Optimal non-linear control for LIGO interferometers

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A Brief Overview

- Motivation - the what and why of the beam tracking project
- Methods and results-
  - Weighted pixel sum
  - OpenCV based image processing
  - Major thrust: Neural networks - CNN and LSTM based approach
- Future work

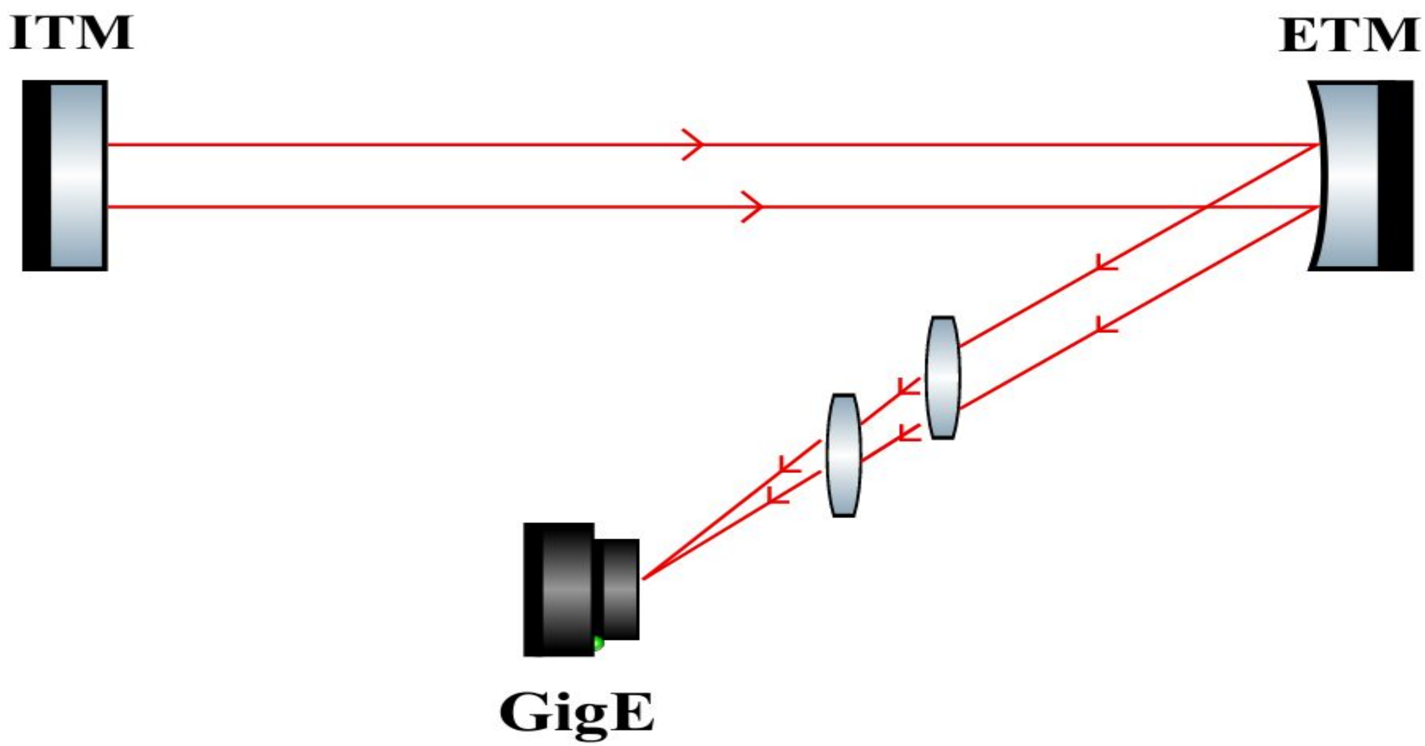
LIGO

Beam tracking - what and why?

- To detect gravitational waves we would like the LIGO interferometers to operate at highest sensitivity.
- Need laser beam spot to be positioned at particular positions despite seismic noise.
- Therefore, the objective is to build a black box that can look at video feed of scattered light from optic and predict position of beam spot on the optic.

Beam tracking - more of the why

- Why a camera feed? Why not a QPD? Why not A2L measurements?



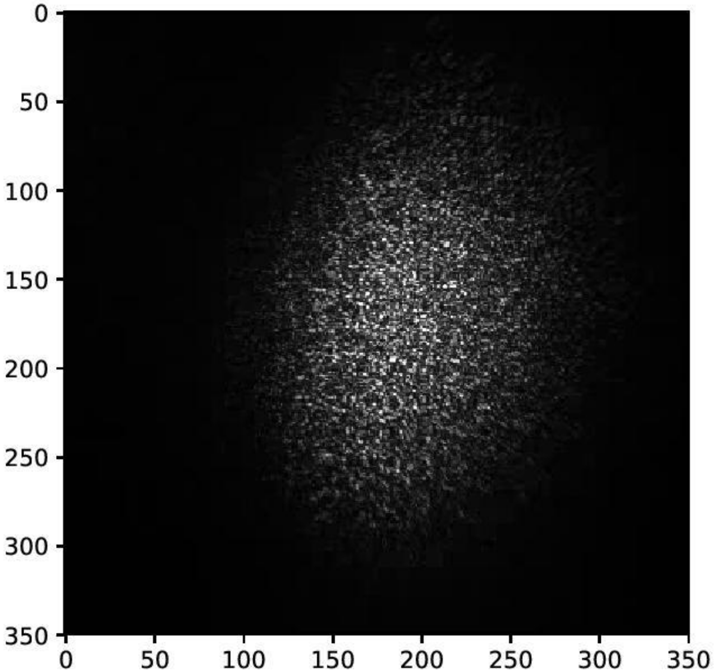
Methods

- Simple techniques
  - Weighted pixel sum
  - Image processing
- More sophisticated/general approach
  - CNNs
  - CNN-LSTMs

Methods

Simple pixel sum

The centroid of the beam spot is calculated as the weighted sum of the pixel coordinates with the pixel intensities as weights. This is essentially a center of mass calculation.

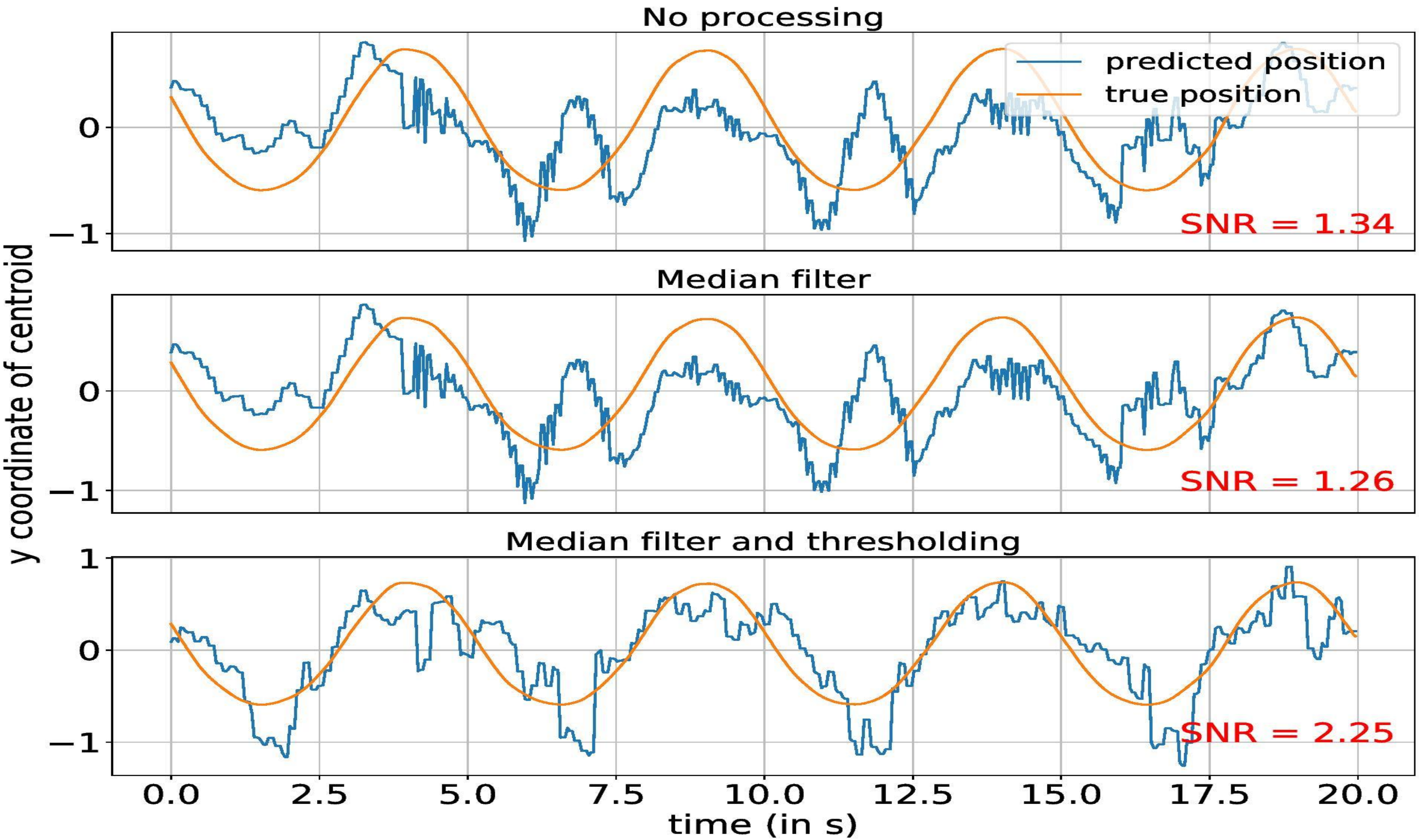


$$\mathrm{X}_{centroid} = \frac{\sum_{pixels} X_{pixel} \times (\text{pixel value})}{\sum_{pixels} (\text{pixel value})}$$

$$\mathrm{Y}_{centroid} = \frac{\sum_{pixels} Y_{pixel} \times (\text{pixel value})}{\sum_{pixels} (\text{pixel value})}$$

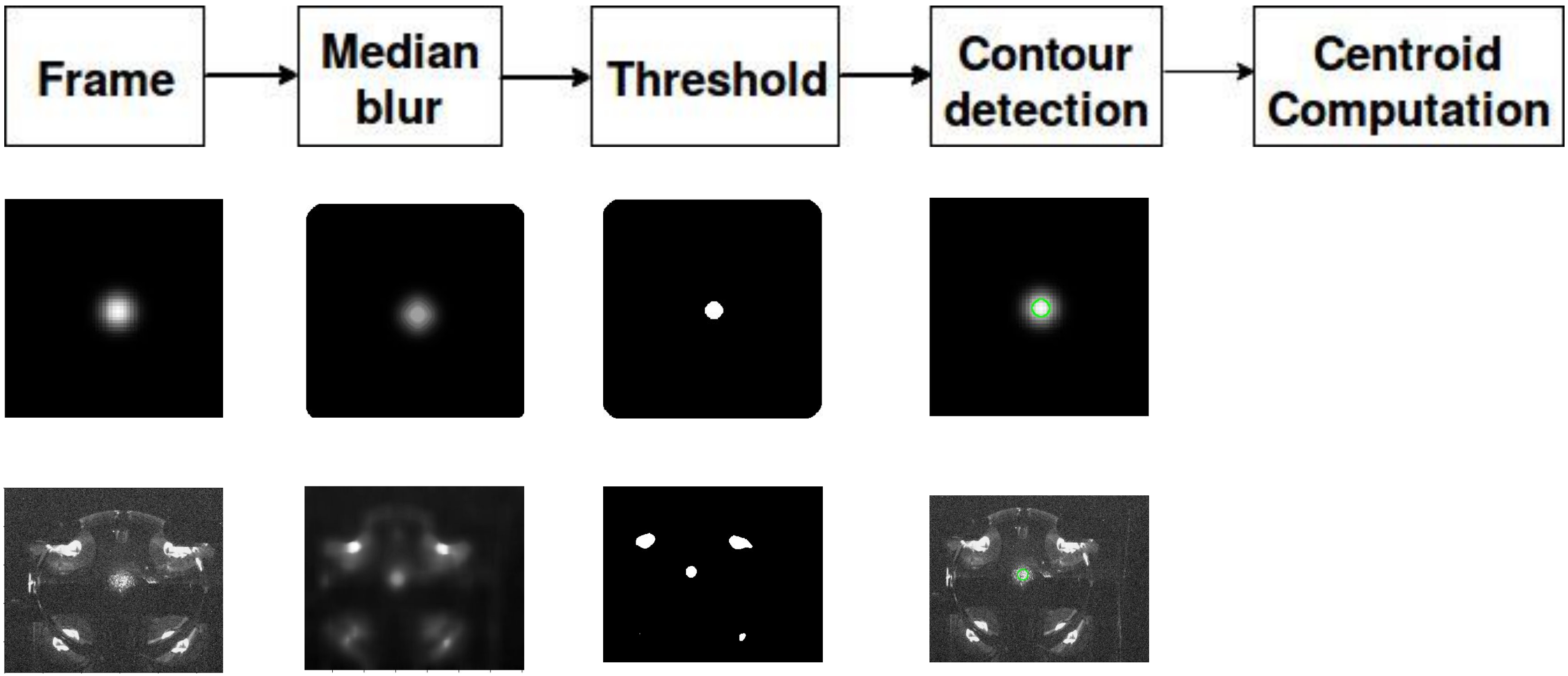
Methods

Simple pixel sum



Methods

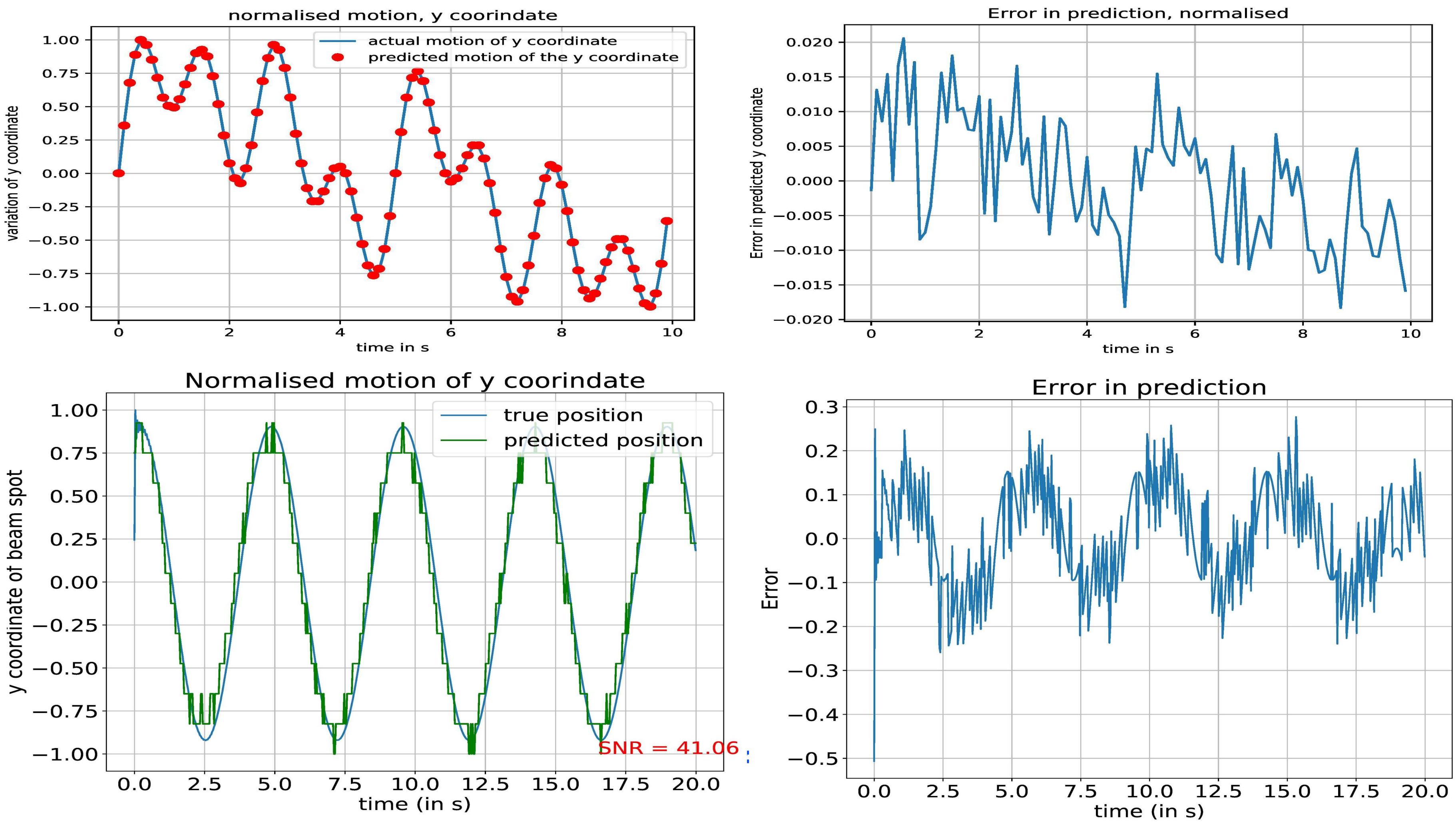
OpenCV based approach



Methods

OpenCV based approach

Works well for simulated Gaussian beam spot data! Fails for real video data.



Methods

Why do simple techniques fail?

- The intensity profile of the beam spot is no longer Gaussian.
- The relation between video of beam spot motion and position of the spot is complex and nonlinear.
- Further, these methods are not general and require a degree of hard coding- threshold value for instance.

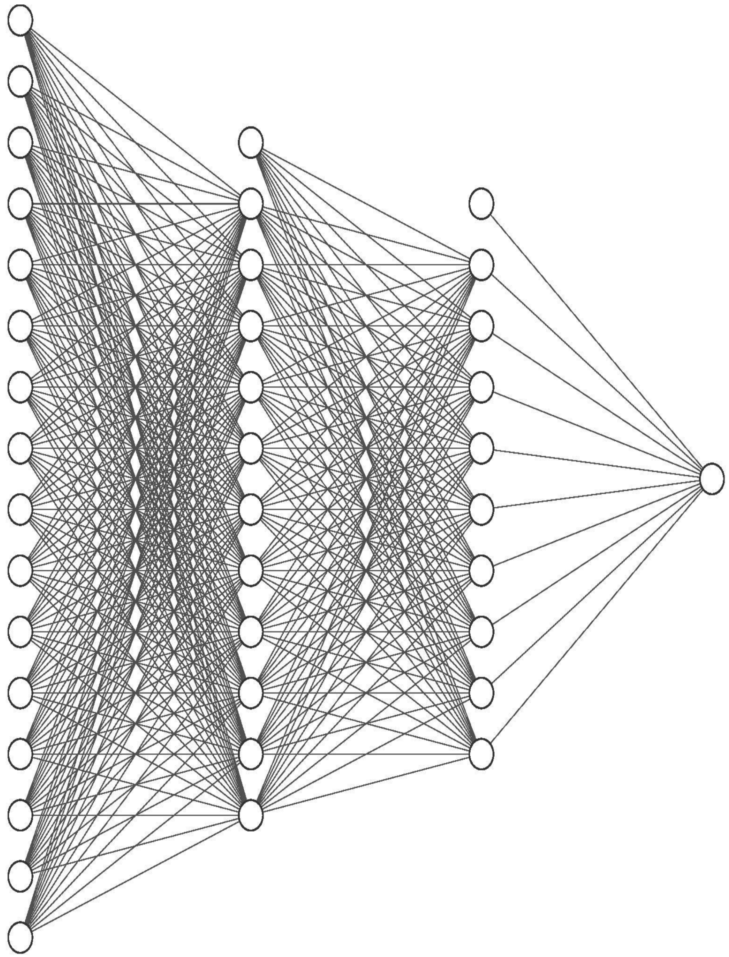
Methods

Neural Networks

- What are neural networks?
  y = f(x;***W,b***)

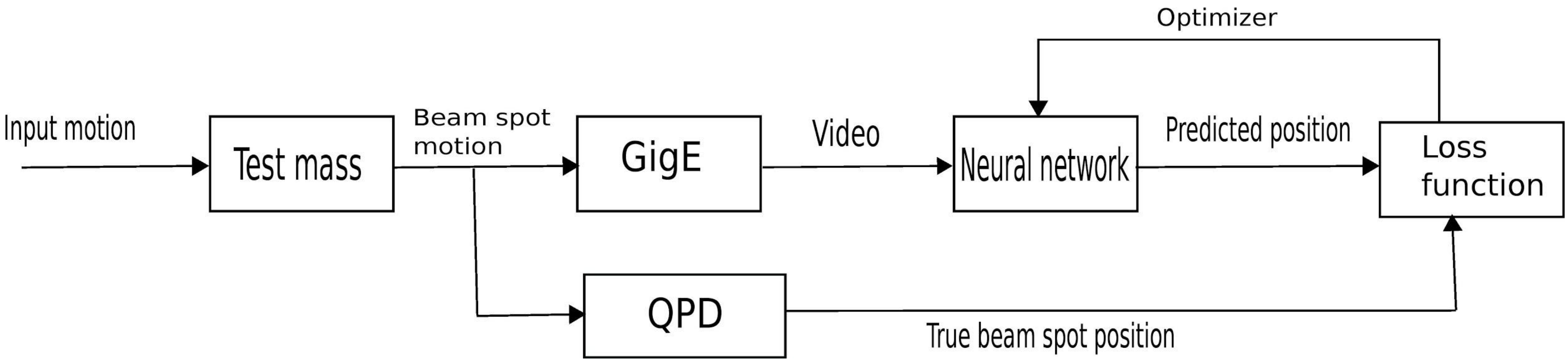
- These weights and biases can be "learnt" using optimization algorithms.

- CNNs are used as this is an image processing task. They are better suited to handling images because of weight sharing.



Methods

Neural Networks - the training

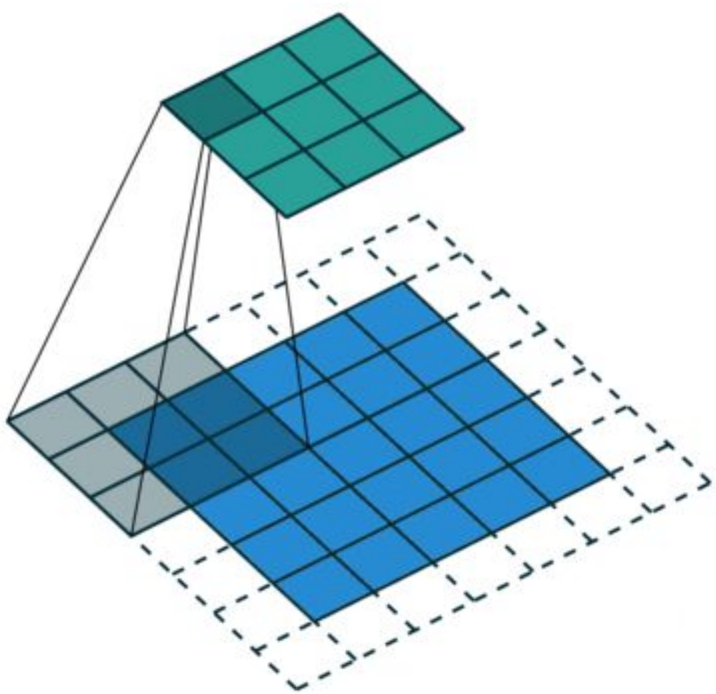


- **Optimizer**: Adam
- **Loss function**: Mean squared error
- **Framework**: Keras with tensorflow backend
- **Hidden layer activation**: relu
- **Output layer activation**: linear
- **Regularization**: Dropout
- **Preprocessing**: crop and apply median blur

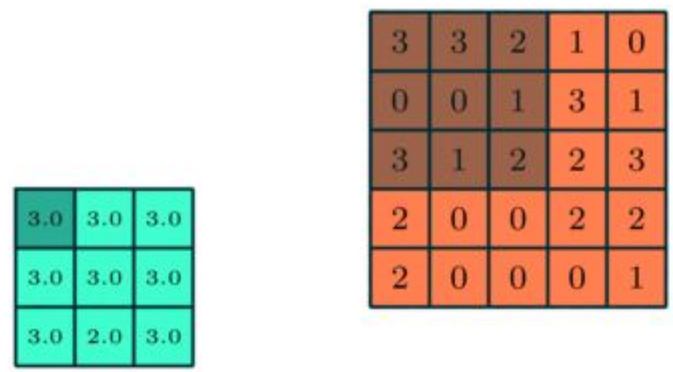
Methods

Neural Networks - CNNs

2D convolution



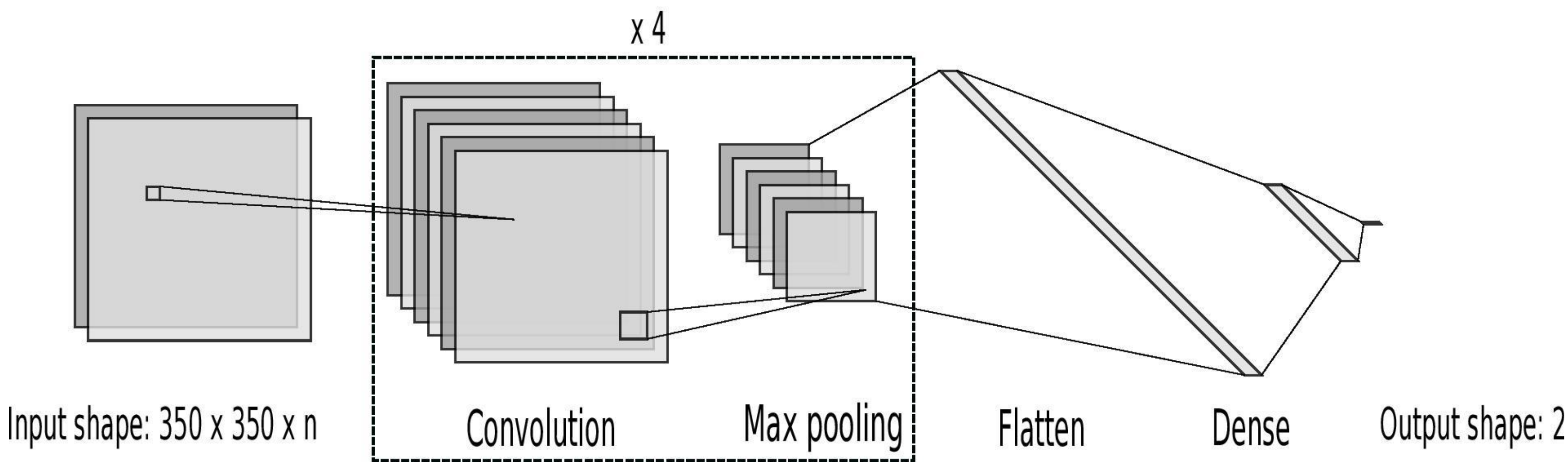
Max pooling



Graphics retrieved from https://towardsdatascience.com/a-comprehensive-guide-to-convolutional-neural-networks-the-eli5-way-3bd2b1164a53

Methods

Neural Networks - CNN architecture

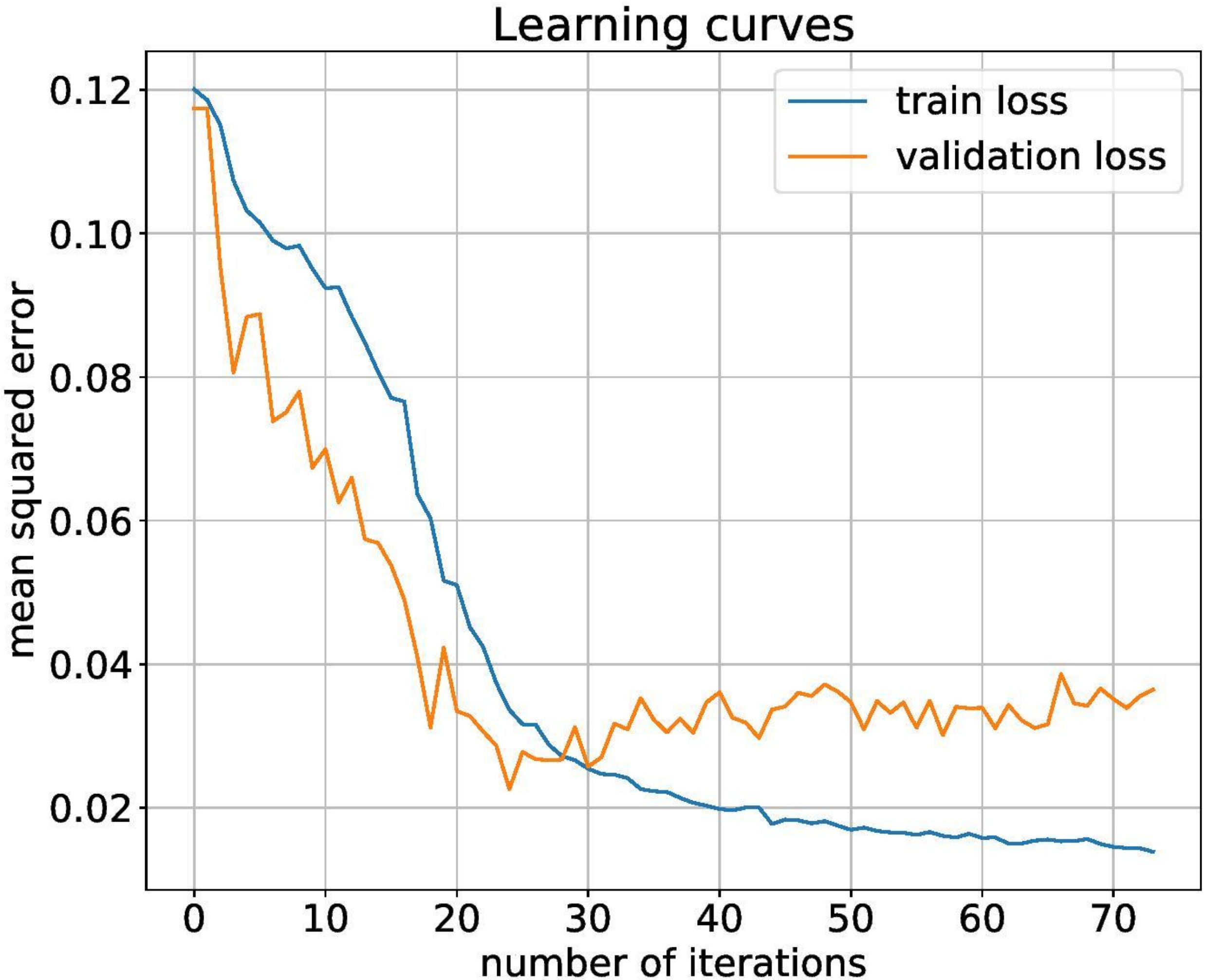


LIGO

Methods

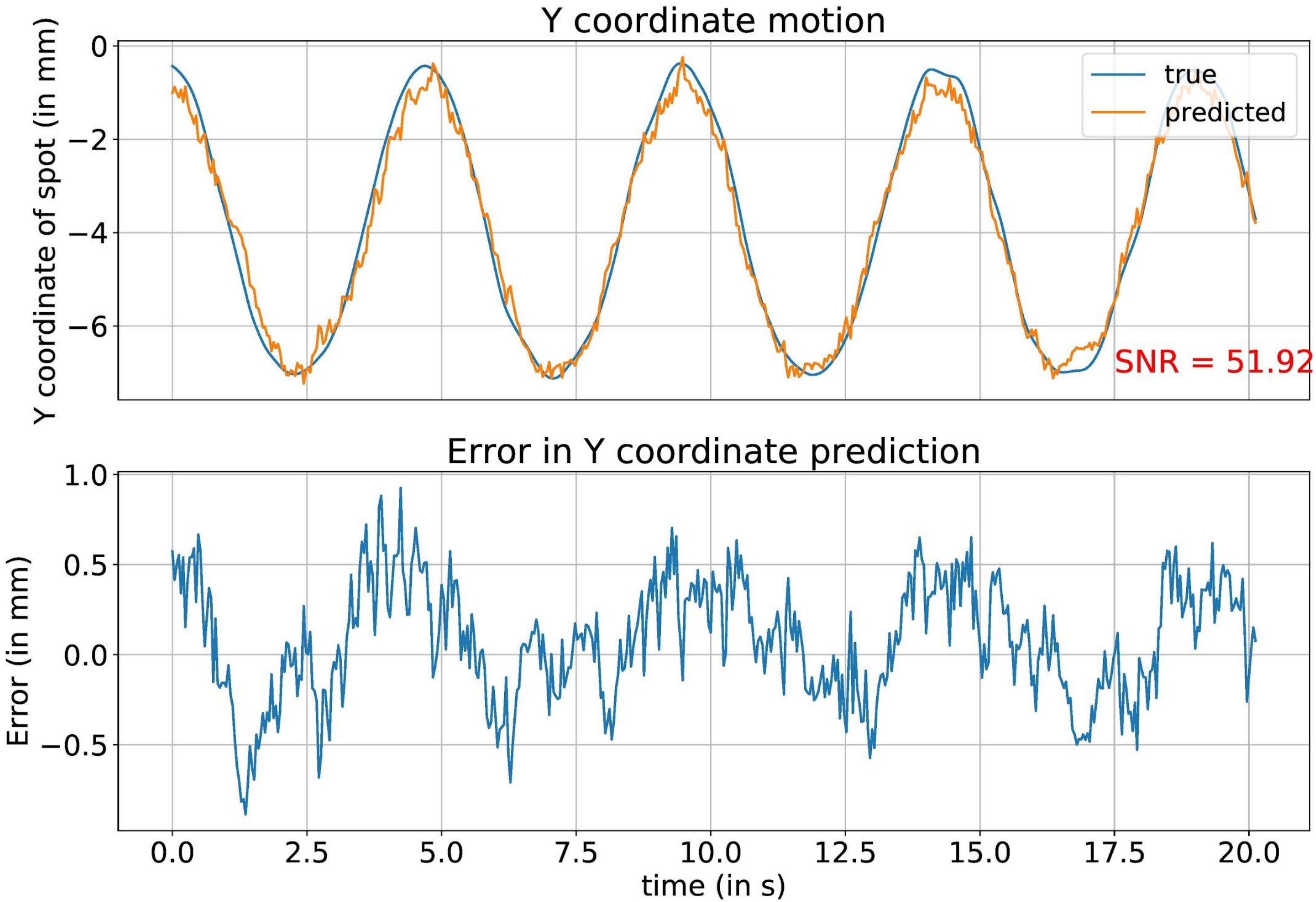
Neural Networks- testing

After much hyper parameter tuning, the following learning curves.



Methods

Neural Networks- testing



LIGO

Future work

- Collect and train on data at different frequencies, amplitudes and exposure times.
- GANs for simulation- data generated is similar to real data.
- Transfer learning using weights from the previous experiments.

Summary

- Need for beam tracking
- Traditional image processing
- Deep learning for beam tracking

Thank You!