SPUD: Simultaneous Phase Unwrapping and Denoising Algorithm for Phase Imaging

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Recent methods for phase unwrapping in the presence of noise include denoising algorithms to filter out noise as a pre-processing stage. However, including a denoising stage increases the overall computational complexity resulting in long execution times. In this paper, we present a non-iterative Simultaneous Phase Unwrapping and Denoising algorithm for phase imaging, referred to as SPUD. The proposed method relies on the least-squares Discrete Cosine Transform (DCT) solution for phase unwrapping with an additional sparsity constraint on the DCT coefficients of the unwrapped solution. Simulation results with different levels of noise and wrapped phase fringe density reveal the suitability of the proposed method for accurate phase unwrapping and restoration. When compared to the 2D windowed Fourier transform filter, SPUD performs better in terms of phase error and execution times. The processing of experimental data from synthetic aperture radar showed the capability for processing real images, including removing phase dislocations. An implementation of the proposed algorithm can be accessed and executed through a Code Ocean compute capsule.

1. INTRODUCTION

Two-dimensional (2D) phase unwrapping is a necessary process in many applications such as synthetic radar aperture, fringe projection profilometry, interferometry, magnetic resonance imaging, among others [1–3]. The unwrapping process consists in retrieving the continuous phase φ from its wrapped version ψ, which lies in the interval $(-\pi, \pi]$ [4]. In the noiseless scenario, phase unwrapping is trivial and straightforward. However, in practice, ψ is affected by noise, which makes phase unwrapping difficult and decreases the measurement accuracy [5, 6].

Phase unwrapping has been traditionally approached from two perspectives [7]. In the classical approach, the goal is to obtain a continuous phase regardless of the presence of noise. Conventional phase unwrapping algorithms such as path-following approaches [8], quality-guided path-following methods [9, 10], mask-cut phase unwrapping [11], Flynn's minimum discontinuity [12], and minimum L^p-norm algorithms [1, 13], follow this perspective [1, 14]. Quality-guided and L^p-norm phase unwrapping algorithms have shown the best performance in the presence of low-level noise [1], although the computation of quality maps increases the complexity [15]. Recently, an iterative least-squares-based phase unwrapping method referred to as CPULSI [16] has proven to be highly suitable even on extremely noisy phases [5]. However, despite obtaining an accurate continuous phase map, a further denoising stage must be applied to estimate a phase map suitable for quantitative measurements [5, 17].

The second perspective includes denoising preprocessing stages to produce a restored wrapped phase map, followed by phase unwrapping. For instance, Montresor and Picart [18] evaluated the performance of state-of-the-art algorithms for phase data denoising including Wiener filtering [19, 20], wavelet thresholding approaches [21, 22], non-local means [23–25], transform-based block-matching 3D (BM3D) filter [26, 27], 2D windowed Fourier transform filter (WFF) [10, 28, 29], and the SPADEDH algorithm [30, 31]. They quantitatively assessed these algorithms and ranked them according to their performance to isolate the genuine phase gradients from the noisy wrapped

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Development and Characterization of a Dispersion-Encoded Method for Low-Coherence Interferometry Christopher Taudt,2021-11-16 This Open Access book discusses an extension to low coherence interferometry by dispersion encoding The approach is theoretically designed and implemented for applications such as surface profilometry polymeric cross linking estimation and the determination of thin film layer thicknesses During a characterization it was shown that an axial measurement range of 79 91 m with an axial resolution of 0 1 nm is achievable Simultaneously profiles of up to 1 5 mm in length were obtained in a scan free manner This marked a significant improvement in relation to the state of the art in terms of dynamic range Also the axial and lateral measurement range were decoupled partially while functional parameters such as surface roughness were estimated The characterization of the degree of polymeric cross linking was performed as a function of the refractive index It was acquired in a spatially resolved manner with a resolution of 3 36 x 10 5 This was achieved by the development of a novel mathematical analysis approach **Wave Propagation, Scattering And Emission In Complex Media** Ya-qiu Jin,2005-01-26 This book contains review papers presented at the International Workshop on Wave Propagation Scattering and Emission on Theory Experiment Simulation and Inversion WPSE The papers are of high quality covering broad areas a new mechanism of interaction of electromagnetic waves with complex media remote sensing information computational electromagnetics etc This book summarizes the most significant progress in wave propagation encompassing theory experiment simulation and inversion It will also serve as a good reference for scientists in future research List of Foreign Invited Speakers Henry Bertoni Brooklyn Polytechnic University Lawrence Carin Duke U Al Chang NASA Goddard Margaret Cheney Rensselaer Polytech Institute Weng Chew U of Illinois at Urbana Champaign Shane Cloude AEL Consultants UK Adrian Fung U of Texas at Arlington Al Gasiewski Environmental Tech Lab NOAA Martti Hallikainen Helsinki U of Technology Akira Ishimaru U of Washington Magdy Iskander U of Hawaii J A Kong MIT Roger Lang George Washington U Alex Maradudin U of California at Irvine Eric Michielssen U of Illinois at Urbana Champaign Eni Njoku Caltech Jet Propulsion Lab Carey Rappaport Northeastern U Marc Saillard Institut Fresnel Kamal Sarabandi U of Michigan David R Smith U of California at San Diego Mitsuo Tateiba Kyushu University George Uslenghi U of Illinois at Chicago and Werner Wiesbeck Karlsruhe U **Proceedings of the 4th International Conference on Cognitive Based Information Processing and Applications–Volume 3** Bernard J. Jansen,Jun Ye,Qingyuan Zhou,2026-01-01 This book contains papers presented at the 4th International Conference on Cognitive based Information Processing and Applications CIPA in Changzhou China from November 22 to 23 2024 The papers represent the various technological advancements in theory technology and application of artificial intelligence including precision mining intelligent computing deep learning and all other theories models and technologies related to artificial intelligence It caters to postgraduate students researchers and practitioners specializing and working in the area of cognitive inspired computing and intelligent computing The book

represents Volume 3 for this conference proceedings which consists of a 3 volume book series **Computer Vision – ECCV 2024 Workshops** Alessio Del Bue,Cristian Canton,Jordi Pont-Tuset,Tatiana Tommasi,2025-05-26 The multi volume set LNCS 15623 until LNCS 15646 constitutes the proceedings of the workshops that were held in conjunction with the 18th European Conference on Computer Vision ECCV 2024 which took place in Milan Italy during September 29 October 4 2024 These LNCS volumes contain 574 accepted papers from 53 of the 73 workshops The list of workshops and distribution of the workshop papers in the LNCS volumes can be found in the preface that is freely accessible online **Innovative Techniques and Applications of Modelling, Identification and Control** Quanmin Zhu,Jing Na,Xing Wu,2018-04-20 This book presents the most important findings from the 9th International Conference on Modelling Identification and Control ICMIC 17 held in Kunming China on July 10 12 2017 It covers most aspects of modelling identification instrumentation signal processing and control with a particular focus on the applications of research in multi agent systems robotic systems autonomous systems complex systems and renewable energy systems The book gathers thirty comprehensively reviewed and extended contributions which help to promote evolutionary computation artificial intelligence computation intelligence and soft computing techniques to enhance the safety flexibility and efficiency of engineering systems Taken together they offer an ideal reference guide for researchers and engineers in the fields of electrical electronic engineering mechanical engineering and communication engineering **Optics Letters** ,2007 **Electrical & Electronics Abstracts** ,1997 **Two- and Three-dimensional Methods for Inspection and Metrology** ,2006 Inertial Fusion Sciences and Applications 2003 B. A. Hammel,2004 **Two-Dimensional Phase Unwrapping** Dennis C. Ghiglia,Mark D. Pritt,1998-04-28 A resource like no other the first comprehensive guide to phase unwrapping Phase unwrapping is a mathematical problem solving technique increasingly used in synthetic aperture radar SAR interferometry optical interferometry adaptive optics and medical imaging In Two Dimensional Phase Unwrapping two internationally recognized experts sort through the multitude of ideas and algorithms cluttering current research explain clearly how to solve phase unwrapping problems and provide practicable algorithms that can be applied to problems encountered in diverse disciplines Complete with case studies and examples as well as hundreds of images and figures illustrating the concepts this book features A thorough introduction to the theory of phase unwrapping Eight algorithms that constitute the state of the art in phase unwrapping Detailed description and analysis of each algorithm and its performance in a number of phase unwrapping problems C language software that provides a complete implementation of each algorithm Comparative analysis of the algorithms and techniques for evaluating results A discussion of future trends in phase unwrapping research Foreword by former NASA scientist Dr John C Curlander Two Dimensional Phase Unwrapping skillfully integrates concepts algorithms software and examples into a powerful benchmark against which new ideas and algorithms for phase unwrapping can be tested This unique introduction to a dynamic rapidly evolving field is essential for professionals and graduate students in SAR interferometry optical interferometry adaptive

optics and magnetic resonance imaging MRI   <u>Consistent 2-D Phase Unwrapping Guided by a Qualtiy Map</u> ,1995 The problem of 2 D phase unwrapping arises when a spatially varying quantity is measured modulo some period One needs to reconstruct a smooth unwrapped phase consistent with the original data by adding a multiple of the period to each sample Smoothness typically cannot be enforced over all of the scene due to noise and localized jumps An unwrapping algorithm may form a mask within which phase discontinuities are allowed In interferometry a quality map is available indicating the reliability of the measurements In this case the mask should be contained as much as possible in areas of low quality This paper presents an algorithm for phase unwrapping in which the mask design is guided by the quality map The mask is grown from the residues as defined by Goldstein et al into areas where the quality is below a threshold A connected component of the mask stops growing when its residue charge becomes balanced The threshold is raised as necessary to allow growth This stage terminates when all components are balanced The mask is then thinned by removing points that are not needed to cover the residues correctly The unwrapped phase is found by simple I D unwrapping along paths that avoid the mask We present an example solution found by the algorithm and discuss possible modifications   **Phase Unwrapping by N-connected TRW-S Algorithm for InSAR Images** Mehrnaz Movahed,2020   <u>Phase Unwrapping Using Discontinuity Optimization</u> ,2001 In SAR interferometry the periodicity of the phase must be removed using two dimensional phase unwrapping The goal of the procedure is to find a smooth surface in which large spatial phase differences called discontinuities are restricted to places where their presence is reasonable The pioneering work of Goldstein et al identified points of local unwrap inconsistency called residues which must be connected by discontinuities This paper presents an overview of recent work that treats phase unwrapping as a discrete optimization problem with the constraint that residues must be connected Several algorithms use heuristic methods to reduce the total number of discontinuities Constantini has introduced the weighted sum of discontinuity magnitudes as a criterion of unwrap error and shown how algorithms from optimization theory are used to minimize it Pixels of low quality are given low weight to guide discontinuities away from smooth high quality regions This method is generally robust but if noise is severe it underestimates the steepness of slopes and the heights of peaks This problem is mitigated by subtracting modulo 2 pi a smooth estimate of the unwrapped phase from the data then unwrapping the resulting residual phase The unwrapped residual is added to the smooth estimate to produce the final unwrapped phase The estimate can be computed by lowpass filtering of an existing unwrapped phase this makes possible an iterative algorithm in which the result of each iteration provides the estimate for the next An example illustrates the results of optimal discontinuity placement and the improvement from unwrapping of the residual phase

Absolute Distance Contouring and a Phase Unwrapping Algorithm for Phase Maps with Discontinuities Xinjun Xie,1997   **Efficient Phase Unwrapping** ,2005 In the field of optical interferometry two dimensional projections of light interference patterns are often analysed in order to obtain measurements of interest Such interference patterns or

interferograms contain phase information which is inherently wrapped onto the range t to it Phase unwrapping is the processes of the restoration of the unknown multiple of 2ir and therefore plays a major role in the overall process of interferogram analysis Unwrapping phase information correctly becomes a challenging process in the presence of noise This is particularly the case for speckle interferograms which are noisy by nature Many phase unwrapping algorithms have been devised by workers in the field in order to achieve better noise rejection and improve the computational performance This thesis focuses on the computational efficiency aspect and picks as a starting point an existing phase unwrapping algorithm which has been shown to have inherent noise immunity This is namely the tile based phase unwrapping method which attains its enhanced noise immunity through the application of the minimum spanning tree concept from graph theory The thesis examines the problem of finding a minimum spanning tree for this particular application from a graph theory perspective and shows that a more efficient class of minimum spanning tree algorithms can be applied to the problem The thesis then goes on to show how a novel algorithm can be used to significantly reduce the size of the minimum spanning tree problem in an efficient manner   **Hybrid 2D Phase Unwrapping Methodology Using Spatial Fuzzy Clustering and Neurofuzzy Classification with Application in Sar Images** ,2001 Existing phase unwrapping PU methodology has arbitrary settings in selection of most optimal algorithm for a particular phase image These arbitraries impose partially trial and error basis in finding for the best phase unwrapping algorithm and tinkering quality map in order to produce the most optimal unwrapped solution Hence a hybrid PU methodology is proposed and developed

The Top Books of the Year Denoising Phase Unwrapping Algorithm For Precise Phase The year 2023 has witnessed a noteworthy surge in literary brilliance, with numerous captivating novels captivating the hearts of readers worldwide. Lets delve into the realm of top-selling books, exploring the engaging narratives that have charmed audiences this year. Denoising Phase Unwrapping Algorithm For Precise Phase : Colleen Hoovers "It Ends with Us" This heartfelt tale of love, loss, and resilience has gripped readers with its raw and emotional exploration of domestic abuse. Hoover masterfully weaves a story of hope and healing, reminding us that even in the darkest of times, the human spirit can prevail. Uncover the Best : Taylor Jenkins Reids "The Seven Husbands of Evelyn Hugo" This captivating historical fiction novel unravels the life of Evelyn Hugo, a Hollywood icon who defies expectations and societal norms to pursue her dreams. Reids absorbing storytelling and compelling characters transport readers to a bygone era, immersing them in a world of glamour, ambition, and self-discovery. Denoising Phase Unwrapping Algorithm For Precise Phase : Delia Owens "Where the Crawdads Sing" This captivating coming-of-age story follows Kya Clark, a young woman who grows up alone in the marshes of North Carolina. Owens crafts a tale of resilience, survival, and the transformative power of nature, captivating readers with its evocative prose and mesmerizing setting. These bestselling novels represent just a fraction of the literary treasures that have emerged in 2023. Whether you seek tales of romance, adventure, or personal growth, the world of literature offers an abundance of compelling stories waiting to be discovered. The novel begins with Richard Papen, a bright but troubled young man, arriving at Hampden College. Richard is immediately drawn to the group of students who call themselves the Classics Club. The club is led by Henry Winter, a brilliant and charismatic young man. Henry is obsessed with Greek mythology and philosophy, and he quickly draws Richard into his world. The other members of the Classics Club are equally as fascinating. Bunny Corcoran is a wealthy and spoiled young man who is always looking for a good time. Charles Tavis is a quiet and reserved young man who is deeply in love with Henry. Camilla Macaulay is a beautiful and intelligent young woman who is drawn to the power and danger of the Classics Club. The students are all deeply in love with Morrow, and they are willing to do anything to please him. Morrow is a complex and mysterious figure, and he seems to be manipulating the students for his own purposes. As the students become more involved with Morrow, they begin to commit increasingly dangerous acts. The Secret History is a brilliant and gripping novel that will keep you guessing until the very end. The novel is a warning tale about the dangers of obsession and the power of evil.

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