Digital watermarking is evolving with time and technology and so are the attacks and attempts to contravene. Robust watermarking techniques are required for the protection of digital contents and deter the copyright infringements. Researchers need to develop robust watermarking techniques that are reliable, cost-effective and which can be implemented widely on commercial basis. It will not only promote the sense of security among the digital media creators but will also motivate them to deliver real, high quality multi-media contents over the public networks like Internet.

7.1. Challenges in Digital Watermarking

In order to be effective, a digital watermarking scheme must satisfy some basic requirements viz. visual imperceptibility, robustness, embedding capacity, uniqueness and minimum computation load for embedding or detecting the watermark [88]. Among these, ensuring watermark robustness to various geometric or other common image processing transformations is considered as the most challenging one. Geometric transformations can be applied easily with any off-the-shelf image processing software resulting in serious problems especially when the original image is not available at the time of extraction. Most of these geometric distortions are modeled as a combination of three basic transforms – rotation, scaling and translation. These transformations destroy the synchronisation of watermark and defeat the purpose of watermarking by misleading the detection or extraction process. In order to solve this synchronisation problem, various schemes prefer to embed the watermark using
moments or transform invariants which themselves suffer from problems of computational inaccuracy, numerical instability and high computational cost.

Another challenge that needs to be faced while designing a robust watermarking scheme is to embed sufficient amount of information without causing a significant loss of quality of the reconstructed images. Different watermarking applications require varying amount of information to be embedded for copyrights protection and data authentication. While a simple watermark may contain an identification code consisting of only few bits, high capacity watermarking systems may need to embed thousands of bits for applications like secure media distribution, thumbnail embedding for authentication, auxiliary data embedding and medical image watermarking. However, few techniques provide high capacity data embedding as increasing capacity adversely affects the visual imperceptibility and watermark robustness to various attacks.

Finally, a well-tuned watermark scheme that offers robustness, visual imperceptibility and high embedding capacity, may be computationally complex and impractical for real-time applications. As most of the digital transmission takes place via high speed public networks, a watermarking scheme must be capable of processing large data size in the limited computing environment. These challenges have motivated us to design a robust and fast watermarking scheme.

7.2. Conclusions

The basic objective of the present research was to design algorithms for the robust and fast watermarking using moments. The invariant transforms were later included due to their comparable performance with invariant moments and better speed advantage. We carried out thorough literature survey and experimental analysis before selecting a particular moment or transform for designing our novel image adaptive scheme for robust and fast digital watermarking. The major contributions of the research are summarised as follows:
7.2.1. Introduction of four RIMTs for Watermarking and their Comparative Performance Analysis

We introduce four invariant moments and transforms, namely, Fourier-Mellin moments (FMMs), orthogonal Fourier-Mellin moments (OFMMs), radial harmonic Fourier moments (RHFMs) and angular radial transform (ARTs) for robust image watermarking applications. Among these, RHFMs provide better performance than existing ZMs/PZMs while the performances of FMMs and OFMMs based watermarking schemes were found the least desirable. Hence, these moments could not be considered for watermarking. Among transforms, we introduce ARTs for watermarking. The performance of ARTs is found better than existing ZMs/PZMs-based watermarking, but lower than PCTs. Based on exhaustive testing, we concluded that ZMs, RHFMs and PCTs are relatively better than other six moments and transforms under investigation.

7.2.2. Investigation of Relationship among Properties of RIMTs and their Performances for Robust Watermarking

We performed comprehensive analysis of properties possessed by various RIMTs and their impact on robust watermarking. For this purpose, we selected one of the best watermarking schemes available [71] and evaluated the comparative performance of nine RIMTs for watermarking. Based on the comprehensive analysis of various properties and performances for robust watermarking, we draw some significant conclusions:

i. Robustness of a watermarking scheme is directly related to the invariance properties inherited by moments and transforms which are compromised due to inaccuracies in their computational framework.

ii. Embedding capacity of a watermarking scheme depends on the computational accuracy and numerical stability of moments and transforms. High capacity embedding can be achieved by employing accurate and numerically stable methods for computation.

iii. Visual imperceptibility or the quality of watermarked images is associated with the reconstruction capabilities of a moment or transform. Better reconstruction capabilities ensure better quality of watermarked images.
iv. The major overhead while embedding or extracting watermark is related to the computation of moments or transform coefficients. Transforms are far less computation intensive and much faster compared to the fastest methods available for the computation of moments. This difference is more significant at high order of moments and transforms.

7.2.3. Improvements in Watermark Performance through Accurate and Fast Computational Framework

We applied accurate and fast framework for the computation of moments and transforms to enhance the robustness, speed and embedding capacity in image watermarking. Based on the thorough literature survey, we observed that the computational framework based on the Gaussian numerical integration technique is more suitable for enhancing the accuracy and stability in computation of moments and transforms for watermarking. Fast algorithms based on recurrence relations and 8-way symmetry/anti-symmetry properties of basis functions were also applied to enhance the speed of computation.

7.2.4. Development of Novel Image Adaptive Embedding Procedure

We developed a novel image adaptive embedding procedure that uses invariant features of the image to generate the information decoded by the host signal. The proposed procedure performs conditional quantization to minimise the distortion added during embedding. Our procedure reduces the average number of moments to be modified during embedding by 50% while the worst case performance is bounded by the existing “best” available watermarking algorithm using orthogonal rotation invariant moments [71]. In addition, the proposed procedure preserves the improved magnitude invariance properties in a better way, thus resulting in better watermark robustness.

7.2.5. Introducing RHFM for Geometrically Robust Watermarking

Existing watermarking schemes widely use ZMs due to their superiority over other moment families. However, on the basis of detailed comparative analysis among various moment families, we observe that when accurate computational
framework is employed, RHFMs outperform in terms of reconstruction capabilities, numerical stability and magnitude invariance properties. These moments also have speed advantage over ZMs because their basis function consists of only sinusoidal terms and are less computation intensive. Therefore, we introduce these moments for image watermarking. It is also found that RHFMs-based watermarking schemes provide better visual imperceptibility, capacity and watermark robustness compared to ZMs-based watermarking schemes.

7.2.6. Other Contributions

Some of the other original contributions of the thesis include the use of relative ranking system for various moments and transforms on the basis of experimental results, wherever possible, to make concrete conclusions. We also present a broader taxonomy of watermarking types, classification of attacks and absolute and relative metrics for measuring embedding capacity in Chapter 2. Furthermore, we group various robust image watermarking techniques on the basis of approaches used to enhance the resilience against various attacks rather than the conventional classification based on the domain used for embedding, that is, spatial domain, transform domain or combined domain. The reason for this grouping is the belief that the choice of domain is independent of the approach used to ensure robustness. For example, block-based techniques can be applied in any domain. Similarly, transform domain can be used for implementing any watermarking scheme based on spread spectrum, geometric invariant or feature-based approach.

7.3. Limitations

Our watermarking method satisfies all the fundamental requirements laid down by Miller et al. [88] for an efficient watermarking system except uniqueness. This makes the proposed watermarking scheme vulnerable to forgery attacks. Hence, our future work will focus on embedding watermark in the selective and secure regions in the host image to counterfeit forgery attack.
Further, the proposed watermarking scheme offers very high embedding capacity theoretically, but in practice we find it infeasible to embed thousands of bits due to massive media quality distortions induced by quantization error.

### 7.4. Future Scope

We tried to achieve the objectives envisioned at the beginning of the thesis through the contributions presented in this thesis, but the research is not yet complete. The proposed watermarking scheme can be further improved in many ways and has enormous scope for expansion. Some of the directions for future work are:

i. **Development of Hybrid Approaches:** Hybrid approaches can be used to enhance the security of watermark against forgery attacks. A dual watermarking scheme based on the combination of geometrically invariant approach with feature-based or block-based approach can be explored for this purpose.

ii. **Realisation of High Capacity Watermarking Applications:** High capacity is required for watermarking applications used for secure media distribution, thumbnail embedding and medical imaging. Therefore, the usability of proposed watermarking system for high capacity data embedding applications can be further investigated.

iii. **Rotation Invariant Transforms for Real-time Watermarking Applications:** Transforms provide speed advantage, but offer poor reconstruction capabilities. Another research direction can be to explore rotation invariant transforms for real-time watermarking applications.

iv. **Extensions to Other Digital Media:** Although our work mainly focused on gray scale images with possible extensions to colour images and video frames as they have similar data representations. Further, through proper transformation 1-D audio signal can also be mapped to 2-D image like signal [118] thus making proposed technique extendible for audio watermarking. But the effects on robustness and visual imperceptibility on different digital contents need further investigation.
Publications based on this Research Work


Paper communicated:
