Monocular kilometer-scale passive ranging by point-spread function engineering[1]

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Abstract

We present a passive-ranging apparatus based on a refractive telescope lens, using point-spread-function (PSF) engineering for monocular distance estimation. The optical system was experimentally demonstrated in a variety of challenging imaging scenarios, including adversarial weather conditions, dynamic targets and scenes of diversified textures, at distances extending beyond 1.7km.

Introduction

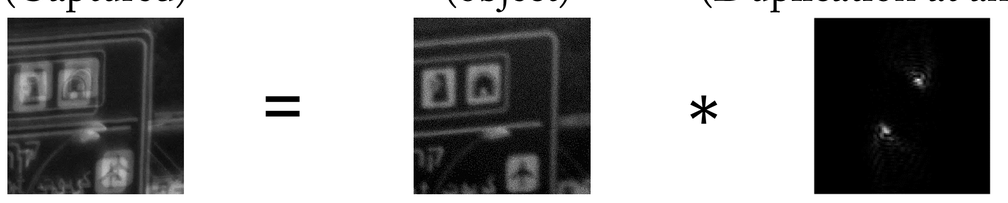
Imaging-based distance estimation is a difficult challenge. Today, most distance estimation methods area active (LIDAR, radar), which is costly in terms of size, complexity, safety and cost, in addition to being detectable. Nevertheless, passive ranging has not yet been performed for distances greater than a few hundred meters. Here, we perform range estimation by employing PSF engineering with a telescope, to measure distances far exceeding 1 km.

Method

1. Distance information is encoded in the image at the PSF. In our setup, the PSF is a duplication at angle θ, which is distance-dependent.

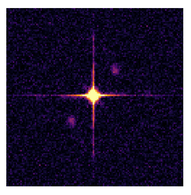
2. Decoding of duplication angle is performed via Cepstrum analysis[2]:

(Captured) = (object) * (Duplication at angle θ)

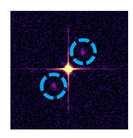


Cepstrum transform:

$$\mathcal{C} = \mathcal{F}^{-1}\left(\log\left(\left|\mathcal{F}\{I_{kl}\}\right|^2\right)\right)$$

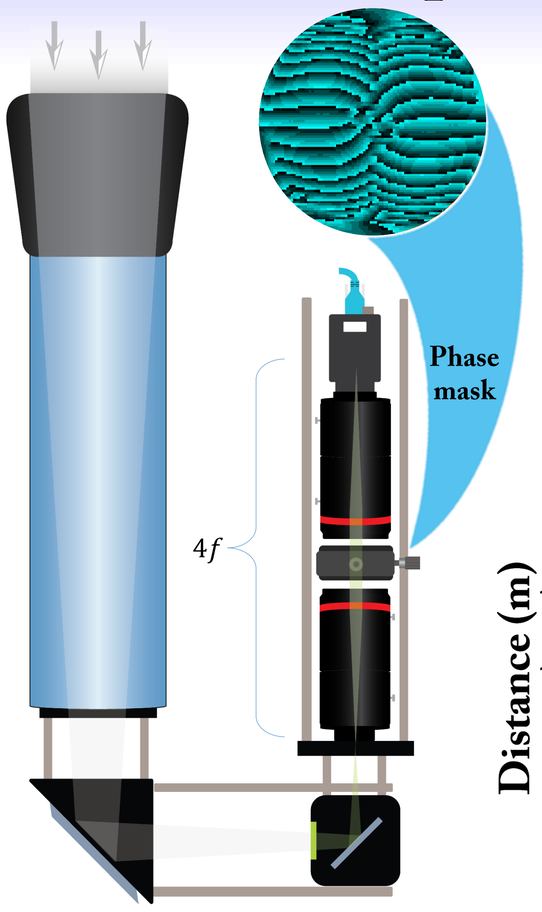


→ Lobe detection → duplication angle → distance

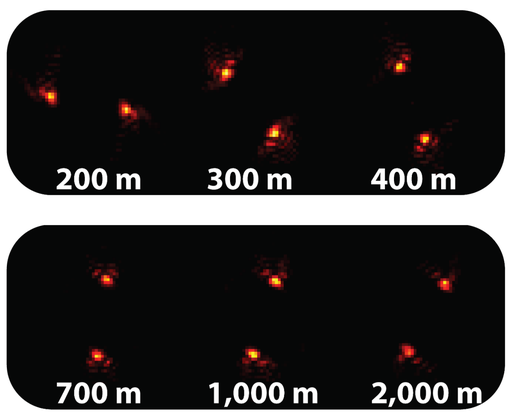


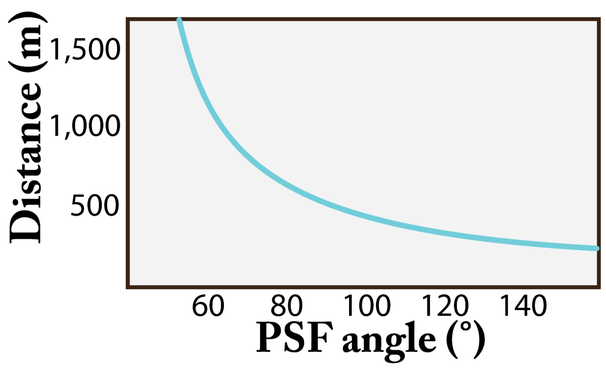
$z = f(\theta)$

Optical setup

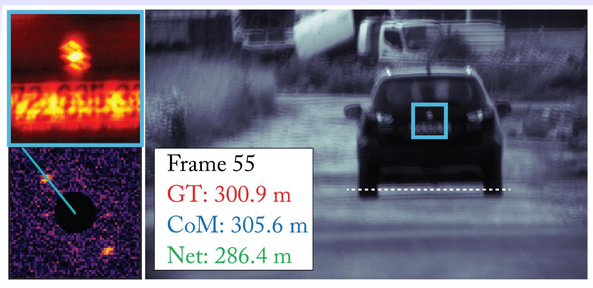


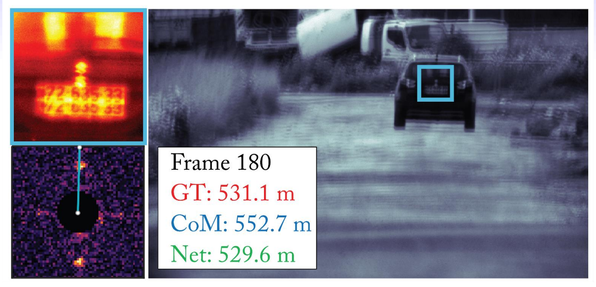
Distance-dependence of the PSF

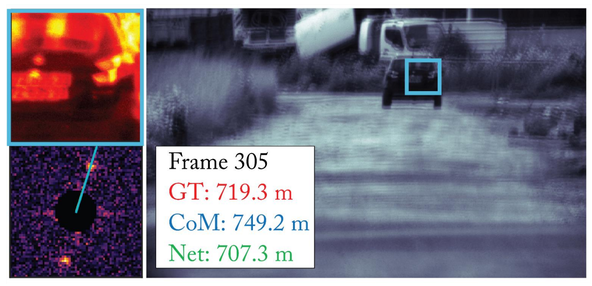


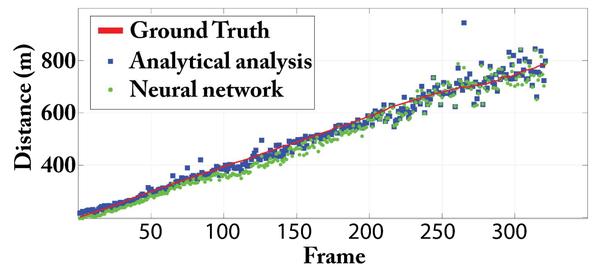


Results – dynamic objects

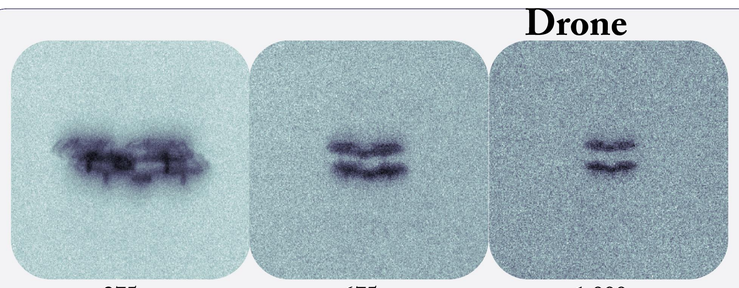


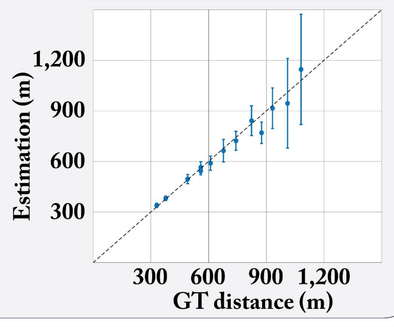




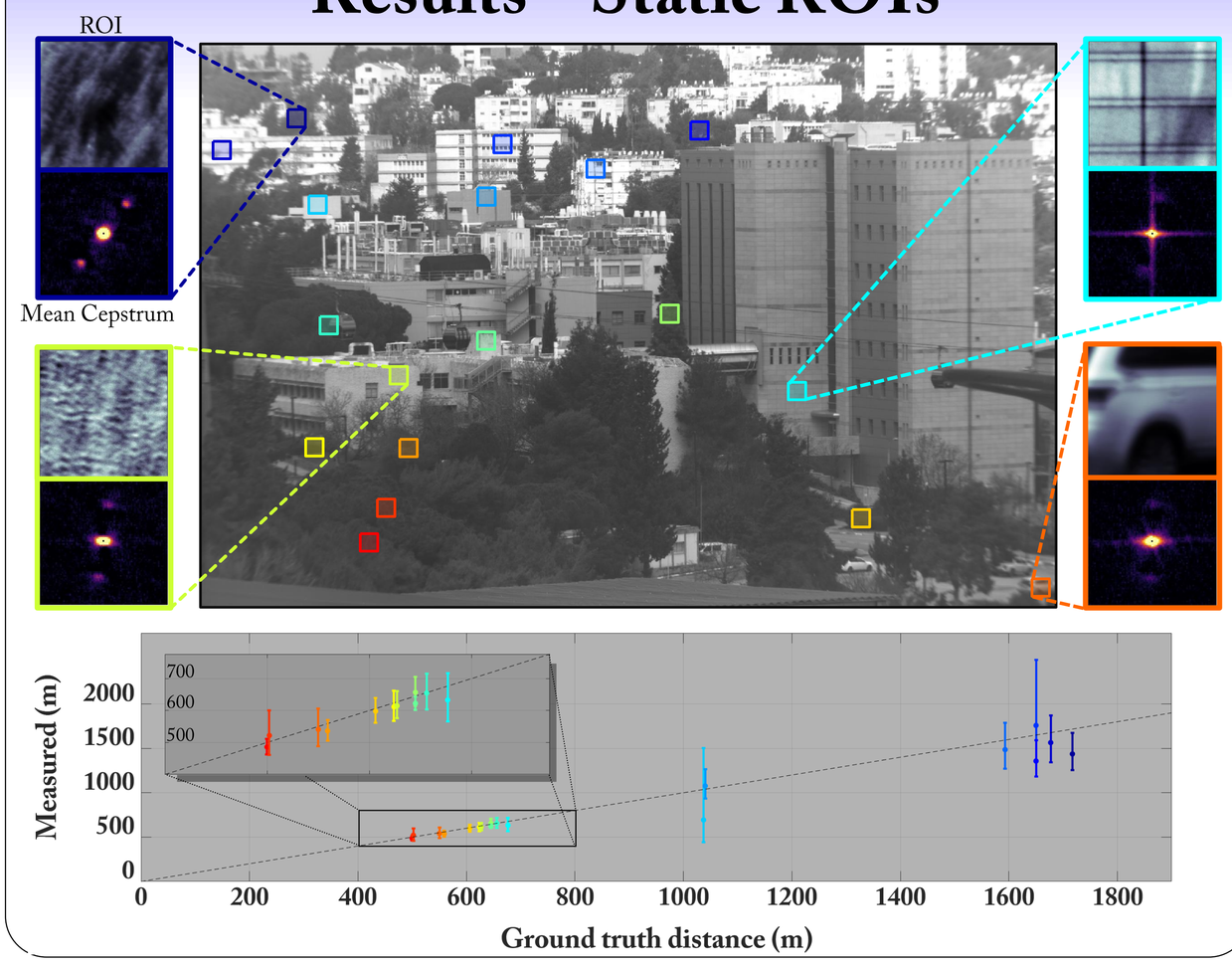


Drone





Results – Static ROIs



Conclusions

We have demonstrated monocular passive ranging at distances never addressed before. Major points we encountered:

Accuracy: Natural duplications at the object may produce false peaks in the Cepstrum domain, leading to a biased/wrong lobe detection. This, in most cases, is handled algorithmically quite well.

Precision: At large distances (>100m) atmospheric turbulence randomly perturbs the wavefront, continuously changing the PSF, thus the measured distance to the object. As experimentally analyzed, under moderate turbulence, the single-shot estimation precision is 10% at 1km distance. Precision can be improved by multiple-frame analysis.

Additionally, in presence of dust in the air, our device has shown significant superiority over an off-the-shelf laser rangefinder. Further details are provided in the recently published paper[1].

References

1. N. Opatovski *et al.* Monocular kilometer-scale passive ranging by point-spread function engineering; Optics express (2022)
2. R. Berlich *et al.* Single shot three-dimensional imaging using an engineered point spread function; Optics Express (2016)