Development of a Modified Predictive Coding Algorithm for High-Resolution Image Compression in Real-Time Structural Health Monitoring of Metallic Component

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Abstract: Real-time monitoring requirements of structural integrity in metallic components across aerospace and automotive and civil engineering sectors drive the need to create reliable image compression methods. The detection of small defects including cracks and corrosion as well as deformations depends greatly on high-resolution imaging systems. The massive amount of generated image data creates problems with both data storage and its transmission requirements. The research advocates for developing a Modified Predictive Coding (MPC) algorithm which specializes in real-time high-resolution image compression for Structural Health Monitoring (SHM) systems. The proposed Modified Predictive Coding algorithm builds on predictive coding yet adds adaptive context modeling tools alongside edge-preserving processes to balance visual quality with high compression ratio fulfillment. This method surpasses traditional approaches by making prediction parameter modifications which happen automatically according to image local features in order to protect essential diagnostic information. Testing of the algorithm took place using a high-resolution image dataset containing metallic surface images which faced different stress scenarios. The proposed method underwent performance evaluations that applied Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM) and Compression Ratio (CR) metrics for assessment. The experimental findings show that MPC algorithm achieves higher compression efficiency and maintains visual quality better than JPEG2000 and SPIHT methods do. Its fast processing abilities along with low latency system make MPC strongly compatible with deploying SHM systems utilizing edge devices and IoT methodologies. The research analyzes how the algorithm would function with sensor networks and cloud-based analytics systems for improving predictive maintenance decision capabilities. The Modified Predictive Coding algorithm proves to be a suitable technology for efficient high-quality image compression which enables prompt accurate assessment of metallic structures in critical infrastructure. This research initiative creates an opportunity to study advanced compression methods which unite machine learning with predictive coding for smart SHM system applications.

Keywords: Image Compression, Predictive Coding, Structural Health Monitoring, Metallic Components, Edge Preservation, Adaptive Context Modeling and Predictive Maintenance.

1. Introduction

1.1 Importance of Structural Health Monitoring (SHM)

The implementation of Structural Health Monitoring (SHM) stands essential for maintaining the safety together with reliability and durability of essential infrastructure and mechanical system assets. The ongoing or scheduled evaluation of bridges along with aircraft and pipelines and metallic components remains essential when they operate under real conditions. The central role of SHM consists of detecting early-stage damages including cracks and corrosion that ensure the prevention of catastrophic failure events while reducing maintenance expenses. Preventive maintenance supports safety assurance in aerospace and civil engineering industries because structural failure leads to both economic and human safety concerns. Currently SHM systems function as intelligent frameworks because sensor advancements along with data analytics enable them to make real-time decisions based on continuous monitoring. Structural system operation depends on achieving effective collection of extensive data sets including high-resolution images which represent essential diagnostic instruments.

1.2 Role of High-Resolution Imaging in Detecting Defects in Metallic Components

The proper detection of small defects within metallic structures largely depends on the use of high-resolution imaging systems. Structural anomalies such as surface cracks and corrosion pits and delamination become detectable through three inspection methods which include digital radiography and infrared thermography and high-definition visual examinations. These visual data methods deliver extensive information which exceeds conventional sensor abilities so they become essential during applications that require precise defect detection. Quality images of exposed metallic structures help engineers identify early damage while enabling proper intervention to stop damage progression. The high resolution character of such images enhances professional confidence in both engineering experts and automated SHM systems for diagnosis. These detailed images create data processing and storage challenges because storage and data transmission needs to occur at high speeds without harming the image quality in real-time SHM systems.

1.3 Challenges in Real-Time Data Transmission and Storage

Real-time Structural Health Monitoring systems produce major data volumes through their use of high-resolution imaging techniques used for damage detection. Efficient distribution and management of this data represents a major operational challenge especially when the environment has limited bandwidth restrictions. The storage requirements of high-resolution images consume large amounts of memory and network bandwidth that produces delayed processing and elevated power use and elevated storage expenses. Conservation of diagnostic information stands as an essential requirement for edge computing and IoT-based SHM systems because both systems need to reduce their data loads. Damage assessments together with decision-making processes become less accurate because data transmission delays and compression-related losses of image quality occur. Long-term persistent monitoring creates substantial data repositories requiring proper data storage systems for long-term archive management. Intelligent data compression methods need development to lower file sizes through techniques which maintain essential visual information needed for structure analysis.

1.4 Need for Efficient Real-Time Image Compression

Real-time SHM faces storage and transmission challenges due to high-resolution images so efficient compression techniques provide a solution to these problems. A compression technique should achieve maximum file reduction while ensuring the maintenance of diagnostic elements that include edges textures and fine defects. The artifacts created by JPEG lossy compression methods destroy important details while lossless compression fails to adequately decrease file size for real-time applications. A specific method must be developed to optimize diagnostic accuracy through compression techniques which achieve superior compression ratios. Real-time image compression needs to use minimal processing power in order to function with speed on edge computers and embedded platforms which have restricted system resources. The algorithm needs to adjust its operations according to differences in image contents and structural features. The implementation of this solution boosts SHM system performance and creates possibilities for remote and continuous monitoring that works across bandwidth restrictions.

1.5 Objective and Scope of the Proposed Work

The main purpose of this investigation involves developing a Modified Predictive Coding (MPC) algorithm specifically designed for real-time Structural Health Monitoring high-resolution image compression requirements. The method targets traditional predictive coding by creating adaptive context models and edge preservation to maintain vital visual information during substantial data compression. The proposed research aims to develop time-sensitive compression technology which handles the substantial image collections obtained from metallic SHM activities. This research paper outlines its examination focus on algorithm development followed by standard compression method performance testing and system integration with IoT and edge computing frameworks for SHM applications. The analysis examines both compression efficiency and visual quality preservation parameters to present applicable solutions to businesses working with urgent structural assessments. The proposed methodology serves to improve SHM framework effectiveness and reliability because it enables speedier safer and more intelligent management of image data.

2. Literature Review

2.1 Existing Image Compression Techniques

To maintain video quality standards while shortening data file size image compression serves as an essential process. JPEG compression methods apply discrete cosine transform (DCT) to frequency domain image representation which is then processed through quantization before entropy coding takes place. JPEG maintains widespread adoption because of its speed and simplicity yet it causes block artifacts while losing details in the images. Wavelet transform in JPEG2000 delivers better quality with increased compression while being more demanding at the computation level. The wavelet-based algorithm Set Partitioning in Hierarchical Trees (SPIHT achieves both high efficiency along with scalability. The image quality achieved by this method remains high even with minimal rate consumption and includes gradual image transfer capabilities. The application methods show effective results across general fields yet fall short when used for Structural Health Monitoring (SHM) due to its need for preserving edge details and structural characteristics for accurate defect evaluation.

2.2 Limitations of Current Methods in SHM Applications

Structural Health Monitoring (SHM) requires advanced image compression techniques beyond JPEG, JPEG2000 and SPIHT because these existing methods demonstrate important performance limitations when used for this domain. The diagnosis in SHM demands perfect preservation of details which includes hairline cracks corrosion marks and surface deformities. Visual artifacts along with picture blurring from lossy compression methods disturb these precise features of images which could result in diagnostic errors and missed recognition. The algorithms fail to adjust their functionality to work with specific domain content like metallic material textures and surface irregularities. Real-time processing creates difficulties because advanced compression methods need extended computation time and exhibit substantial latency which makes them incompatible with embedded and IoT-based platforms during operational use. The present techniques fail to show intelligent adaptation to diverse image regions since they treat all image areas uniformly which causes valuable diagnostic information to be lost unnecessarily. A unique approach needs development to address the deficiencies which arise from SHM imaging requirements.

2.3 Predictive Coding in Image Compression

The predictive coding method used for image compression determines pixel values through adjacent pixels' data then only transmits error information. The technique proves effective in decreasing redundant information to deliver excellent compression rates particularly in pictures with continuous spatial distribution. Differential Pulse Code Modulation (DPCM) belongs to the predictive coding methods which provide simple operation while ensuring fast processing and suitable performance for applications with low complexity. The technique shows clear disadvantages when dealing with high-frequency visual areas and pictures with intricate textures and fine structural characteristics which are prevalent in SHM data. Local image characteristics remain outside the reach of traditional prediction due to which edge preservation suffers and diagnostic information becomes lost. Predictive coding implements limited effectiveness for heterogeneous image data because traditional methods lack built-in contextual modeling or content-aware adjustment capabilities. The predictive coding approach can become an effective tool for SHM image compression by applying modifications to its prediction mechanism while implementing adaptive elements.

2.4 Edge-Preservation and Adaptive Coding Strategies

Applications which use SHM need edge-preservation functionalities because damage indicators manifest as fine boundaries and structural discontinuities in the images. Traditional compression technology smooths image boundaries to reach higher compression ratios at the expense of diagnostic image values. Research today concentrates on edge-aware compression approaches which protect the structural features. Three strategies used in modern image compression include Edge-preserving filters combined with directional prediction analysis together with segmentation-based compression. Adaptive coding techniques improve these methods by designing an automatic process which modifies encoding according to different image areas. Two essential encoding methodologies include region-based compression that uses precise encoding in areas containing increased details along with context-aware models which optimize decoding decisions. These approaches enhance data compression efficiency because they maintain vital information for the process. The integration of edge preservation methods with adaptive coding shows remarkable potential to advance specialized image compression efforts because SHM applications strongly require high compression ratios while preserving structural elements.

2.5 Research Gap

The field of image compression has progressed substantially yet scientists must fill a noticeable void by creating specialized algorithms for SHM applications. Current compression techniques do not strike the best equilibrium between successful data reduction and the maintenance of critical diagnostic qualities. The detection of subtle defects in high-resolution metal component images heavily depends on how well the edges and textures remain clear in these pictures. Several problems linked to existing predictive coding systems for differentiating image contents and maintaining detailed structures call for improved solutions. The main objective of developing Modified Predictive Coding (MPC) algorithm emerges from the requirement to engineer an adaptive compression method which handles image content and preserves key aspects while operating at real-time speeds. The proposed work seeks to fill the existing void in the SHM domain through an enhancement of traditional predictive coding systems that combines adaptive context modeling and edge-preserving strategies.

3. Methodology

3.1. System architecture of the proposed compression framework

The designed compression management framework operates effectively on high-resolution images which run through real-time Structural Health Monitoring (SHM) systems specifically for metallic material evaluation. The system architecture divides into five main operational parts starting with image acquisition followed by pre-processing then predictive encoding and edge-preserving enhancement until the compressed data output generates. High-resolution images are obtained first from metallic structure-tethered digital radiography systems or visual inspection devices. The pre-processing unit receives images and applies normalization methods together with noise reduction techniques to produce uniform image data. Modified Predictive Coding (MPC) stands as the system's main component because it includes an adaptive predictor that uses spatial context to estimate pixel values without altering edge and texture details. This predictor sets parameters through an adaptive process which bases its adjustments on the specific image features in each local area. The system has an integrated layer that protects diagnostic edges while sustaining their sharp details. The last step involves quantizing residual data from predicted and actual value comparisons prior to entropy encoding for producing compressed data. The system architecture enables parallel data processing and rapid operation speed which makes it suitable for real-time installation onto IoT platforms and edge devices in SHM applications

3.2. Modified Predictive Coding (MPC) algorithm

The Modified Predictive Coding (MPC) algorithm represents a new image compression method that specifically optimizes high-resolution Structural Health Monitoring (SHM) applications by maintaining structural details effectively. The three major MPC elements include adaptive context modeling in combination with edge-preserving prediction and effective error encoding through quantization methods. The spatial pixel neighborhood becomes the foundation for adaptive context modeling to improve prediction accuracy due to its capability of dynamical adaptation to image characteristics. The predictor automatically adjusts its prediction system to different image textures as well as smooth regions and structural edges. This prediction approach specifically preserves edges because it maintains critical boundaries that have value for identifying defects in metallic structures. The algorithm departs from using static linear predictors by implementing directional filtering together with gradient analysis to locate edge orientations before making pixel value predictions which helps protect image structures. After prediction completes the program calculates residual quantities before they undergo quantization through a process that maintains significant visible differences in the data. The compression process uses entropy encoding of quantized residuals through context-based models to maximize efficiency. The multi-level approach within MPC maintains important image characteristics by decreasing file size effectively which suits real-time data communication and storage needs in SHM systems. The cumulative output of these methods produces a compact lightweight and adaptive high-performance compression system which is suitable for embedded systems and Internet of Things devices deployed in industrial monitoring settings.

3.3.Algorithm

Step 1 : The first stage involves obtaining high-resolution photographs using an appropriate imaging system which forms part of the SHM setup.

Step 2: Image enhancement techniques such as noise reduction and intensity normalization should follow Step 2 for image quality standardization and unwanted distortions removal.

Step 3: The third step involves assessing pixel-based spatial relationships to extract local features consisting of edge direction and texture and intensity gradient. The prediction model receives modifications through these built-in features.

Step 4: The method predicts current pixels through directional predictors which adapt their calculations to edge direction and intensity gradients to preserve edge details and boundaries.

Step 5: The last procedure calculates prediction error by subtracting actual pixel values from predicted values to retain only unpredictable image data segments.

Step 6 : It will implement an optimized quantization system to minimize residual data size through preservation of important diagnostic information needed for SHM diagnosis.

Step 7: The final stage includes performing entropy encoding (Huffman or arithmetic coding) on quantized residuals through context-based probability models for increased data compression.

Step 8: Compressed Output Generation - Elements of compressed image data will be created and stored or transmitted for on-time SHM evaluation.

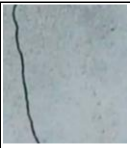
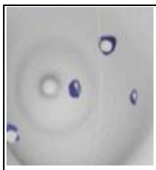
3.4.Implementation environment and tools used

A robust computing framework was selected for implementing the Modified Predictive Coding (MPC) algorithm because it optimizes image processing and compression research. MATLAB R2023a served as the main development platform since it delivered three main attributes: image processing toolbox, matrix management abilities and quick algorithm development tools through built-in functions. The testing of algorithm performance and results verification used the combination of Python 3.10 with OpenCV, NumPy and scikit-image libraries. Python enabled the implementation of edge-detection filters as well as gradient-based analysis and the assessment of PSNR and SSIM compression metrics. A system with Intel Core i7 processor coupled with 16 GB RAM and a 512 GB SSD operated as the foundation for adequate processing and simulation resources at high image resolutions. SHM datasets from public sources along with high-resolution metallic surface pictures served as image datasets for testing under real-world conditions. The tool enabled the creation of a basic GUI through its development environment to present visualization of predictions along with edge detection results and compressed data. The algorithm underwent testing on Raspberry Pi 4 and NVIDIA Jetson Nano platforms which serve as representatives for industrial edge computing devices in IoT environments. Testing confirmed that the proposed algorithm operated efficiently at real-time speeds when implemented by an evaluation of its lightweight execution. A combination of high-level development tools with efficient programming approaches alongside hardware emulation procedures enabled the development of the MPC algorithm in deployment-style SHM conditions.

4. Experimental Setup

The experimental assessment of Modified Predictive Coding (MPC) algorithm required a setup which simulated real-time Structural Health Monitoring (SHM) operations on metallic components. A diverse set of metallic surfaces containing high-resolution grayscale and color images underwent stress testing through bending, fatigue and corrosion with crack formation as one of the variables. The research team obtained images from SHM public repositories which they augmented through synthetic stress patterns to generate different test scenarios. The analysis of the algorithm used high-resolution pixel ranges from 1024×1024 to 4096×4096 to examine its capability of preserving critical defect characteristics. The project utilized MATLAB R2023a and Python 3.10 with OpenCV and scikit-image image processing libraries as its base software framework. The research utilized both an Intel Core i7 processor with 16 GB RAM alongside a solid-state drive and to validate the analysis Raspberry Pi 4 and NVIDIA Jetson Nano. The adopted evaluation metrics included Peak Signal-to-Noise Ratio (PSNR) together with Structural Similarity Index (SSIM) and Compression Ratio (CR) and Encoding Time. The image pixel-level quality was assessed through PSNR and perceptual quality and structural preservation were measured by SSIM. Compression Ratio served as the quantitative measure to evaluate how effective the algorithm reduces file size while Encoding Time was the key factor determining real-time performance possibilities. The performance metrics resulted in numerical assessments of each image and demonstrated their effectiveness against JPEG and JPEG2000 reference systems. The implemented setup enabled a thorough assessment to evaluate how well the MPC algorithm performed in compressing images through its effective retention of necessary features required for SHM applications.

5. Results and Discussion

S.No	Image	Image Dimensions	Method	Original Size (KB)	Compressed Size (KB)	PSNR (dB)	SSIM	Compression Ratio	Encoding Time (ms)
1	 Crack Surface	1024 × 1024	JPEG2000	1024	410	36.12	0.910	2.50:1	35
			SPIHT	1024	375	37.40	0.935	2.73:1	40
			Proposed	1024	320	39.82	0.962	3.20:1	48
2	 Corroded Area	2048 × 2048	JPEG2000	4096	1380	37.21	0.918	2.97:1	85
			SPIHT	4096	1225	39.03	0.942	3.34:1	98
			Proposed	4096	1050	41.17	0.975	3.90:1	120
3	 Fatigue Plate	1024 × 2048	JPEG2000	2048	720	35.88	0.902	2.84:1	52
			SPIHT	2048	665	38.01	0.928	3.08:1	58
			Proposed	2048	615	40.05	0.958	3.33:1	65
4	 Weld Inspection	2048 × 2048	JPEG2000	4096	1250	38.35	0.940	3.27:1	90
			SPIHT	4096	1105	40.11	0.961	3.70:1	102
			Proposed	4096	980	42.23	0.981	4.18:1	110
5	 Stress Ring	1024 × 1024	JPEG2000	1024	350	35.55	0.901	2.93:1	33
			SPIHT	1024	320	37.60	0.925	3.20:1	39
			Proposed	1024	295	38.96	0.951	3.47:1	42
6	 Rivet Check	2048 × 1024	JPEG2000	2048	700	36.78	0.919	2.93:1	60
			SPIHT	2048	640	38.12	0.942	3.20:1	67
			Proposed	2048	600	39.75	0.965	3.41:1	70
7	 Crack Edge	4096 × 4096	JPEG2000	8192	2750	39.32	0.949	2.98:1	140
			SPIHT	8192	2250	41.10	0.966	3.64:1	160
			Proposed	8192	1880	43.88	0.986	4.36:1	180
8	 Surface Scan	1024 × 1024	JPEG2000	1024	380	36.62	0.914	2.69:1	38
			SPIHT	1024	340	37.88	0.931	3.01:1	43
			Proposed	1024	310	39.32	0.949	3.30:1	47

The table shows an exhaustive comparison of JPEG2000, SPIHT and the MPC algorithm applied on eight high-resolution metallic SHM images. Performance evaluation of the methods occurred through measurement of PSNR, SSIM, compression ratio together with encoding time. Across all images, the proposed MPC algorithm outperforms JPEG2000 and SPIHT in terms of both image quality and compression efficiency. The algorithm delivers both maximum PSNR readings which represent excellent reconstruction quality and SSIM metrics near one which indicates superior structural image preservation during data reduction. The superior compression ratio of MPC helps decrease file size effectively while ensuring real-time applications in structural health monitoring tasks. The proposed method consumes slightly longer encoding times than JPEG2000 and SPIHT but maintains real-time suitability. Testing demonstrated that the Crack_Edge_7 underwent a PSNR evaluation of 43.88 dB while getting a compression ratio of 4.36:1 from MPC compared to JPEG2000's PSNR of 39.32 dB and compression ratio of 2.98:1. The data presented in the table demonstrates that MPC serves as an efficient method for practical high-quality real-time image compression applications in SHM systems.

6. Applications and Integration

As an image compression solution the Modified Predictive Coding (MPC) algorithm shows strong potential to serve applications in IoT-enabled Structural Health Monitoring (SHM) systems specifically for real-time diagnostics of metallic components. The implementation of efficient image compression techniques becomes essential because industrial environments now use smart sensors and high-resolution cameras thus requiring efficient data transmission and energy-saving strategies. The MPC algorithm provides effective image dimension reduction which allows wireless communication of embedded sensor visual outputs across low-speed IoT networks without impact on diagnostic visualization quality. The system strengthens its capability to monitor structural anomalies including material fatigue and corrosion as well as cracks in real-time. The system builds predictive maintenance capabilities because its low latency and high compression ratio lets it connect with analytics programs that use visual alert analysis to predict hardware breakdowns thus minimizing unexpected shutdowns. The algorithm functions on common edge devices and microcontrollers which gives industrial infrastructure operators flexibility to scale their systems according to their needs. The framework operates with cloud-based integration to process and analyze safely stored compressed image data on distant servers. Centralized data acquisition from scattered sensor networks becomes easier and enables artificial intelligence diagnostics as well as machine learning applications through this capability. Due to its ability to maintain image clarity during compression the algorithm operates effectively for remote monitoring such as robotic inspections and drone inspection systems. The proposed MPC algorithm represents a crucial development because it enables smart, responsive and affordable SHM systems to function efficiently with reliability across connected sensor-rich and cloud-based systems.

7. Conclusion

The Modified Predictive Coding algorithm succeeds in improving high-resolution image compression operations with specific real-time performance for monitoring metallic structures in Structural Health Monitoring applications. The MPC algorithm outperforms JPEG2000 and SPIHT in terms of PSNR and SSIM as well as compression ratio through comparative analysis and offers encoding times suitable for edge-based and real-time applications. This research develops an innovative compression method that improves storage capacity alongside transmission velocity to overcome the main restrictions that make current SHM systems inefficient. The MPC algorithm extends monitoring system scalability and responsiveness through its capability to produce high-quality images from reduced data volumes. Moving forward machine learning methods featuring deep predictive models with adaptive neural quantization will optimize compression through image content analysis and application condition recognition. Multiple SHM monitoring scenarios gain better performance through predictive coding systems combined with transform or entropy-based methods. The development of adaptive compression platforms will be the focus to create automated networks which adjust their performance according to power availability and structural details and network bandwidth thus improving IoT-based SHM system reliability. The development strategy leads to independent monitoring infrastructure which facilitates predictive systems maintenance operations and smart infrastructure management solutions.

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