Robust Surface Imaging Method based on Quantum Single Pixel Imaging

Elie Magnon[1,#]

1 Department of Mechanical Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565-0871 Japan
Corresponding Author / Email: elie@optim.mech.eng.osaka-u.ac.jp, TEL: +81-6-6879-7321

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Surface characterization is a fundamental aspect of scientific and technological fields. In recent years, quantum single pixel imaging has garnered significant attention, particularly Quantum Ghost Imaging. However, this approach has been shown to be susceptible to external perturbations, limiting its surface characterization capabilities. To address this issue, this research publication proposes an expansion of the classical QGI design. The proposed approach utilizes the spatial correlation of the imaging particles and includes a calibration experiment to calculate the Joint Probability Distribution of the optical setup. This enables more precise signal filtering, which effectively suppresses shot noise and noise due to parasite light. The results are compared to direct imaging and regular Ghost Imaging, and the findings clearly indicate that the novel approach is significantly less sensitive to noise, producing clearer images even in challenging conditions. The key advantages of this design include the ability to perform surface measurements at low light levels and with a high robustness to noise. This research presents a novel approach that enhances the robustness and quality of quantum imaging for surface analysis. The results have paved the way for advanced surface characterization techniques that leverage quantum imaging principles, providing valuable insights into surface properties.

1. Introduction

Quantum single pixel imaging (QSPI) has emerged as a promising approach for surface characterization. Leveraging quantum mechanics principles to overcome limitations of classical imaging techniques, it can achieve better noise robustness and adaptability. The most representative method from the QSPI family is Quantum Ghost Imaging (QGI) which demonstrated its ability to reconstruct images in noisy environments and with a reduced number of photons [1]. This unique capability has led to remarkable results in diverse applications, including imaging through scattering media and remote sensing [2]. However, practical applications of QGI face challenges related to the availability of ideal detectors.

The current limitations are mainly associated with the lack of efficient detectors. Although bucket detectors with sufficient efficiency are available in visible and near-infrared spectral ranges, this is no longer the case for other wavelengths. Also, camera-like detectors are limited in their timing capabilities. Conversely, imaging detectors based on single-photon avalanche diodes show potential with the prospect of increased efficiencies and timing but currently lack significant spatial resolution.

To address these challenges and fully harness the potential of quantum imaging for surface analysis, this research proposes an innovative extension of the classical QGI design. By measuring the position of both photons and exploiting their spatial correlation in addition to their time correlation, our objective is to enhance the robustness and quality of quantum single pixel imaging for surface characterization. The core idea underlying our approach revolves around the use of quantum entanglement properties to achieve precise signal filtering. This enables the extraction of clear and accurate surface information even under challenging conditions, where conventional imaging techniques may fail to deliver reliable results.

In this paper, we compare the results obtained from the extended QGI design with those from direct imaging and regular Ghost Imaging. Through this investigation, we aim to demonstrate the advantages of our approach in achieving improved noise robustness and surface characterization capabilities considering the limitations of available detectors.

2. Theoretical Framework of the Proposed Approach

2.1 Quantum Ghost Imaging

Quantum Ghost Imaging exploits the correlation between photons in an entangled pair, generally produced through Spontaneous Parametric Down-Conversion (SPDC) [3]. In the QGI scheme, as depicted in Fig. 1, a pair of correlated photons is split into two separate beams. The “object” beam illuminates the object of interest, and the transmitted object photons are detected using a bucket detector, while the “reference” beam is directed towards a spatially resolving single-photon detector. Although each detector on its own cannot provide a direct image of the object, the image emerges in the correlation signal obtained from the two measurements. This is due to the high temporal and spatial correlation between the photons of the pair [4]. The detectors perform coincidence counting, identifying the pairs of photons that arrive within a narrow time window as part of the same entangled pair. By recording the position of the photon on the reference arm (not passing through the object), the collection of "validated" positions on the reference arm forms an image of the object.

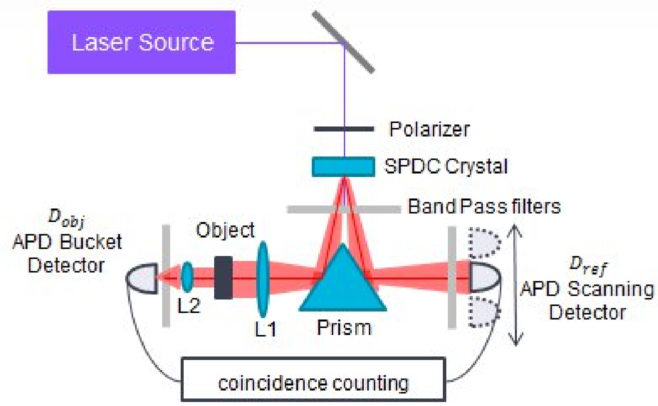

Fig. 1 Typical Quantum Ghost Imaging setup with two Avalanche Photo Diode (APD) detectors.

While QGI is theoretically robust to noise due to the high spatial and temporal correlation in photon pairs, practical limitations arise in real setups. Indeed, one major condition for robustness is that the setup will only record pairs of entangled photons. Experimentally, time-gating methods are employed to perform the coincidence count, potentially leading to accidental pair detection and reducing the method's robustness. In addition to background noise, the detectors' quantum efficiency also affects the accuracy of the measurements [5].

2.2 Revised Design for Quantum Ghost Imaging

The proposed modification preserves the overall operation of the conventional QGI setup, yet it introduces two significant enhancements. Firstly, it involves the precise measurement of the position of both photons, and secondly, it utilizes this positional information to implement an improved filtering strategy, particularly useful when the conventional time gating approach proves inadequate.

Inspired by Quantum Illumination [6], the design incorporates the use of the Joint Probability Distribution (JPD) of the system to comprehend the correlation between pixels in one camera and pixels in the other. The JPD quantifies the likelihood that two photons belong to the same pair based on their respective positions. Consequently, the JPD facilitates the retrieval of comprehensive characteristics of the photon pairs, contributing to the filtering process by effectively eliminating accidental correlations that may arise due to imperfect coincidence detection. Defienne et al. [7] provided a method to estimate the JPD of the system using single-pixel detectors, summarized by the equation Eq. 1, where $x_i^{(l)}$ and $x_j^{(l)}$ denote the values at pixels i and j on the object and reference cameras, respectively on the frame l.

$$R_{i,j} \approx \frac{1}{M}\sum_{l=0}^{M} x_i^{(l)} x_j^{(l)} - \frac{1}{M^2}\sum_{l,l',l\neq l'}^{M} x_i^{(l)} x_j^{(l')} \quad (Eq.\ 1)$$

With M the total number of frames captured.

The image reconstruction process follows a similar approach to conventional QGI, commencing with coincidence counting and recording a point on the reference side only when another photon is detected within a specified time window on the object detector. However, to address the challenge of "accidental coincidence," particularly in the presence of substantial background noise, the JPD plays a pivotal role. By recording the position of both photons and consulting the JPD, the feasibility of a given spatial configuration within the system is determined. Points that are inconsistent with the JPD are identified as noise and subsequently discarded, ensuring the fidelity of recorded points to the actual signal rather than background noise.

3. Simulation Setup and Methodology

3.1 Description of the Optical Setup for QSPI Simulation

In our simulation study, we replicate the key elements of a Quantum Ghost Imaging experiment. The optical setup presented in Fig. 2 consists of a source of entangled photons generated by a Spontaneous Parametric Down-Conversion crystal type-II illuminated by a pump laser. The emerging photons are then split into two optical paths, referred to as the object arm and the reference arm. Both arms are directed towards a spatially resolved detector for photon intensity measurements.

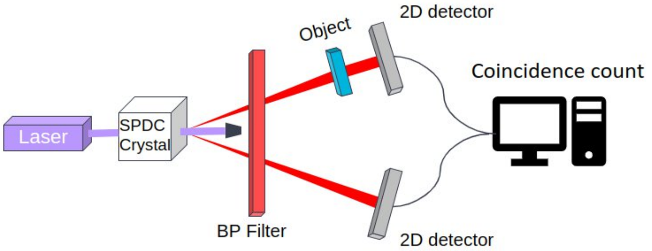

Fig. 2 Simplified Quantum Ghost Imaging setup used as a model for the simulation

3.2 Simulation of the Revised Design for Quantum Ghost Imaging

3.2.1 Simulation of Regular Quantum Ghost Imaging

- Photon Pair Generation:

The simulation program emulates the generation of photon pairs originating from a laser pump beam illuminating a type-II SPDC crystal. To maintain simplicity, we model the spatial energy distribution of the laser beam on the crystal using a circular bivariate normal distribution. By incorporating the conversion rate of the crystal, typically around 10^{-9}, and this distribution, the origins of the photon pairs are generated.

- Direction of Propagation:

The SPDC process adheres to energy and momentum conservation laws, leading to two emission cones for type-II SPDC crystals, as demonstrated by Karan et al. in [8]. To model this process, we employ a straightforward geometrical approach derived from the work of Boeuf et al in [9], characterized by three angles: ϕ_{out} representing the half emission angle of the crystal, θ_r the cone separation angle, and θ_{out}, the azimuthal angle. Crystal properties, such as ϕ_{out} and θ_r are determined (e.g., for a BBO type-II crystal, typical values are $\phi_{out} = 4.36°$ and $\theta_r = 2.5°$).

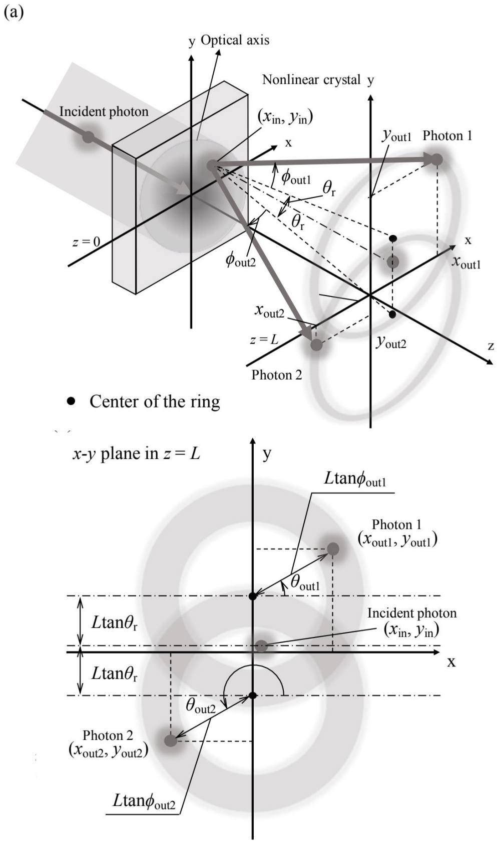

Fig 3 Details of the geometric model for SPDC photon pairs emission

- Photon Propagation:

Once the origin and direction of photons are established, they can be readily propagated over designated distances, corresponding to the separation between the crystal and their respective detectors.

- Noise Modeling:

To account for noise sources, the simulation incorporates the quantum efficiency of the detectors and introduces background noise. The quantum efficiency of the detectors influences the probability of a photon being recorded. We model this property as a variable of the detector, introducing the possibility of a photon reaching the camera but not being recorded. Background noise is introduced by considering a light source positioned near the crystal. Each photon's origin is randomly generated using a uniform distribution over a circle, and each photon is individually propagated along a random direction. As such, the light is uncorrelated, and each photon's direction remains independent.

- Object Representation:

The presence of the object is simulated using a mask, selectively blocking or transmitting photons based on their positions in space.

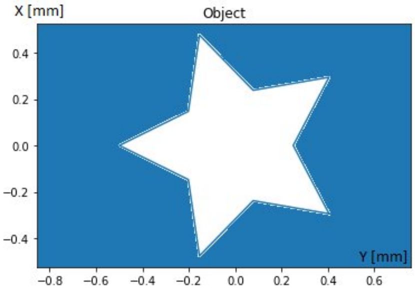

Fig. 4 Object mask used in the simulation program

- Image Reconstruction:

The simulation closely replicates the real experiment, where a photon detected on the object camera triggers a signal check for simultaneous detection on the reference camera. If a coincidence is detected, the position of the photon recorded on the reference camera is noted. By accumulating points on the reference side, the simulation reconstructs the image of the object.

3.2.2 Simulation of the Revised Design for Quantum Ghost Imaging

Initially, the method presented in section 2.2 is employed to estimate the Joint Probability Distribution of our virtual QGI setup. The simulation program generates a substantial number of frames recorded on each arm in the absence of an object. By applying Eq. 1, we can estimate the correlation between each pair of pixels in the object and reference cameras.

Once the JPD of our virtual setup is determined, the simulation proceeds following the same steps as the regular QGI simulation, with an additional aspect integrated into the Image Reconstruction phase. Specifically, during this stage, the program records the position of both photons when the pair is validated by the coincidence check. Subsequently, the program employs the JPD as a lookup table to assess the likelihood that the two recorded photons belong to a pair produced by our photon source. By comparing the recorded spatial configuration with the JPD data, the program decides whether the position of the reference photon is to be recorded, thus contributing to the image reconstruction process.

4. Results and Discussion

4.1 Noise Robustness Comparison

In this section, we compare the results of the imaging simulation of the star sample (Fig. 4) using three different methods. Firstly, direct imaging, which involves recording the positions of the photons received on the object detector without requiring quantum entanglement, as it represents a simple transmission picture of the sample. The second method is the regular Quantum Ghost Imaging, as described in section 3.2.1, and the third technique is the proposed QGI method.

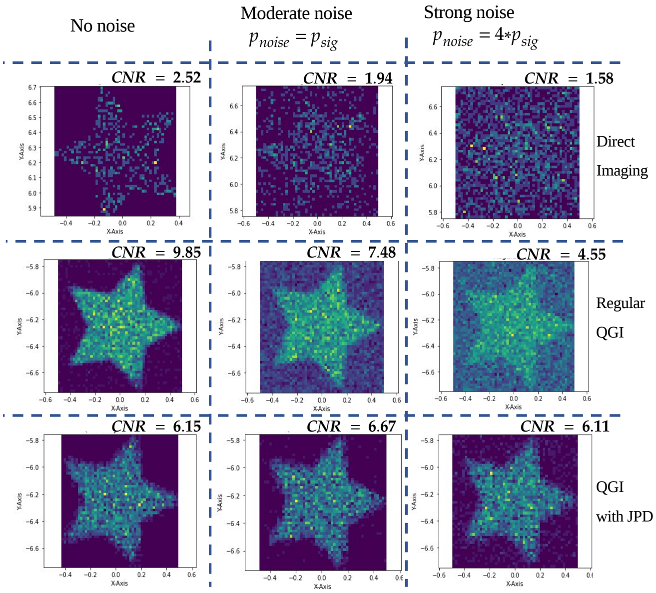

Fig. 5 Simulation results. Exposure time 100ns, 10 000 frames, p_{noise}: number of noise photons, p_{noise}: number of signal photons, CNR : Contrast to Noise Ratio (higher is better)

QGI has a natural robustness to noise, however when a certain threshold is reached, noise start to accumulate. The proposed methods achieve better results even in very harsh conditions. However, due to limited computational resources available, the JPD accuracy was limited. Generating a better JPD will improve its filtering capabilities.

4.2 Discussion

From the results presented in Fig.5, it can be concluded that the Joint Probability Distribution is an effective tool for suppressing noise in a Quantum Ghost Imaging experiment without altering the signal. The introduced calibration experiment to calculate the JPD enables noise reduction and facilitates faster measurements. As a result, fewer photons are required for image reconstruction, making this design particularly suitable for light-sensitive samples, such as living cells or other biological specimens. Combined with compressed sensing techniques, our new Quantum Ghost Imaging design may enable accurate image reconstruction with less than 1 photon per pixel. This promising outcome reinforces the advantages of QGI while addressing some of its limitations, such as extended measurement times.

Looking ahead, future research will focus on strengthening the theoretical basis of the model by incorporating quantum theory to model the SPDC process. Further simulations will be conducted to generate more data for an improved JPD, demonstrating enhanced noise removal capabilities. The final stage of this research will be to conduct an experimental demonstration of the capabilities and advantages of this new QGI design.

5. Conclusion

In this study, we have introduced a novel design variation of Quantum Ghost Imaging with the objective of addressing a key limitation encountered in conventional quantum single pixel imaging techniques for surface characterization. By estimating and leveraging the Joint Probability Distribution of our optical setup, we have demonstrated the potential to construct more efficient configurations that approach photon pair identification, thereby unlocking the full advantages of quantum imaging.

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