Science and Engineering. He is currently a Professor and Head of the Department of Computer Science and Engineering at the GITAM School of Technology,