COMPUTATIONAL CAMERA WITH AN EXTENDED FIELD OF VIEW: DEMONSTRATION OF A NOVEL SYSTEM CONCEPT WITH INFORMATION EFFICIENT DESIGN

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Computational Camera with an Extended Field of View: Demonstration of a Novel System Concept with Information Efficient Design

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To my parents, teachers, & siblings

For your endless support,
unwavering belief, and constant encouragement.

I dedicate this work to you with all my gratitude.

THESIS CERTIFICATE

This is to certify that the thesis entitled, **"Computational Camera with an Extended Field of View: Demonstration of a Novel System Concept with Information-Efficient Design,"** submitted by **Ms. Ritika Malik** to the Indian Institute of Technology Delhi, in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy,** is a bonafide record of original research work conducted under our supervision.

To the best of our knowledge, the work presented in this thesis meets the requisite academic standards. **Ms. Ritika Malik** has fulfilled all the necessary requirements for the submission of her thesis, and this research has not been submitted in part or full to any other institution or university for the award of any degree or diploma.

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If I have seen further, it is by standing on the shoulders of giants

— Isaac Newton,
"Letter to Robert Hooke: 1675"

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This thesis represents my effort to explore computational imaging systems from an information transfer perspective, focusing on how optical design influences information capture and how computational techniques can enhance this capability. While not every avenue explored led to concrete results—whether due to unforeseen challenges in simulations or the need for deeper investigation—each step has been a learning experience. The progress documented here is the result of numerous stimulating discussions, particularly with my advisor, Prof. Kedar Khare, whose guidance, insightful discussions, and unwavering encouragement have been pivotal in the completion of this work.

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ABSTRACT

Computational imaging is a methodology that comprises the joint design of optical hardware and inverse algorithms to indirectly collect and retrieve an object's information from the recorded data, even if the data is not immediately interpretable. By leveraging this approach, we have engineered a novel imaging system that achieves an extended field of view while retaining near-diffraction-limited resolution, thereby enhancing the system's overall information capacity. This enhancement is achieved by strategically exploiting the inherent signal structure of the object through sophisticated encoding techniques embedded within the optical system design.

In this dissertation, I will provide a comprehensive explanation of my research on "*extended field of view imaging*." The objective is to enhance the space bandwidth product or information capacity of the computational imaging system by making modifications to the optical hardware through point spread function engineering and computational recovery algorithms. We show theoretically and experimentally an increment in field of view by a factor of 2 over the conventional imaging system. Our technology enables a system to capture a single-shot image with increased field of view (FoV) performance without compromising the native image resolution. We have also demonstrated the analogous relation between our study and structured illumination microscopy (SIM), which expands the Fourier domain rather than the spatial domain.

These findings guide us towards generalizing the concept of information capacity for computational imaging systems, a topic that will be explored in detail later in this dissertation. I describe this approach as *"information-efficient design"* since it facilitates encoding information tailored to specific experimental requirements. Additionally, we have examined the impact of detector bit depth on the design of computational imaging systems. This investigation led to the proposal of a new data-domain information measure that leverages the characteristics of detected information to predict system performance a priori to image reconstruction.

This work aims to establish a comprehensive framework for analyzing computational imaging systems, devise algorithms to solve related inverse problems, and determine the practical limits on recoverable information using a computational imaging system. Compressive imaging, which involves acquiring a small number of measurements, plays a critical role in this work. It efficiently reconstructs images with sparse object information and addresses challenges caused by the discrete, quantized nature of the measurements.

सार

कम्प्यूटेशनल इमेजिंग एक ऐसी पद्धति है जिसमें ऑप्टिकल हार्डवेयर और व्युत्क्रम एल्गोरिदम का संयुक्त डिज़ाइन शामिल है ताकि रिकॉर्ड किए गए डेटा से किसी वस्तु की जानकारी को अप्रत्यक्ष रूप से एकत्र किया जा सके और फिर एल्गोरिदम के माध्यम से उस जानकारी को पुनर्प्राप्त किया जा सके, भले ही रिकॉर्डेड डेटा तुरंत समझने योग्य न हो। इस दृष्टिकोण का लाभ उठाते हुए, हमने एक नया इमेजिंग सिस्टम विकसित किया है जो विवर्तन–सीमित (near–diffraction–limited) रिज़ॉल्यूशन को बनाए रखते हुए एक विस्तारित दृश्य क्षेत्र (field of view) प्राप्त करता है, जिससे सिस्टम की समग्र सूचना क्षमता में वृद्धि होती है। यह वृद्धि ऑप्टिकल सिस्टम डिज़ाइन में अंतर्निहित परिष्कृत एन्कोडिंग तकनीकों के माध्यम से वस्तु की अंतर्निहित सिग्नल संरचना का रणनीतिक रूप से लाभ उठाकर हासिल की जाती है।

इस शोध प्रबंध (dissertation) में, मैं "विस्तारित दृश्य क्षेत्र इमेजिंग" पर आधारित अपने शोध का विस्तृत विवरण प्रस्तुत करूंगी। इसका उद्देश्य पॉइंट स्प्रेड फंक्शन इंजीनियरिंग और कम्प्यूटेशनल रिकवरी एल्गोरिदम के माध्यम से ऑप्टिकल हार्डवेयर में संशोधन कर कम्प्यूटेशनल इमेजिंग सिस्टम की स्पेस–बैंडविड्थ प्रोडक्ट अथवा सूचना क्षमता को बढ़ाना है। हमने सैद्धांतिक और प्रयोगात्मक रूप से यह दर्शाया है कि पारंपरिक इमेजिंग प्रणालियों की तुलना में हमारे सिस्टम में दृश्य क्षेत्र (field of view) में लगभग 2 गुना की वृद्धि होती है। हमारी तकनीक एक सिंगल–शॉट प्रणाली है, जो मूल छवि रिज़ॉल्यूशन से समझौता किए बिना विस्तारित दृश्य क्षेत्र को एक ही इमेज में कैप्चर करने में सक्षम बनाती है। इसके अतिरिक्त, हमने अपने अध्ययन और स्ट्रक्चर्ड इल्यूमिनेशन माइक्रोस्कोपी (SIM) के बीच एक समानता भी प्रदर्शित की है, जो स्थानिक डोमेन (spatial domain) के बजाय फूरियर डोमेन का विस्तार करता है।

ये निष्कर्ष हमें कम्प्यूटेशनल इमेजिंग सिस्टम के लिए सूचना क्षमता की अवधारणा को सामान्यीकृत करने की दिशा में मार्गदर्शन करते हैं। यह विषय इस शोध प्रबंध में आगे विस्तार से विवेचित किया जाएगा। मैं इस दृष्टिकोण को "सूचना–कुशल डिज़ाइन" के रूप में वर्णित करती हूँ, क्योंकि यह विशिष्ट प्रायोगिक आवश्यकताओं के अनुरूप सूचना को एन्कोड करने की सुविधा प्रदान करता है। इसके अतिरिक्त, हमने कम्प्यूटेशनल इमेजिंग सिस्टम के डिज़ाइन पर डिटेक्टर बिट डेप्थ (bit–depth) के प्रभाव का अध्ययन किया है। इस विश्लेषण के परिणामस्वरूप, हमने एक नया डेटा–डोमेन सूचना मापदंड प्रस्तावित किया है, जो प्राप्त सूचना की विशेषताओं का उपयोग करके इमेज पुनर्निर्माण से पहले ही सिस्टम के प्रदर्शन का पूर्वानुमान लगाने में सक्षम है।

इस शोध का उद्देश्य कम्प्यूटेशनल इमेजिंग प्रणालियों के विश्लेषण के लिए एक समग्र ढांचा स्थापित करना, संबंधित इनवर्स समस्याओं को हल करने हेतु एल्गोरिद्म विकसित करना, तथा कम्प्यूटेशनल इमेजिंग सिस्टम के माध्यम से पुनः प्राप्त की जा सकने वाली सूचना की व्यावहारिक सीमाओं का निर्धारण करना है। इस कार्य में कम्प्रेसिव इमेजिंग की एक महत्वपूर्ण भूमिका है, जिसमें सीमित मापनों के माध्यम से डेटा अधिग्रहण किया जाता है। यह पद्धति विरल वस्तु सूचना वाले चित्रों का कुशलतापूर्वक पुनर्निर्माण करती है और मापन की विसंलग्न (discrete) तथा क्वांटाइज्ड प्रकृति से उत्पन्न चुनौतियों का समाधान करती है।

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ACRONYMS

CCD	Charge-Coupled Device
CMOS	Complementary Metal-Oxide-Semiconductor
FOV	Field of View
DOF	Depth of Field
SBP	Space-Bandwidth Product
PSF	Point Spread Function
LSF	Line Spread Function
ISO	International Organization for Standardization
CGH	Computer-Generated Holography
MPIR	Multiple Point Impulse Response
SLM	Spatial Light Modulator