Monitoring Elevator Usage With a ToF Camera

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Problem formulation

For effective building management, it is valuable to understand the movement of people between floors. Specifically, detailed data on elevator usage can provide significant benefits.

The goal of this project was to develop a robust algorithm capable of accurately counting individuals as they enter and exit an elevator, using data from a ToF camera.

Solution summarized

- A multiple hypothesis detection model for deciding the number of passengers in a frame.
- Estimation of unknown parameters under the different hypotheses before performing a GLRT.
- If passengers detected, append/save estimated positions.
- If zero passengers detected, process saved position estimates to determine exits and entries.

Hypotheses

The detection is based on a multiple hypothesis test. The measurements are modeled under three different hypotheses:

No passengers, $H_0 : \boldsymbol{y_k} = \boldsymbol{e}_k$

One passenger, $H_1 : \boldsymbol{y_k} = \alpha\boldsymbol{\varphi}(\boldsymbol{\mu_1}) + \boldsymbol{e}_k$

Two passengers, $H_2 : \boldsymbol{y_k} = \alpha_1\boldsymbol{\varphi}(\boldsymbol{\mu_1}) + \alpha_2\boldsymbol{\varphi}(\boldsymbol{\mu_2}) + \boldsymbol{e}_k$

where $\varphi(\boldsymbol{\mu})$ is the 2D kernel function

$$f(\boldsymbol{x};\boldsymbol{\mu}) = \exp\left(-\|\boldsymbol{x}-\boldsymbol{\mu}\|^2/\sigma^2\right) \qquad (1)$$

evaluated in a 8x8 frame and vectorized. We estimate the kernel heights $(\alpha, \alpha_1, \alpha_2)$ and positions $(\boldsymbol{\mu}, \boldsymbol{\mu}_1\boldsymbol{\mu}_2)$ assuming constant and equal widths σ. This simplifies the estimation to a grid search for $\boldsymbol{\mu}$ in H_1 and $(\boldsymbol{\mu_1}, \boldsymbol{\mu_2})$ in H_2.

Estimate position of H_1-kernel

The position $\hat{\boldsymbol{\mu}}$ is obtained through grid search over given sensor zones which minimize least squares problem

$$\hat{\boldsymbol{\mu}} = \arg\min_{\boldsymbol{\mu}} \sum_{k=1}^{L} \|\boldsymbol{y_k} - \hat{\alpha}(\boldsymbol{\mu})\boldsymbol{\varphi}(\boldsymbol{\mu})\| \qquad (2)$$

where

$$\hat{\alpha}(\boldsymbol{\mu}) = \frac{\boldsymbol{\varphi}^T\bar{\boldsymbol{y}}_{\boldsymbol{k}}}{\boldsymbol{\varphi}^T\boldsymbol{\varphi}}, \quad \bar{\boldsymbol{y}}_{\boldsymbol{k}} = \frac{1}{L}\sum_{k=1}^{L}\boldsymbol{y_k}$$

Estimate positions of H_2-kernels

The positions $\hat{\boldsymbol{\mu}}_1, \hat{\boldsymbol{\mu}}_2$ is obtained through grid search over given sensor zones which minimize least squares problem

$$(\hat{\boldsymbol{\mu}}_1, \hat{\boldsymbol{\mu}}_2) = \arg\min_{\boldsymbol{\mu_1},\boldsymbol{\mu_2}} \sum_{k=1}^{L} \|\boldsymbol{y_k} - \hat{\alpha}(\boldsymbol{\mu_1},\boldsymbol{\mu_2})(\boldsymbol{\varphi}(\boldsymbol{\mu_1}) + \boldsymbol{\varphi}(\boldsymbol{\mu_2})\|)$$

Estimates $\hat{\boldsymbol{\mu}}_1$ and $\hat{\boldsymbol{\mu}}_2$ used to optimize for different α_1, α_2 from the new linear least squares problem

$$(\hat{\alpha}_1, \hat{\alpha}_2) = \arg\min_{\boldsymbol{\mu}} \sum_{k=1}^{L} \|\boldsymbol{y_k} - \alpha_1\boldsymbol{\varphi}(\hat{\boldsymbol{\mu}}_1) + \alpha_2\boldsymbol{\varphi}(\hat{\boldsymbol{\mu}}_2)\| \qquad (3)$$

Detection of passengers in frame (GLRT)

The detection is done in two steps. First, decide between 1 and 0 passangers:

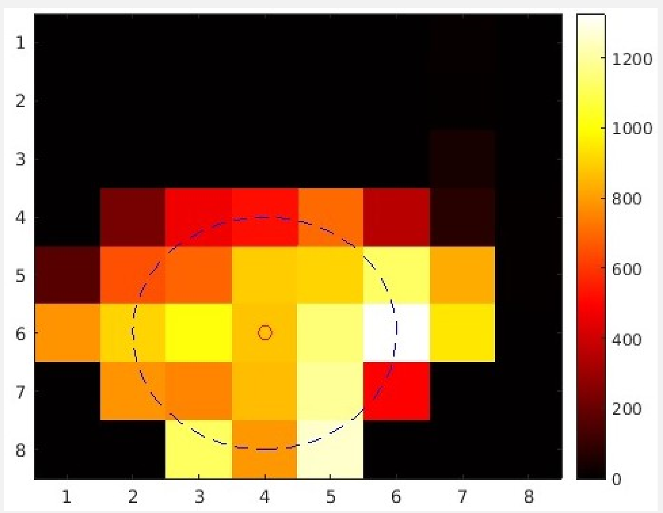
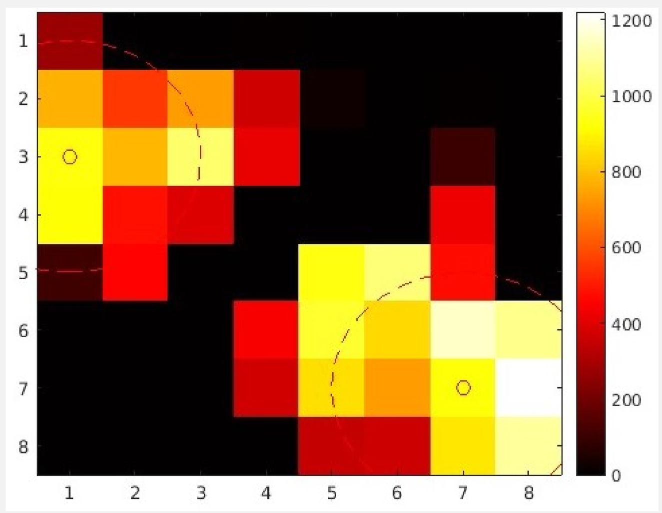
$$\frac{p(\boldsymbol{y}|H_1)}{p(\boldsymbol{y}|H_0)} > \text{Detection Threshold} \qquad (4)$$

If 1 passanger detected, perform a second test to distinguish between 1 or 2 passangers:

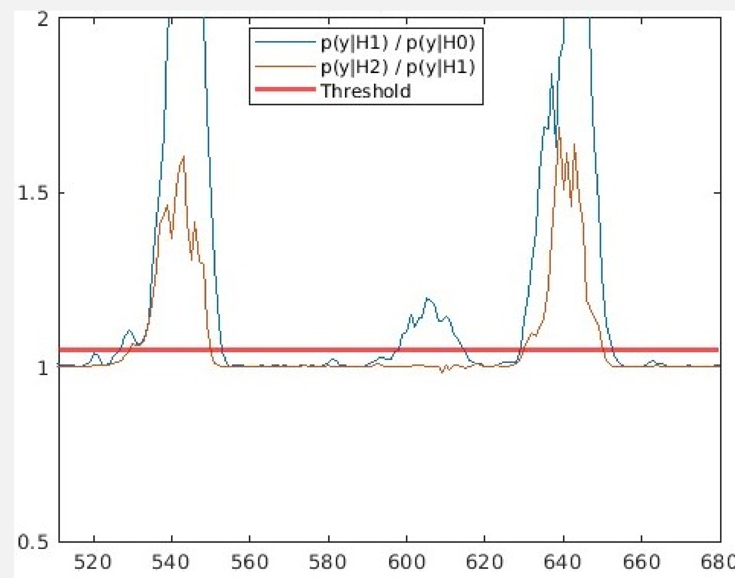
$$\frac{p(\boldsymbol{y}|H_2)}{p(\boldsymbol{y}|H_1)} > \text{Detection Threshold} \qquad (5)$$

$p(\boldsymbol{y}|H_0), p(\boldsymbol{y}|H_1)$ and $p(\boldsymbol{y}|H_2)$ are likelihoods for the respective models.

Example figures and counting idea

Above are example plots of estimated position of H_1-kernel to the left and H_2-kernels to the right.



To the right is an example plot of test statistics. As shown in the figure, if both tests are above the red threshold, it indicates a H_2-detection. If only the blue curve is above the threshold, it is considered an H_1-detection. When a detection occurs, estimated positions are saved. After a detection sequence, the saved position estimates are processed to determine entries and exits elevator. This process involves checking if previous estimates can be associated with the next. If not, positions without association are assumed to mark the end of a passengers trajectory, and direction can be deciphered based on the position index.

Further work

Our solution is only able to detect two or less people in the same frame. A next step could be to improve the model to be able to detect more than two people in same frame.

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