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Laser Radar Point-Target Localization at High Photon Efficiency

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Abstract: Minimum error-probability laser radar point-target localization is analyzed, including the effects of dark counts, background counts, and target speckle. Results from preliminary table-top experiments are reported.
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Laser radars offer superior resolution in comparison with their microwave counterparts. Laser radar, however, suffers from the ill-effects of target-induced speckle and atmospheric propagation. Moreover, laser radar’s superior resolution capability can dictate a longer time to interrogate a particular target region. Thus a useful scenario to consider is for a high-resolution laser radar to be cued by a lower-resolution microwave system. An interesting question that arises is determining the ultimate sensitivity when quantum-mechanical resources—nonclassical transmitter states and nonstandard reception techniques—are provided. This paper addresses the photon efficiency for the cued-sensor scenario in which a point target is to be localized.

Suppose that a pulsed-laser transmitter floodlights a volume known to contain a point target, and an \( M_T \)-pixel photon-number resolving array detects the returned light. The localization task is to determine the target’s transverse location within these \( M_T \) pixels and its range within \( M_S \) range bins. In the absence of background light and detector dark counts, this scenario can yield an extraordinary number of bits per detected photon (bpdp), viz., a \( 32 \times 32 \) pixel array combined with 15 cm range resolution and a 1 km uncertainty in target range will yield \( \log_2(M_T M_S) = 22.7 \) bits from the detection of one photon. There is still, however, the possibility of no detections, even though the target is present. Forcing the radar to randomly choose among the \( M = M_T M_S \) possible target locations when no photons are detected then reduces bpdp to 3.3 when the error probability—\( \Pr(\text{error}) \) when dark counts are the only nonideality—and \( \Pr(\text{erase}) \) when background counts are the only nonideality—are dominated by the probability that no target-return photons are detected. Figures 1(b) and (d) show the mutual information and bpdp for the dark-counts only and dark-counts plus background-counts cases, respectively.

Both situations can provide more than 2 bpdp with \( \Pr(\text{erase}) \leq 10^{-3} \) and \( \Pr(\text{error}) \leq 10^{-3} \). Figure 2 shows \( \Pr(\text{erase}) \) and \( \Pr(\text{error}) \) in (a) and the mutual information and bpdp in (b) when, in addition to dark and background counts, the target produces fully-developed speckle. Here we see a substantial performance degradation has been incurred, but 2 bpdp can still be obtained.
In a preliminary experiment, we have used the Fig. 3 arrangement to emulate point-target localization. Light from a low power HeNe laser is attenuated to the single-photon level with neutral-density (ND) filters and coupled into a single-mode fiber for spatial filtering. The fiber’s output illuminates a one-to-one imaging system with digital micro-mirror devices (DMDs) in the object and image planes. The first DMD introduces a point target into the system, and the second emulates a detector array by scanning the light from its elements onto a gerger-mode avalanche photodiode.

Figure 4 compares results from an experiment in which the target is to be localized within a 16×16 pixel (M = 256) array in dark-count limited operation (600 dark-counts/sec on each pixel): (a) and (b) show the performance when a single pulse interrogates each pixel; (c) and (d) show the performance when each pixel is interrogated until at least one count occurs. This pulse-until-detect (PUD) protocol completely suppresses erasures, but at the expense of more errors. Figure 4 shows that this error-probability penalty is not severe, and that our experiments are in excellent agreement with theory.

References