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Dynamic Target Detection and Tracking Based on Quantum Illumination LIDAR

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Abstract: In the detection process of classic radars such as radar/lidar, the detection performance will be weakened due to the presence of background noise and loss. The quantum illumination protocol can use the spatial correlation between photon pairs to improve image quality and enhance radar detection performance, even in the presence of loss and noise. Based on this quantum illumination LIDAR, a theoretic scheme is developed for the detection and tracking of moving targets, and the trajectory of the object is analyzed. Illuminated by the quantum light source as Spontaneous Parametric Down-Conversion (SPDC), an opaque target can be identified from the background in the presence of strong noise. The static objects obtained by classical and quantum illumination are compared, respectively, and the advantages of quantum illumination are verified. The moving objects are taken at appropriate intervals to obtain the images of the moving objects, then the images are visualized as dynamic images, and the three-frame difference method is used to obtain the target contour. Finally, the image is performed by a series of processing on to obtain the trajectory of the target object. Several different motion situations are analyzed separately, and compared with the set object motion trajectory, which proves the effectiveness of the scheme. This scheme has potential practical application value.

Keywords: Quantum illumination; LIDAR; target detection; moving target tracking

1 Introduction

Classical RADAR/LIDARs are widely used in many areas [1–3], they exploit radio waves or lights to detect objects and analyze their motion. The object may only reflect a small percentage of light, and it is probably immersed in environmental noise, which influences the detection efficiency. An essential question in the detection technique is to improve the detection efficiency so that objects can be clearly identified from the environment. Many classical protocols have been proposed [4–7], however, the detection ability is still not satisfying if the signal wave is too weak compared to the environment noise.

Recent works show that quantum correlation is helpful for the problem, a quantum enhancement can be achieved in the detection of the target by using twin photons. Quantum correlation and quantum entanglement are the quintessential characteristics of quantum physics, which also come into scientific and engineering applications including quantum simulation [8], quantum machine learning [9], quantum-enhanced sensing [10] and quantum illumination [11]. Quantum illumination (QI) protocol was first introduced by Lloyd [12] in 2008. Lloyd et al. proved that entanglement can in principle give an enhancement of sensitivity for photon counting. Moreau et al. [13–15] did a series of works about the detection of spatial quantum correlations of Spontaneous Parametric Down-Conversion (SPDC) sources and the application of electron-multiplying charge-coupled device (EMCCD) array detectors. Lopaeva et al. [16] performed an experimental demonstration of the quantum illumination principle to determine the presence or absence of a semitransparent object in 2013. Gregory et al. [17] reported an image contrast improvement with both environmental noise and transmission losses in 2020.

Based on those works, the experimental condition is satisfied for the motional object detection and tracking. In this work, we develop a theoretic scheme for the quantum LIDAR detection of moving objects. The light source is set to be SPDC, which produces twin photons with spatial correlation. By using a reflection mirror as background, non-transparent objects can be identified from a bright background. This detection is achievable by either classical illumination (CI) protocol which uses only one of the twin photons or QI protocol which exploits the quantum correlation of twin photons. When the environmental noise (illuminated by thermal light) is strong, QI protocol shows its advantage and improves the SNR of the image significantly. For a moving target, the motional function can be obtained by the three-frame difference method operating on the tracking images. Two types of motions are considered in this scheme, and the tracking results coincide well with the motion setting in all testing cases. This scheme is a demonstration of the potential real-world applications of QI protocol via photon counting rather than phase-sensitive measurements, which make it easier for the experimental realization.

2 Scheme Design

2.1 Experiment Setting

Entangled photon pairs are generated by SPDC. The twin beams are transformed into parallel light by lenses, then directed to two identical EMCCD detectors respectively. The idler beam (reference beam) falls on EMCCD1 (noted as E_1), and the signal beam (probe beam) is reflected by a background mirror, detected by EMCCD2 (noted as E_2), shown as Fig. 1. For E2, there is also an environmental illumination which is treated to be thermal noise.

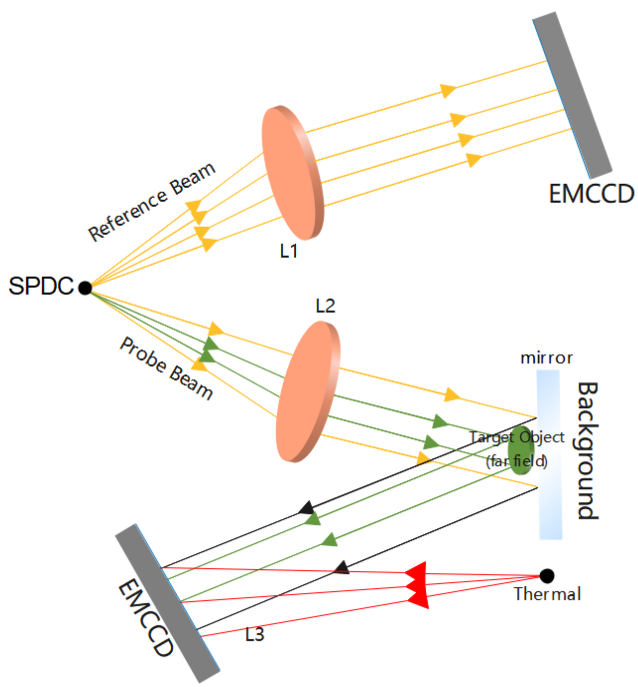


Figure 1: Equipment and optic path

Setting the optical path carefully, we can establish the corresponding relationship between E_1 and E_2, i.e., entangled photon 1 will be located at pixel (i, j) in E_1 and photon 2 will be located at the same coordinates (i, j) in E_2. The experimental setting can be calibrated as this: AND-operation between the images of E_1 and E_2 is performed to generate AND-images and these images are comparied with the original image to quantify the correlation. After that, the optical path can be adjusted to optimize the correlation. The Initial letter of each notional word in all headings is capitalized.

2.2 Parameters

The main parameters are based on the experimental result in references [16–17].

(1) Detection range of EMCCD1&2, pixels 100 * 100, 0.015 s for each frame

(2) Detection probability of photon:

idler photon 0.01 per pixel*frame

signal photon 0.007 per pixel*frame (considering reflection rate of mirror 70%)

noise photon 0.0035–0.035 per pixel*frame (50%–500% comparing to signal)

object reflection photon 0.003 per pixel*frame (diffuse reflection rate 30%).

2.3 Thermal Noise

Consider the presence of thermal noise from the environment, it causes an extra detection rate of the photon on E_2 with equal probability on each pixel, which we set as 50%–500% comparing to the normal signal photon detection rate. Comparing the images corresponding to different signal-noise ratios, the distinguishability of classical detection image decreases when SNR is getting smaller. The distinguishability of images can be greatly improved by considering the quantum correlation of twin photons, using pixel-by-pixel AND-operation between the two images on E_1 and E_2. Most of the noise photons will be rejected in the AND- image, this is the advantage of Quantum LIDAR.

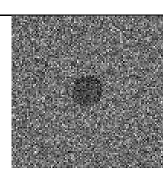
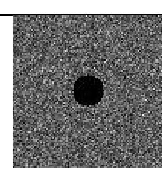
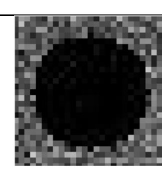
2.4 Object Detection and Motional Tracking

The region of the background mirror is also the detection region, any object in front of the mirror will block the signal photons and change the detection probability distribution on E_2. Apply AND operation to eliminate the noise, and sum N frames of AND-image to obtain a detection image of the target, which is a dark area in a bright background. The contour of the target can be revealed by tracking the detected target image, using three-frame difference method as described in Section 3. A motional animation/video can be generated to demonstrate the motion, and a comparison between tracking orbit and setting orbit shows the validity and precision of tracking.

3 Results and Analysis

3.1 Stationary Target Detection

According to the scheme, we first set a stationary circular disk to be the target. Under different noise conditions, the images are generated via CI protocol and QI protocol respectively. For each image, it is generated from a sequence of 1000 frames. The comparison is shown in Fig. 2.

Noise to SPDC illumination ratio	Classical illumination image	Quantum illumination AND-image	AND-image Target analysis
0.5			

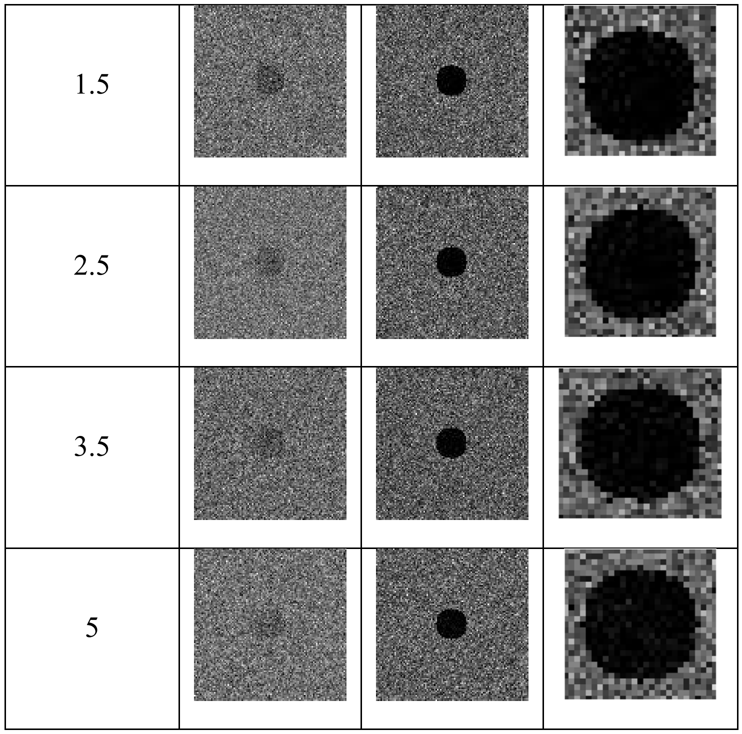


Figure 2: Images obtained by CI and QI protocols

As the environmental noise increases, the object rapidly becomes indistinguishable in classical images, while it still remains clear in the quantum-enhanced images. The detailed image shown in the third column of Fig. 2 shows that QI images are also influenced by the noise, which is caused by the "false-correlation" between the idler photon and noise photon. When the environment noise is set as 100 times higher than the signal illumination light, the QI image is shown in Fig. 3 where the target is still barely distinguishable. In general, the QI has certain advantages in the case of high loss and noise.

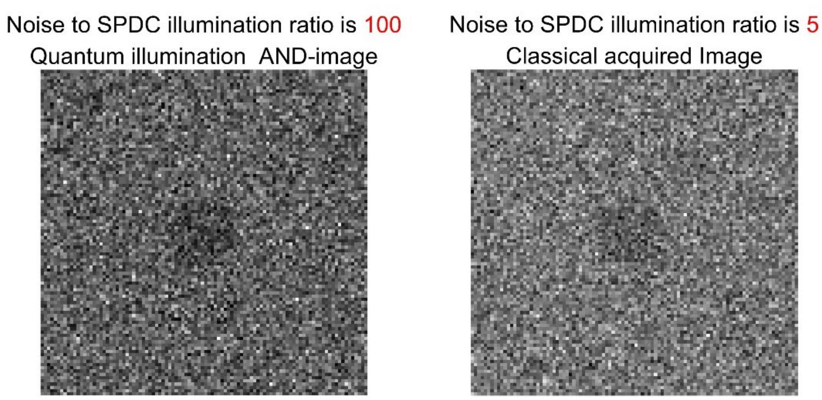


Figure 3: The left is QI image in 100-times noise; the right is CI image in 5-times noise

3.2 Moving Target Tracking

The moving target tracking is based on the three-frame difference method, which is simple and fast to realize.

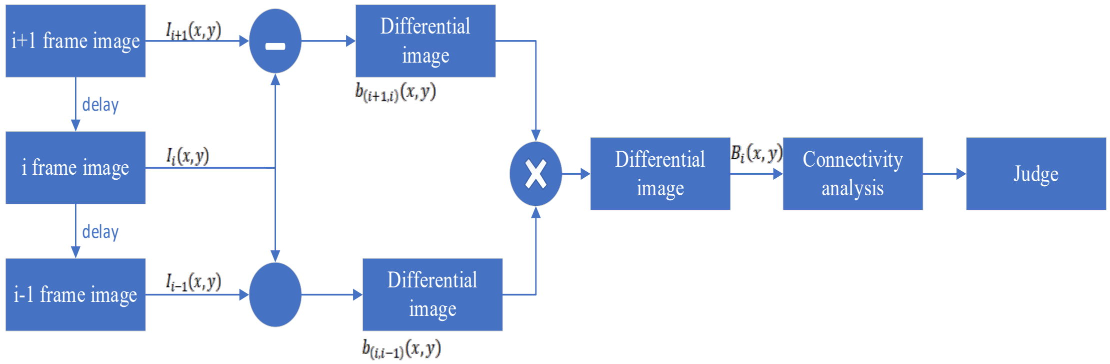


Figure 4: Three-frame difference method

Choose a sequence of 3 frames (each of them is actually created by the sum of N AND-images), $I_{i-1}(x,y), I_i(x,y), I_{i+1}(x,y)$, and calculate the difference between two neighbor frames:

$$\begin{cases} d_{(i,i-1)}(x,y) = |I_i(x,y) - I_{i-1}(x,y)| \\ d_{(i+1,i)}(x,y) = |I_{i+1}(x,y) - I_i(x,y)| \end{cases} \tag{1}$$

Binarize the difference functions by a proper threshold value:

$$\begin{cases} b_{(i,i-1)}(x,y) \begin{cases} 1, & d_{(i,i-1)}(x,y) \ge T \\ 0, & d_{(i,i-1)}(x,y) < T \end{cases} \\ b_{(i+1,i)}(x,y) \begin{cases} 1, & d_{(i+1,i)}(x,y) \ge T \\ 0, & d_{(i+1,i)}(x,y) < T \end{cases} \end{cases} \tag{2}$$

The pixels $B_i(x,y)$ of moving target are obtained from AND operation on the difference functions.

$$B_i(x,y) \begin{cases} 1, & b_{(i,i-1)}(x,y) \cap b_{(i+1,i)}(x,y) = 1 \\ 0, & b_{(i,i-1)}(x,y) \cap b_{(i+1,i)}(x,y) \neq 1 \end{cases} \tag{3}$$

For the convenience of motion tracking, the images are transformed with following several steps.

Step 1: Image generated from N AND-images (N = 100);

Step 2: Transform the image to grayscale;

Step 3: By a threshold conversion, transform into binary image;

Step 4: Use connectivity analysis, remove the noise points.

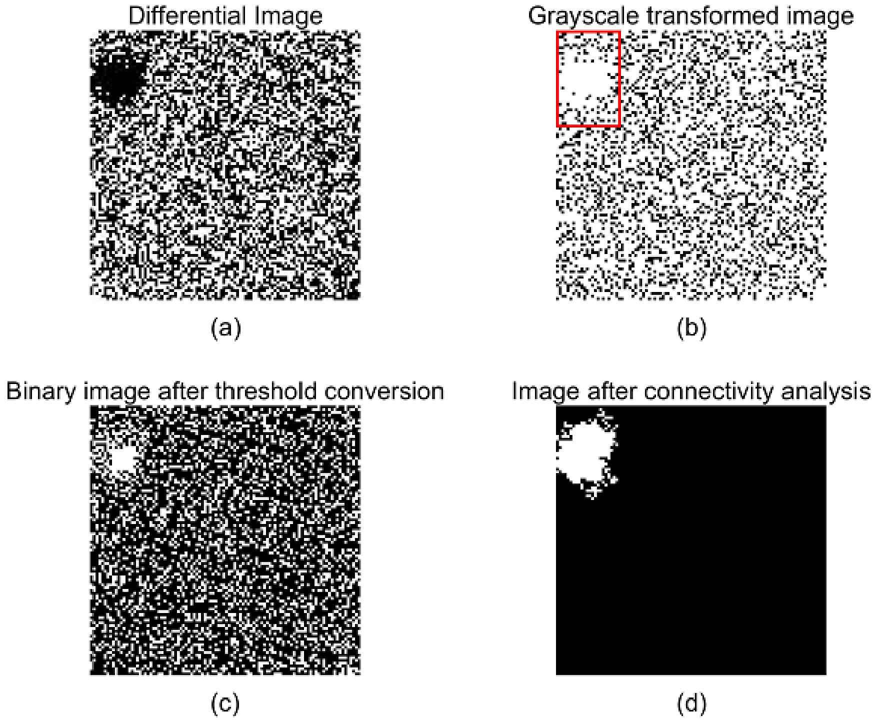


Figure 5: Image processing preparation

Because of the motion, the detected target has irregular margins which may cause errors in the position tracking process. The bright part in Fig. 5(d) is identified as the target, labeled by a red rectangle. The orbit of the target can be determined and demonstrated by an animated video. And can be used to determine the trajectory of the object target.

3.3 Tracking Results

Here we set the target to be a circular disk, the static images are already shown in previous figures. When the target is moving, a sequence of frames is required for the difference method. Each frame is generated from N AND-images, and the target is deformed more or less in these frames because of the motion.

The noise intensity is set to be 50% of the signal intensity, two types of motion are analyzed as follows:

(i) The center of mass about the disk has the following motion equation:

$$\begin{cases} y = 30\cos\frac{kt}{5} + \frac{kt}{2} + 30 \\ x = kt \end{cases} \tag{4}$$

The actual motional orbits and the corresponding tracking orbits are shown in Fig. 6. If the speed of the target is not too fast, the tracking precision is satisfying, which shows the validity of the scheme.

The tracking precision decreases when the target is moving faster. The shape of the target in each frame (generated from 100 AND-images) changes more or less, and the detected orbit has deviated from the actual motion. This may be improved by increasing the signal intensity and decreasing the parameter N for the frame-sum process.

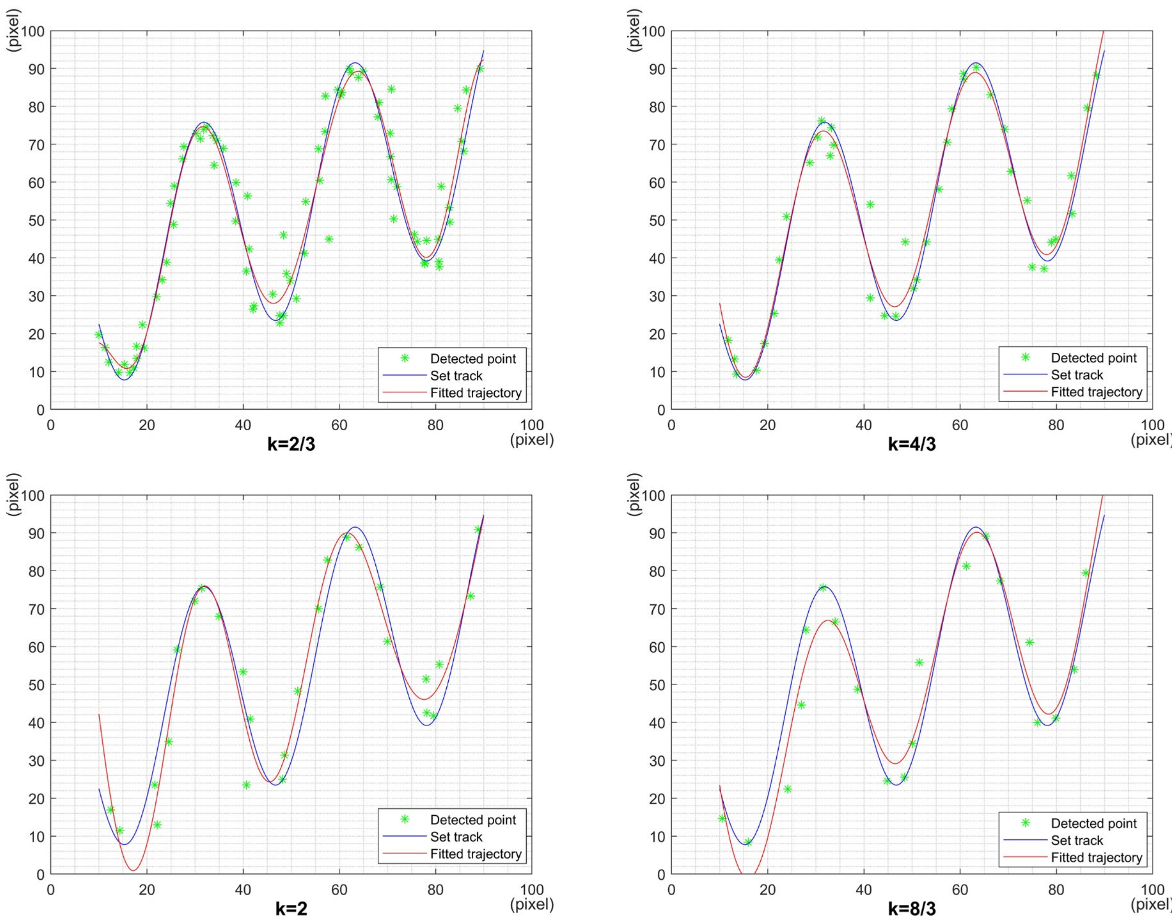


Figure 6: Motional tracking (i) for different speeds

The four pictures in Fig. 6 are 100-by-100 pixels pictures with different values of speed parameter k. The green "*" marks represent the positions of the target detected at equal time intervals; the blue curve shows the actual trajectory of the object; and the red curve is the Fourier fitting curve obtained from the detected position data. It can be seen that as the speed parameter k increases, the deviation between the fitted curve trajectory and the actual trajectory gradually increases.

It is shown in Fig. 5 that the detection shape of the target in each frame changes more or less, which is the reason why the detected orbit has deviated from the actual motion. This may be improved by decreasing the parameter N for the frame-sum process meanwhile increasing the signal intensity.

(ii) Another motion of disk, the center of mass moves as:

$$\begin{cases} x = 50\exp(-\dfrac{\omega t}{20})\cos(\omega t) + 50 \\ y = 50\exp(-\dfrac{\omega t}{20})\sin(\omega t) + 50 \end{cases} \tag{5}$$

The tracking figure is shown by Fig. 7:

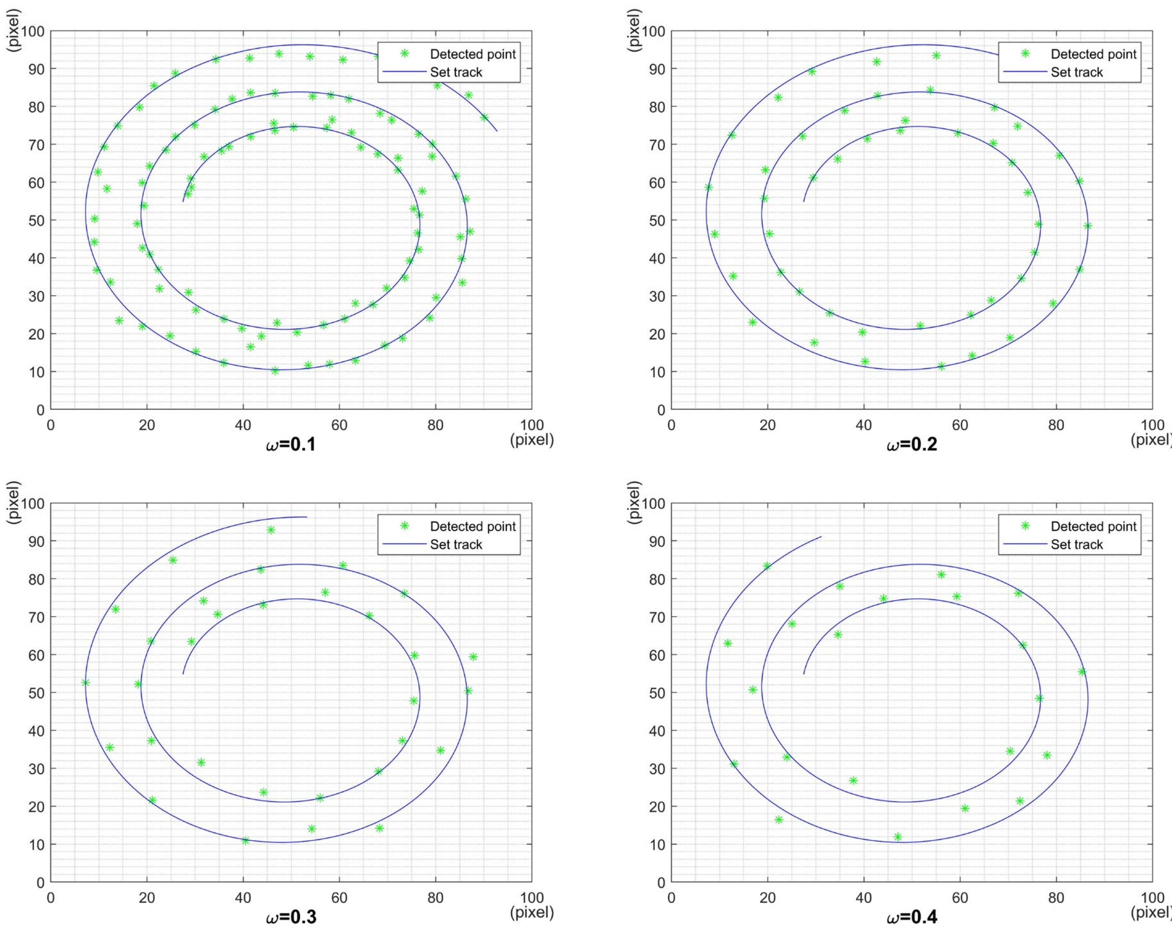


Figure 7: Motional tracking (ii)

In Fig. 7, The green "*" marks represent the positions of the target detected at equal time intervals and the blue curve shows the actual trajectory of the object. Similar to case (i), it can be seen that as the angular speed ω increases, the deviation between detected positions and the actual trajectory also increases, which means that the precision of tracking decreases.

4 Conclusion

In this paper, we have developed a theoretic scheme for the detection and tracking of moving targets. In the presence of noise, the scheme shows its advantage to classical methods. Due to the quantum correlation between twin photons, applying AND-operation between the detection image and reference image can eliminate the noise events and greatly improve the quality of the detection image. Up to the 100-times noise, a stationary target can be recognized from the environment. For the tracking of moving targets, two different types of motion have been tested. The trajectory is obtained by analyzing the AND-image of moving target and the precision is acceptable for low-speed situation. The validity of scheme has been verified, and this work may enable real-world applications such quantum microscopy for low–light level imaging, quantum radar imaging, etc.

There are some possible improvements about the work, such as more complicated targets or more general motion which may be expressed by numerical functions. The parameters could be adjusted to achieve better tracking performance for high-speed case. These problems will be considered in the future work.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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