Efficient range estimation and material quantification from multispectral Lidar waveforms

Yoann Altmann, Aurora Maccarone, Abderrahim Halimi, Aongus McCarthy, Gerald Buller and Stephen McLaughlin

Heriot-Watt University, Edinburgh, U.K.

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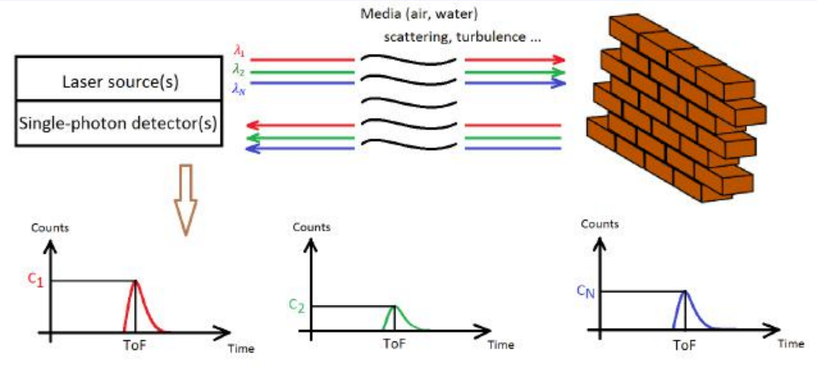
Ranging using multispectral Lidar (MSL)

Principle



- Pulsed laser (20 MHz), low power ($\approx \mu$W)
- Detector: single-photon avalanche diode (SPAD)
- Time of flight: for each detected photon (precision $\approx 10^{-12}$s)

Multispectral Lidar

Motivations

- Joint extraction of geometric and spectral information
  - Limited data registration issues (fusion Lidar/HSIs)
- Range estimation: robustness
  - Energy spread across wavelengths
- Scene reconstruction with few photons
  - < 10 useful photons per pixel and band
- Robustness: illumination conditions (active imaging)
  - Shadowing effects

Multispectral Lidar

Observation model

$$y_{n,\ell,t} \sim \mathcal{P}\left(r_{n,\ell} g_{0,\ell}\left(t - t_n\right) + b_{n,\ell}\right) \quad t \in \{1, \dots, T\}$$

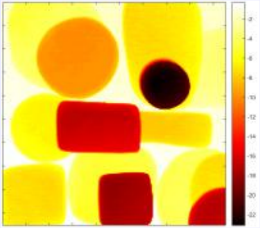
- $y_{n,\ell,t}$: photon count in the tth bin (ℓth band)
- $r_{n,\ell}$: target reflectivity
- t_n: ToF
- $g_{0,\ell}(\cdot)$: instrumental response
- $b_{n,\ell}$: background level

- Single target model
- Estimation of t_n, $\mathbf{r}_n = \{r_{n,\ell}\}$ (and $b_{n,\ell}$)
- Here $b_{n,\ell} << r_{n,\ell}$

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Clustering/Classification

RGB image (5×5 cm)


Range profile (mm)


Spectral classification

Altmann et al., "Joint range estimation and spectral classification for 3D scene reconstruction using multispectral Lidar waveforms", SSP, June 2016.

Single-photon Multispectral Lidar

Proposed Bayesian approach

$$\mathbf{r}_n = \mathbf{M}\boldsymbol{a}_n$$

- $\mathbf{M}$: known endmember matrix
- $\boldsymbol{a}_n$: nth abundance vector
- Observation model: joint likelihood (Poisson noise)
- Standard priors for the unknown parameters
  - smooth abundance maps + sparse mixtures: Total-variation (TV) and ℓ_1 regularizations
  - No abundance sum-to-one constraint
  - Uniform prior for t_n (regular grid)
- Estimation of $\mathbf{A} = \{\boldsymbol{a}_n\}$ and $\mathbf{T} = \{t_n\}$

Single-photon Multispectral Lidar

Previous method

- $f(\mathbf{A}, \mathbf{T}|\mathbf{Y}) \propto f(\mathbf{Y}|\mathbf{A}, \mathbf{T}) f(\mathbf{A}, \mathbf{T})$: highly multimodal
  - MCMC method to exploit $f(\mathbf{A}, \mathbf{T}|\mathbf{Y})$
  - Measures of uncertainty but high computational cost

Proposed method

$$(\widehat{\mathbf{A}}, \widehat{\mathbf{T}}) = \underset{\mathbf{A}, \mathbf{T}}{\operatorname{argmax}} \quad f(\mathbf{A}, \mathbf{T}|\mathbf{Y})$$

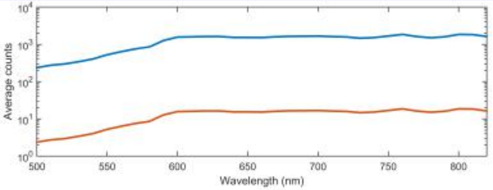
- Main assumption: pulses not cropped
  - $\widehat{\mathbf{A}}$ does not depend on $\mathbf{T}$.
- Estimation of $\widehat{\mathbf{A}} \rightarrow$ convex problem
  - Standard spectral unmixing of hyper/multi-spectral data
- Estimation of $\widehat{\mathbf{T}}|\widehat{\mathbf{A}}$: Multi-modal cost function but ...
  - Optimization on a regular grid

$\Rightarrow$ Fast linear unmixing and range estimation by integration of the 4D data cube over the temporal dimension

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Spectral unmixing

RGB image



Average photon counts

- Identifying and quantifying the materials of the scene (range ≈ 1.80m)
- Acquisition time per pixel: 10 ms or 0.1 ms per band
- Here: 14 types of polymer clays + backboard

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Spectral unmixing

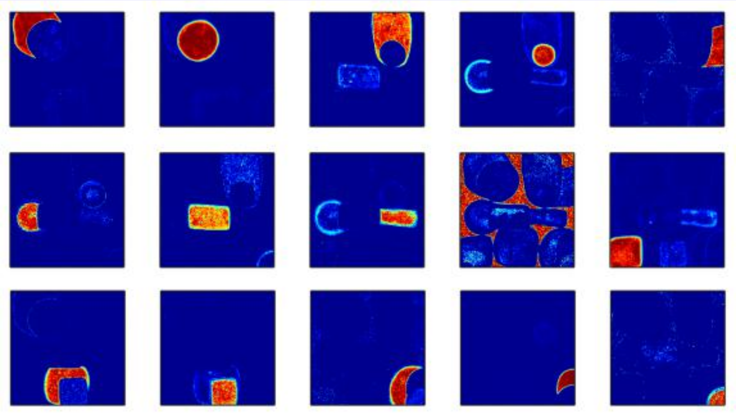
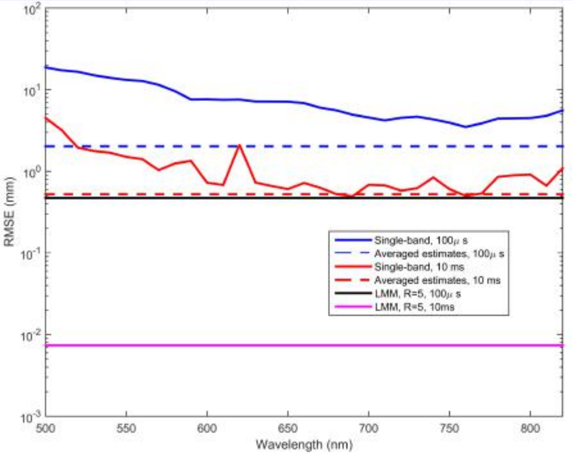


Figure: Example of estimated abundance maps

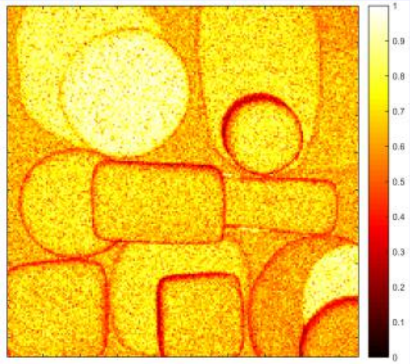
Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Depth estimation



Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Depth estimation (≈ 10 photons per pixel and band)

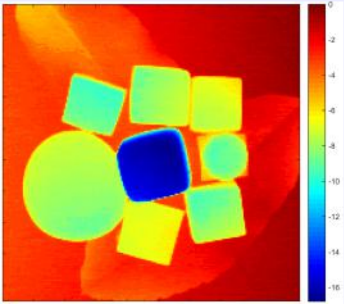


- Posterior measure of uncertainty:
  $$p\left(d_n \in \left[\hat{d}_n - 0.5mm; \hat{d}_n + 0.5mm\right] \middle| \mathbf{Y}, \widehat{\mathbf{A}}\right)$$

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Spectral unmixing (example II)

RGB image (5 × 5 cm)

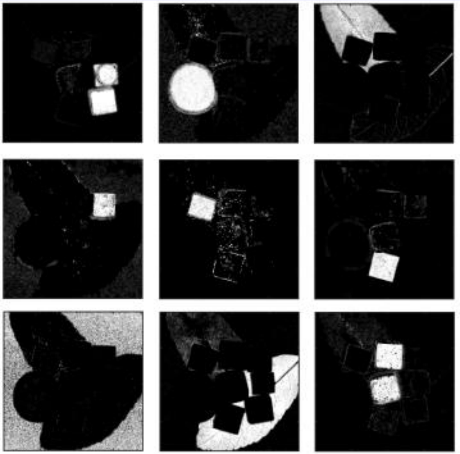


Range profile (mm)

- Mixtures of natural and man-made objects

Single-photon Multispectral Lidar (33 wavelengths / 500 – 820nm)

Spectral unmixing (example II)



Estimated abundances

Conclusion and future work

Conclusions

- Joint extraction of spectral and geometric information
- Fast unmixing using convex optimization
- Uncertainty about depth estimation

Future work

- Generalization to actual 3D unmixing → multiple surface detection
- Scanning system: sampling strategies
- Spectral analysis from extremely low photon counts

Thanks for your attention!

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