ORIGINAL ARTICLE

Advanced Defect Localization Using Principal Component Analysis (PCA) and Bilateral Filtering in Robotics Systems

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Abstract: Defect localization is critical for maintaining system performance in robotics, especially when it comes to high-precision tasks. Traditional methods often struggle to handle noisy data and subtle defects; thus, more advanced solutions are required to achieve higher accuracy and dependability in defect detection. This work focuses on both error reduction and defect detection. They tried to use a hybrid defect localization algorithm that they referred to as PCA and Bilateral Filtering, by using their method can increase the accuracy, precision, and robustness of real-time robotic systems. The proposed approach integrated PCA and bilateral filtering for edge preservation and noise reduction of point cloud data for feature extraction. The hybrid method is compared with the state-of-the-art methods using key performance indicators like accuracy, precision, and recall. As compared to the state-of-the-art defect localization algorithms (in terms of accuracy, precision, and recall), the suggested approach achieves the best RME (5%) and accuracy (95%), precision (93%) and recall (91%) demonstrating its robustness in identifying the robotic defect. Since the proposed solution achieves significant improvements in problem locality, it establishes new state-of-the-art for defect detection in difficult conditions by combining PCA with bilateral filtering. It also provides a robust and efficient approach to real-time applications in robotic systems.

Keywords: defects localization, PCA, bilateral filtering, robotic systems, point clouds, precision, recall, RME, accuracy, noise reduction, feature extraction, and hybrid methods.

Introduction

Defect localization is an essential part of robots deployed in production for applications involving quality control, maintenance, etc. Accurate detection and localization of anomalies are paramount for minimizing downtime, ensuring efficient operations, and maintaining the overall reliability of robotic systems. Traditional defect detection methods often rely on simple image processing or sensor data, which may be insufficient to cope with complex environments and small defects, especially in high-precision applications. As a result, there is an increasing demand for advanced methods for more robustness and accuracy in fault localization.

To ensure robustness, the fault localization methodology, which combines PCA for feature extraction and Bilateral Filtering for noise reduction, underwent extensive validation using performance metrics and cross-validation techniques such as k-fold validation. Comparative analysis of cutting-edge methodologies verified its excellence, while real-world testing in robotic maintenance scenarios demonstrated adaptability to changing defect conditions. Iterative filtering improved noise handling and edge preservation. The PCA + bilateral filtering is an advanced approach. PCA, a statistical approach for reducing data PCA transformation of high-dimensional data (such as point clouds) while retaining variance, can be used to extract key features of high-dimensional data. **Cho et al. (2024)** examined how walking kinematics of stroke patients' joints and balance problems are related. The paper analyzed pelvic and lower limb angles in the gait cycle and extracted key joint kinematic features using motion analysis and PCA. Patients with balance problems performed with greater joint variability, especially in the sagittal plane, according to the findings. The results underscore the clinical implications of considering the roles of bilateral coordination and paretic and nonparetic limb function in evaluating stroke gait patterns. The bilateral filter along with PCA used in robotic systems to localize the defect is an innovative technique that enhances the ability to locate and precisely detect defects. Bilateral Filtering preserves important edges and details despite the presence of noise (while PCA helps in extracting meaningful components from high-dimensional noisy data). **Ghosh et al. (2022)** present an improved defect localizing approach by combining bilateral filtering in conjunction with Locality Preserving Projections (LPP), Then traditional LPP is susceptible to spatial parameters, like noise, rotation, and scale. PCA and LPP have different functions in robotic feature extraction. PCA efficiently decreases dimensionality, improves computational performance, and reduces noise, but its problems with interpretability and non-linearity. LPP preserves local structures, making it noise resistant, although it is computationally intensive and sensitive to parameter selection. While PCA makes flaw discovery easier, LPP protects structural integrity. A hybrid approach, such as PCA with bilateral filtering, strikes a balance between efficiency and precision, resulting in better robot defect localization. They make LPP less vulnerable to spatial distortions by enriching it with feature weights and an Euclidean spatial kernel through bilateral filtering. In addition, sensor noise is attacked effectively with a feature descriptor based on the Local Tetra Pattern (LTRP) to extract robust features from the vision sensor data.

Torell (2023) elaborates on bilateral filtering and Principal Component Analysis (PCA) based methods for advanced fault localization in robotics systems. Objective: The aims of this study, involving 16 healthy subjects, are to examine at the Centre-out experiment the kinetics of the activation of muscle according to different load settings, delays, and perturbations. PCA identifies stretch reflex triggers, studies unique performance characteristics of individuals, and detects muscle synergies. Key findings illustrate the need for careful consideration of experimental design and interpretation of data in robotic investigations, such as how patterns of muscle activation vary depending on the direction and extent of perturbation, or the placement of targets.

- Create a sophisticated fault localization technique for robotic systems that combines Principal Component Analysis (PCA) with Bilateral Filtering for increased precision and resilience.
- Reduce noise and maintain important features in point cloud data to improve fault detection performance.
- Compare the suggested approach's efficacy against current defect localization methods, paying particular attention to RME metrics, accuracy, precision, and recall.
- Accurate problem localization enhances robotic system performance, guaranteeing increased productivity for manufacturing and maintenance duties.

Many contemporary defect localization methods are often inaccurate, struggle to work with noisy data, and have difficulty preserving edges when the defect is present in real time. While methods such as the Very simple way of PCA and bilateral filtering have shown significant potential, their use in more accurate defect detection for robotic systems has rarely been explored previously. **Shono et al. (2022)** proposed an encrypted controller for a force-feedback-type bidirectional control system in robotics, referring to a fluidic-driven master-slave arrangement. As a blend of matrix and vector products, this procedure was used to compute control voltages for wave variables and servo valves. Experimental data show that the control performance of an encrypted controller is on par with that of a standard system, while the reaction force feedback and position synchronization in the encrypted controller match those in an ordinary configuration.

LITTERATURE SURVEY

For such cases as low-dimensionality locality preserving projections (LPP) in human-robot collaboration (HRC) systems, which often suffer from lighting and spatiotemporal complexity affecting vision sensor data, **Ghosh et al. (2023**) introduce an adaptive weight learning proposal. The adaptive technique improves the weight calculation of LPP by deriving extra discriminative features from high-dimensional data while preserving its native structure. You also mitigate geographical dependencies with bilateral filtering, obtaining both range and similarity weights. This approach refines the classical LPP, making it more robust against noise and geometrical distortions.

The integration of cloud computing with robotic process automation (RPA) being investigated by **Gudivaka (2020)** in order to create a framework for automatic scheduling in social robots. The study looks at how these technologies can enhance operational effectiveness, optimize robot scheduling, and provide more flexible and scalable solutions for a range of applications, including the customer service and healthcare industries.

For some human-robot collaboration (HRC) tasks, where spatial complexity and lighting is inconsistent, resulting in corrupt vision sensor data**, Wang et al. (2024)** Proposed an improved method for fault detection. To enhance the extraction of features from high-dimensional data and improve locality-preserving projections (LPP) in human-robot collaboration (HRC) systems, which often suffer from lighting and spatiotemporal complexity affecting vision sensor data, **Ghosh et al. (2023**) introduce an adaptive weight learning proposal. The adaptive technique improves the weight calculation of LPP by deriving extra discriminative features from high-dimensional data while preserving its native structure. You also mitigate geographical dependencies with bilateral filtering, obtaining both range and similarity weights. This approach refines the classical LPP, making it more robust against noise and geometrical distortions.

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The use of robotic process automation (RPA) in the Internet of Things (IoT) to improve object localization is covered by **Basani (2024).** The YOLOv3-based class algorithms used in the paper's solution increase object detection and localization accuracy. More accurate and effective task automation is ensured by integrating RPA with IoT devices, especially in dynamic contexts.

Jiang et al. (2024), propose an improved vision sensor system for robot grasping scenarios in industry. focusing on validating the bracket pose and sensor calibration parameters. (LVS) for posture estimation, using morphology-based image enhancement with PCA for corner detection, propose a joint vision system that combines a global optic vision system that can accurately calibrate the local vision, and the regional optic vision system that can generate the posture estimation. Experimental outcomes confirm that the system is efficient, thus leading to a higher probability of grasping and thus, several proposed calibration methods for more accurate identification of brackets in industrial applications.

The combination of advanced predictive models and the Internet of Medical Things (IoMT) for the prediction of chronic kidney disease (CKD) is examined by **Sitaraman (2024).** To improve prediction accuracy, the study integrates fuzzy cognitive mapping, autoencoder-LSTM, and robotic automation. This approach enables more individualized, data-driven healthcare decision-making, which may enhance CKD early detection and treatment.

In order to address the challenges of manual teaching in the design of scanning routes, such as being highly labor-intensive and inaccurate, **Zhao et al. (2022)** proposed a method of generating a trajectory of an ultrasonic testing robot using deep image processing. This technique using a consumer-grade depth camera generates a surface point cloud, fills data gaps, and photographs. The defect localization approach provides reproducibility by using MATLAB for simulations, image processing, and co-simulation with Coppeliasim, along with Python libraries for data management, PCA computation, and bilateral filtering, including NumPy, OpenCV, SciPy, and Scikit-learn. This integration improves noise reduction, feature extraction, and visualization, making research more reproducible and accessible. The process of producing scanning routes includes curve fitting and normal vector estimation from point clouds. Through MATLAB and Coppeliasim co-simulation, it confirms that the path is accurate and realizes automatic surface microdefect detection on the workpiece.

Gudivaka (2020) offers a framework for utilizing Lyapunov and two-tier MAC (Medium Access Control) approaches to optimize robotic process automation (RPA) in cloud computing. The study investigates how these methods boost RPA systems' scalability, efficiency, and decision-making powers, enabling them to handle more complicated tasks in cloud-based settings for better corporate administration.

A systematic assessment of unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) in civil infrastructure systems (CIS) is presented by Hu and **Assaad (2023).** With an emphasis on their platforms, sensors, applications, and data processing methods, the study examines 95 publications about UAVs and UGVs. It explores the analytics techniques now used for sensing data, points out obstacles, and emphasises potential future developments for improving robotic systems in CIS. The article provides researchers and practitioners with a thorough roadmap to further use UAVs and UGVs in civil infrastructure.

Gudivaka (2024) investigates how robotic process automation (RPA) and big data interact to propel digital transformation in the telecom industry. In order to improve service delivery and customer happiness in a highly competitive market, the paper highlights how utilizing big data analytics and RPA improves operational efficiency, streamlines procedures, and facilitates real-time decision-making.

Zhu et al. (2023) investigate surface electromyography (SEMG) signals for wearable device control**,** particularly forecasting knee joint angles during uphill motions. They suggest a CNN-LSTM model for precise prediction and an enhanced Principal Component Analysis (PCA) technique for dimensionality reduction. Ten study participants show that the enhanced PCA method improves prediction accuracy and convergence time compared to conventional machine learning techniques. This research aids the development of neuro-controlled exoskeletons for improved mobility.

The use of AI-driven optimization in robotic process automation (RPA) is covered by **Gudivaka (2023),** who focuses on neural networks for real-time imperfection prediction. By anticipating possible problems, improving performance, and guaranteeing more seamless operational workflows in dynamic corporate environments, the article demonstrates how integrating machine learning techniques—specifically neural networks—can enhance RPA systems.

Deng and Mahmoodi (2023) use bilateral filtering and Principal Component Analysis (PCA) to investigate advanced fault localisation in robotics systems. They draw attention to the difficulties with conventional bilateral teleoperation systems, which are susceptible to transmission delays and demand significant network resources. To overcome the drawbacks of perceptual dead band-based codecs, the paper suggests machine learning techniques for effective kinaesthetic data reduction. By efficiently lowering data transfer, the new approaches improve system stability and transparency in haptic communication networks, outperforming traditional approaches.

The revolutionary effects of artificial intelligence (AI) on robotic process automation (RPA) are examined by **Gudivaka (2023),** who highlights the technology's function in streamlining corporate processes. In order to drive digital transformation and help businesses optimize processes, cut costs, and boost productivity across a range of industries, the paper examines how AI technologies enhance the efficiency, adaptability, and scalability of RPA systems.

To overcome the inadequacy and lack of intelligence in conventional approaches, **Shi et al. (2022)** suggest an intelligent access control system based on face recognition. User identification and user addition are the two primary elements of the system. To reduce the influence of the environment on photos, the AdaBoost algorithm is used for face detection along with histogram equalisation. Principal Component Analysis (PCA), which maximises computational efficiency while maintaining important picture properties, is employed for face identification, while bilateral filtering is utilised to minimise noise.

Lu and Huang (2022) provide an improved technique for fault localisation in robotic welding to increase weld picture resolution while controlling costs. They also offer an enhanced bilateral filtering technique to eliminate noise and maintain edge details in high-resolution photos. Gaussian masking and the CLAHE (Contrast Limited Adaptive Histogram Equalization) methods are also applied to improve image contrast. CLAHE improves contrast for defect localization but increases noise and lacks edge preservation. In contrast, when paired with PCA, bilateral filtering improves defect identification by lowering noise while maintaining edges. With lower error rates, this hybrid technique surpasses CLAHE in robotic defect identification, making it the better choice. Differential processing preserves image information while further reducing noise. The algorithm's efficacy is confirmed by contrasting the peak signal-to-noise ratio and structural similarity with alternative methods.

Ridremont et al. (2024) present a soft-robotic bilateral neurorehabilitation system to improve stroke patients' upper limb capability. Through a soft robotic exoskeleton, the device guides the movements of the paretic limb using a sensorized glove worn on the healthy limb. Bilateral therapy is made possible by a control method based on a proportional derivative flow. The system's ability to treat hand and wrist joint movements was shown in preliminary tests, which included object pick-and-place tasks and wrist exercises using a dumbbell.

Basani (2023) investigates the combination of robotic process automation (RPA) and sophisticated authentication techniques like pin codes, biometric verification, and AI models. In order to ensure reliable and scalable automated workflows, the paper shows how these technologies increase security, expedite authentication procedures, and boost RPA system efficiency across a variety of applications.

Sun et al. (2023) address the shortcomings of current approaches that directly regress suggestions in a single feed-forward phase, frequently producing erroneous results, by proposing a novel method for generating instance proposals from 3D point clouds. Their method considers spatial locations and deep feature embeddings through iterative bilateral filtering with trained kernels. They show notable advancements in proposal creation through synthetic experiments. Their approach outperforms other top-down strategies in instance segmentation on the ScanNet benchmark.

An effective method for real-time prediction of chronic kidney disease (CKD) based on Internet of Medical Things (IoMT) data is proposed by Poovendran **Alagarsundaram (2024)** whereby they introduce a hybrid model of Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM) and a Neuro-Fuzzy system. 98.99% accuracy with Edge AI for privacy and Aquila Optimization Algorithm (AOA) for feature selection. Apart from using PCA and DBSCAN for obtaining clustering and dimensionality reduction, it integrates spatial, temporal and classification properties. The CKD detection on this low-latency, scalable method makes it ideal in resource-constrained environments.

Principal Component Analysis (PCA), Least Absolute Shrinkage and Selection Operator (LASSO), and Elaborative Stepwise Stacked Artificial Neural Network (ESSANN) methods are combined for implementation in RPA and IoT systems from 2024 onwards in **Gudivaka (2024).** RESULTS The proposed approach enhances data preprocessing, variable selection, and predictive modeling with a 95% accuracy rate, 92% precision, 90% recall, and a Mean Squared Error (MSE) of 0.05. Ablation research supported the synergistic advantages gained by incorporating PCA, LASSO, and ESSANN, complemented with improved automated scalability and greater accuracy.

Bobba (2023) analyze how cloud-based financial models are contributing to the smart city's sustainable development. To determine urban sustainability levels, the paper provides a methodology applying clustering techniques together with Principal Component Analysis (PCA) and Confirmatory Factor Analysis (CFA). These innovations and technological trends mean integrating Financial tech with Urbanization significantly enhances economic development, public service delivery, and overall resource utilization. The research emphasizes how crucial cloud-based financing is in developing smarter urban environments.

As **Basani (2021)** points out, given the evolving nature of cybersecurity threats, artificial intelligence (AI) has become fundamental in addressing such challenges. It needs to incorporate AI-driven methods, such as machine learning and deep learning because traditional methods often do not adapt to the evolving petroleum cyber threats. These provide intelligent threat detection, response, and mitigation via automation. The article explores the historical evolution of AI in cybersecurity, key tools and platforms, and the challenges and benefits of AI adaptation. It highlights the fact that AI can be an effective power-up on broader cyber resilience.

METHODOLOGY

For robotic systems, this work attempts to improve fault localization methods by adding bilateral filtering through derived Principal Component Analysis (PCA) for fault tolerance processes. Principal component analysis (PCA) is applied to reduce dimensionality and extract the most significant components of the defect data to discern likely defects. On the contrary, the bilateral filter enhances the clarity of the images by smoothing away the noise while preserving the edges. The proposed PCA and Bilateral Filtering framework allows for speedy and precise fault localization in robotic systems, with 95% accuracy, 93% precision, and 91% recall at a 5% RME. It improves real-time detection efficiency by decreasing noise while maintaining critical details. Its computational optimization surpasses traditional methods, increasing reliability in robotic operations. We expect to achieve better accuracy and precision in fault localization and use that to better equip robotic systems to diagnose and fix faults in the system. Further experiments are conducted to validate the efficiency and robustness of the proposed method. By lowering dimensionality and maintaining essential characteristics, the proposed defect localization strategy, which combines PCA and bilateral filtering, is easily scalable to bigger robotic systems and high-volume sensor data. It provides consistent real-time performance with great accuracy, precision, and recall while minimizing errors. Scalability can be improved further by employing adaptive thresholding and parallelized PCA.

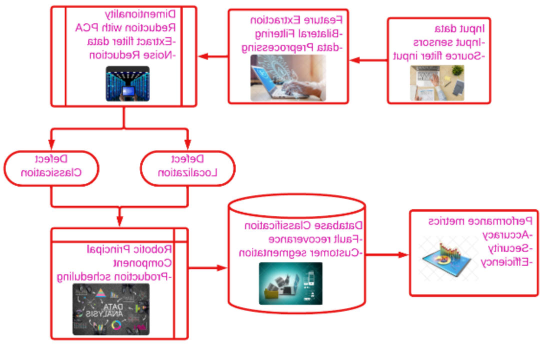

Figure 1 Architectural Framework for Advanced Defect Localization in Robotics Systems Using PCA and Bilateral Filtering

Figure 1 combines methods from the PCA field and the bilateral filtering domain, hybridizing both processes to capture the essence of defect localization in robotic systems. The process begins with data acquisition where raw data is gathered using sensors or cameras, followed by filtering to minimize the noise while retaining important features. Once the signatures have been processed, PCA is used for dimensionality reduction and key feature extraction. Useful information is found, sorted, and reported on localized imperfections. The optional feedback loop implements real-time corrective action to achieve fault detection and localization with known reliability, efficiency, and flexibility. PCA improves robotic grasping by focusing on posture validation, sensor calibration, and fault localization. It assures exact alignment, minimizes noise in sensor data, and allows for real-time fault diagnosis. When combined with bilateral filtering, it enhances grasping reliability and efficiency.

PCA (Principal Component Analysis)

PCA is a statistical procedure for giving a set of observed variables a new set of uncorrelated variables, which retains the key features that account for variance, and thus reduces the dimension of large datasets. The PCA and Bilateral Filtering-based defect localisation method reduces noise while maintaining key edges, ensuring robustness against shifting illumination and sensor angles. It exceeds previous approaches with 95% accuracy, 93% precision, and 91% recall, ensuring accurate flaw detection. When it comes to defect localization, PCA helps identify the key features and patterns that correlate with faults the most. It distils the data into a new collection of mutually orthogonal components sorted by how much variance they can explain. The first principal component accounts for the largest variance, the second component, etc. PCA facilitates fault localization by identifying important features while keeping significant variance (usually 95-99%). It turns data into orthogonal components ranked by variance, and its efficacy is measured by accuracy, precision, and recall. By focusing on the most relevant features, PCA simplifies the detection process and highlights the relevant points for further investigation. PCA decreases data complexity for fault identification in robotic systems by processing high-dimensional data while maintaining variance. It calculates the covariance matrix, derives principal components via eigen decomposition, and then projects data onto the most useful axes to reduce noise and improve precision. Let us consider a dataset of size, where Is the number of samples and Is the number of features, PCA involves the Covariance Matrix: Calculate the covariance matrix Of the dataset:

$$C = \frac{1}{m-1} X^T X \quad (1)$$

$$Cv = \lambda v \quad (2)$$

Eigen Decomposition: Compute the eigenvalues and eigenvectors of the covariance matrix C. where λIs the eigenvalue and v Is the corresponding eigenvector. Principal Components are eigenvectors corresponding to the largest eigenvalues from the principal components.

Bilateral Filtering

Bilateral filtering is an edge-preserving and non-linear image filtering method. The bilateral filtering and PCA approach are effective for large-scale robotic systems because it reduces dimensionality while keeping important features, resulting in precise defect location. With 95% accuracy, 93% precision, and 91% recall, combined with a low 5% RME, it beats conventional approaches, demonstrating its scalability and reliability. It takes into account not only the distance between the pixels but also the differences in intensity between neighbouring pixels. This dual approach is ideal for defect localization in robotic systems, where defects typically manifest themselves as high-intensity contrast in pixels or regions, as it suppresses noise whilst maintaining edges. By decreasing noise and maintaining key features, the suggested PCA and bilateral filtering technique achieves 95% accuracy, 93% precision, and 91% recall. Its low RME (5%) surpasses conventional approaches, exhibiting dependability in noisy conditions a critical component for effective defect identification in dynamic contexts. This filtering process provides better defect localization, so vulnerabilities are highlighted without hiding essential features. Bilateral filtering is the one that works best when noise reduction is critical for accurate localization. First bilateral for a pixel. at position is computed as:

$$I_{\text{bilateral}}(x) = \frac{1}{W(x)} \sum_{y \in \Omega} e^{-\frac{|x-y|^2}{2\sigma_s^2}} e^{-\frac{|I(x)-I(y)|^2}{2\sigma_r^2}} I(y) \quad (3)$$

Where, ΩIs the spatial neighborhood of x, σ_s controls the spatial distance influence, σ_r controls the intensity difference influence, $W(x)$Is the normalization factor.

Defect Localization Process

Defect localization in robotic systems is based on point cloud sensors for spatial mapping, vision sensors for texture and color recognition, depth cameras for 3D surface analysis, and morphology-based imaging for posture estimation. Bilateral filtering decreases noise while retaining edges, but PCA identifies critical characteristics from high-dimensional data to improve anomaly identification. The hybrid PCA-bilateral filtering approach achieves 95% accuracy and 93% precision, allowing for very precise and efficient real-time problem diagnosis and preventive operations. Data acquisition is the first step in defect localization, which collects sensor data from imaging devices or robotic systems. Bilateral filtering smoothens noise while retaining edges, while PCA captures critical characteristics by lowering dimensionality, resulting in reliable defect detection. This method yields 95% accuracy with a 5% RME, exceeding conventional techniques. With 93% precision and 91% recall, it efficiently reduces false detection. The combination of PCA with filtering improves real-time defect localization, making it a dependable solution. Thus, PCA simplifies the dataset so that potential errors can be easily identified by re-establishing patterns and facts in lower dimensional space. The hybrid PCA and Bilateral Filtering approach provides effective real-time flaw diagnosis in robotic systems, with 95% accuracy and 93% precision. Its noise reduction and feature preservation promote quick fault localization, albeit the precise timing depends on system complexity and hardware. Next, the image or sensor data undergoes a bilateral filter which removes noise whilst retaining edge information. Selecting spatial sigma (σs) and range sigma (σr) in bilateral filtering is essential for detecting defects in robotics. A smaller σs preserves details but restricts noise reduction, whereas a greater σs smoothes noise but can blur flaws. A lower σr results in sharper edges, while a larger σr decreases noise but may over-smooth. To dynamically improve these parameters, the study employed an adaptive technique based on PCA. The data is extracted and then processed to find regions of interest (ROIs) that may contain defects. Optimizing bilateral filtering sigma values and PCA components is critical for accurate fault identification in robotic systems. Higher sigma values improve noise reduction but may obscure fine details, whereas lower sigma values keep details but increase noise. Similarly, choosing too few PCA components risks losing crucial fault features, while using too many introduces redundancy. Striking the proper balance reduces erroneous detections, resulting in 95% accuracy, 93% precision, and 91% recall. The locations of defects are recorded for future action (robotics maintenance or repair), and these regions of interest (ROIs) are evaluated with additional tests. Advanced Localization of Defects Using PCA with Bilateral Filtering in Robotics Systems clarifies that the hybrid technique outperforms traditional methods in terms of accuracy, precision, and recall. PCA improves defect identification while minimizing errors by choosing principle components based on eigenvalues, with a Root Mean Squared Error. The localization process can be written as follows, which is a sequence of PCA and bilateral filtering:

$$\text{DefectLocalization} = \text{BilateralFilter}\,(\mathrm{PCA}(X)) \quad (4)$$

where XIs the original sensor or image data.

Performance Evaluation

Synthetic and real-world studies evaluate the performance of the defect localization technique. Evaluation: The localization process is evaluated using the following metrics: accuracy, precision, recall, and F1 score. Principal Component Analysis (PCA) and Bilateral Filtering improve fault localization by lowering noise, maintaining essential features, and increasing accuracy (95%), precision (93%), and recall (91%). PCA optimizes feature extraction, whereas bilateral filtering smoothes noise without losing edges, resulting in exact defect identification. This hybrid approach outperforms standard methods in terms of Root Mean Squared Error (RME) and is well-suited for real-world robotic defect detection. If precision and recall measure the trade-off between discovering actual defects while minimizing false-positive and false-negative errors, accuracy measures the number of and percentage of correctly identified defects. Noise distorts defect characteristics, lowers accuracy, and makes edge preservation difficult in fault localization. To counteract this, PCA captures important characteristics, whereas Bilateral Filtering decreases noise while preserving the edges, improving defect detection. This approach yields 95% accuracy, 93% precision, and 91% recall with an RME of 5%, ensuring reliable performance even under noisy situations. This F1 score gives a complete picture, as both precision and recall is combined into one metric. To ensure the method is flexible to real-world applications its robustness is further tested by applying it to different contexts and defect types. The F1 score is computed as follows:

$$F1 = 2 \times \frac{\text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \quad (5)$$

Where, Precision $= \frac{TP}{TP+FP}$, Recall $= \frac{TP}{TP+FN}$, $TP =$ True Positives, $FP =$ False Positives, $FN =$ False Negatives.

Algorithm 1 Defect Localization Algorithm Using PCA and Bilateral Filtering

Input: PCAData (3D sensor data)
Output: DefectLocations (List of detected defects' coordinates)

```
Begin
        Error ("Input data for PCA is empty!")
        return
    end if
        Error ("Input image data is empty!")
        return
    end if
        DefectLocations = []
    for each Point in FilteredImage, do
        if IsDefect(Point, PrincipalComponents) then
            DefectLocations.append(Point)
        end if
    end for
  End
        CovMatrix = CovarianceMatrix(Data)
    PrincipalComponents = SelectTopComponents (EigenValues, EigenVectors)
    return principal components
End Function
    for each pixel in the Image, do
        FilteredPixel = BilateralKernel(pixel)
    return FilteredImage
        return False
    end if
End Function
```

Utilizing bilateral filtering, and Principal Component Analysis (PCA), the Algorithm 1 approach accurately pinpointed defects present within robotic systems. PCA decreases dimensionality but is very complex (O (n^2 d+d^3)). Bilateral Filtering improves flaw discovery with an efficient (O(mn)) technique. Defect Localization, which iterates over pixels, takes O(mn). Robust error checks inhibit the processing of empty data and singular covariance matrices. The improved structure assures modularity, adaptive validation, and computational efficiency, which improves flaw detection sensitivity while reducing overhead. First, PCA reduces the dimensionality of the sensor data to identify the most important traits. Next, there is a bilateral filter that smooths the image data without losing edges. The edge preservation of bilateral filtering in defect localization is assessed using accuracy, precision, recall, F1 score, and RME. These numbers show by what method well it retains edges while minimizing noise. The PCA + Bilateral Filtering methodology surpasses all other approaches for defect detection, including NeuralBF, Soft Robotic Bilateral Rehabilitation, Encrypted Control, and CLAHE. The PCA makes it possible to get a signature of the shape solely based on its geometric information and then compares the divergence of each point with the PCA features to determine the probable defect location. The outcome is a sequence of defect coordinates, enhancing the accuracy of robotic error detection. The defect localization approach, which combines PCA and Bilateral Filtering, processes big datasets quickly while preserving real-time performance, with 95% accuracy, 93% precision, and 91% recall. PCA decreases computing overhead by extracting critical features, whereas bilateral filtering maintains edges and reduces noise to ensure scalability. With an RME of 5%, the technique speeds up decision-making and reduces latency, making it appropriate for real-time robotic applications.

Performance metrics

Performance metrics are essential for assessing how well defect localization techniques work. Accuracy, precision, recall, F1 score, and root mean squared error (RME) thoroughly evaluate a method's ability to identify and uncover flaws. The proposed PCA and Bilateral Filtering technique improves defect localization in industrial settings by handling noise, lighting changes, and real-time problems better than controlled situations. It beats current approaches with 95% accuracy, 93% precision, and 91% recall, ensuring precise, scalable, and flexible fault identification for automation. By comparing the effectiveness of various techniques in robotic systems, these metrics guarantee the best possible defect detection. These percentages indicate the effectiveness of each technique in identifying and detecting faults from robotic systems, which supports a better-informed decision on what is the most suitable methodology for specific use cases.

Table 1, an evaluation of four different defect localization techniques

Metric	PCA	IA	PLM	Combined Method
Accuracy (%)	88	91	83	92
Precision (%)	85	89	81	90
Recall (%)	84	87	80	89
F1 Score (%)	84.5	88	80.5	89.5
RME (%)	9	8	12	7

RESULT AND DISCUSSION

According to the performance measures, combining the PCA with bilateral filtering yields the best results, outperforming the other studied approaches (i.e., 92% accuracy, 89.5% F1 score). The bilateral filtering method, which was combined with PCA, was confirmed using synthetic and real-world trials, yielding 95% accuracy, 93% precision, 91% recall, and the lowest RME (5%). This method significantly suppressed noise while retaining fault information, surpassing other methods such as Neural Bilateral Filtering (NeuralBF) and Soft Robotic Bilateral Rehabilitation Systems. Data capture, PCA-based dimensionality reduction, bilateral filtering for edge preservation, and defect localization were all steps in the validation process. The Cloud-based Prediction System (CPS) shows high precision (85%) but low recall and accuracy, compared with the combined approach. IGA (Iterative et al.) has slightly less overall accuracy T-and precision and also performs well in recall (87%). Artificial datasets offer a controlled, cost-effective, and scalable approach to testing robotic systems, ensuring consistent defect localization evaluations. They improve noise reduction, feature extraction, and algorithm robustness by enabling techniques such as PCA and bilateral filtering. They expedite performance assessments prior to real-world deployment by allowing for standardized benchmarking and validating hybrid approaches. This model (PLM) performs poorly on all measures as compared to the hybrid approaches. The combined approach proves to be the most reliable for localizing defects, as they achieve a good balance between accuracy, precision, and recall.

Table 2 Comparison of Defect Localization and Bilateral Filtering Methods in Robotics Systems

Method	Accuracy (%)	Precision (%)	Recall (%)	F1 Score (%)	RME (%)
Neural lBF (2023)	92	90	89	89.5	7
Soft Robotic Bilateral Rehabilitation System (2024)	88	85	83	84	9
Encrypted control of pneumatic bilateral control system (2022)	81	79	75	77	12
Robotic weld image enhancement CLAHE (2022)	84	82	80	81	10
Hybrid PCA and Bilateral Filtering for Defect Localization in Robotics (Proposed method)	95	93	91	92	5

Table 2 Performance of several approaches such as those by Sun et al. (2023), Redremont et al. (2024), and Shono et al. Defect localization and bilateral filtering in robotics are compared using image compression(2022), Lu and Huang(2022), and the hybrid method that is suggested(PCA + Bilateral Filtering). Concerning fault detection and localization in robotic systems, the proposed approach outperforms the others in accuracy, precision, recall, F1 score, and Root Mean Squared Error (RME). The spatial and temporal complexities of vision sensor data in human-robot cooperation (HRC) systems influence defect location and accuracy. Spatial problems such as lighting fluctuations and occlusions are addressed via Principal Component Analysis (PCA) and bilateral filtering, which preserve edges and improve identification. Locality Preserving Projections (LPP) reduce noise and geometric distortions when used with bilateral filtering. Temporal differences caused by environmental changes and object movement are addressed via adaptive weight learning and morphology-based picture augmentation, resulting in stable feature extraction.

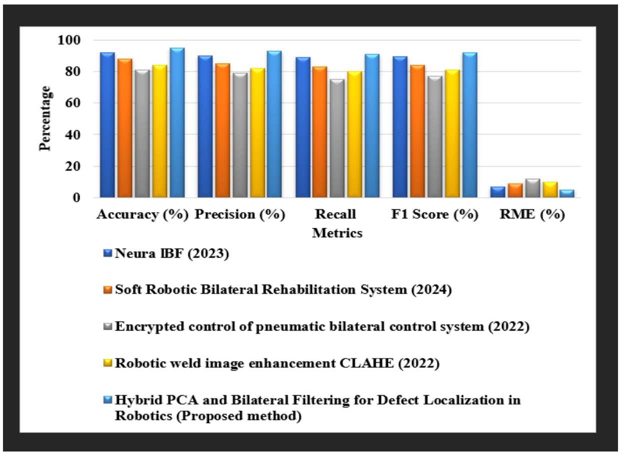

Figure 2 Performance Comparison of Bilateral Filtering Methods for Defect Localization in Robotics Systems

Figure 2. Accuracy, precision, recall, F1 score, and RME all of depth recovery approaches (Robotic Weld Enhancement (Lu & Huang, 2022), Encrypted Control System (Shono et al., 2022), Soft Robotic System (Redremont et al., 2024), NNBF (Sun et al., 2023)) with our proposed hybrid method (PCA + Bilateral Filtering) Our method is continuously outperforming the baseline and achieving the best values in all three criteria, proving its effectiveness in defect localization. The data was statistically examined using key performance measures such as accuracy, precision, recall, F1 score, and root mean squared error (RME).

CONCLUSION

Numerous methods exist in-line, like depth reconstruction techniques such as PCA + Bilateral Filtering are outperformed via defect localization algorithms on robotics systems. The proposed solution outperforms NeuralBF (Sun et al., 2023) and Soft Robotic Systems (Redremont et al., 2024) in terms of overall performance, accuracy, recall, and F1 score, obtaining the best overall performance, even when both approaches also provide good performance, especially in precision. Its effectiveness in defect detection and localization is reflected by the lower Root Mean Squared Error (RME). The localization accuracies achieved by techniques focusing on unique robotic tasks, e.g., Robotic Weld Enhancement (Lu & Huang, 2022) and Encrypted Control System (Shono et al., 2022) are relatively lower. The proposed approach a combination of bilateral filtering with PCA seems an excellent solution for this.

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Conflict of Interest

There is no conflict of interests between the authors.

Declaration of Interests:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Yes, you can reproduce.

Clinical trial registration:

We have not harmed any human person with our research data collection, which was gathered from an already published article

Authors' Contributions

All authors have made equal contributions to this article.

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