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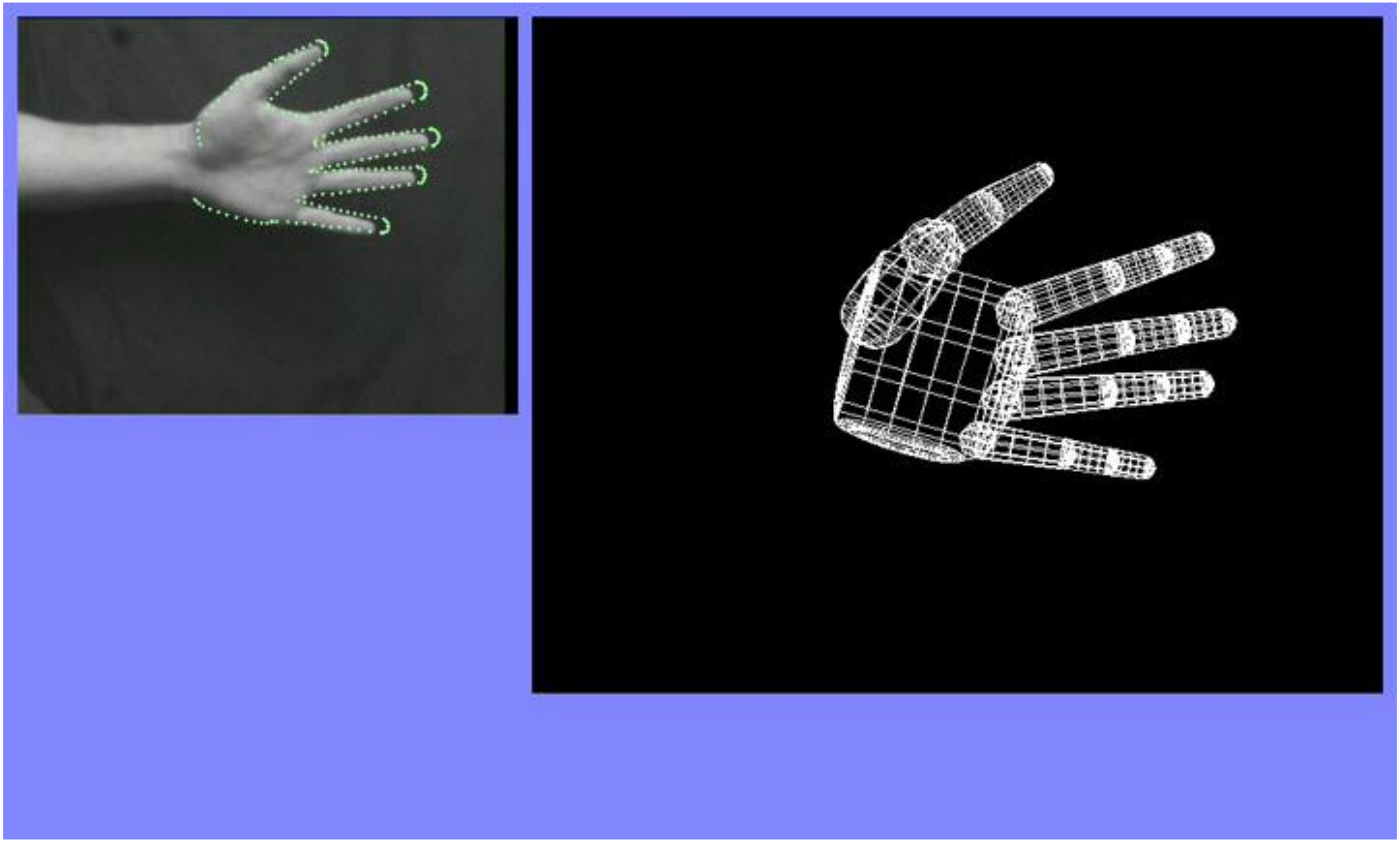
Model-Based Hand Tracking Using an Unscented Kalman Filter

Björn Stenger and Roberto Cipolla

The Problem



Contributions

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- What's new?
  - Regh & Kanade, ECCV'94
    - Truncated cylinders, no self-occlusion, 10 Hz.
  - Heap & Hogg, F&G'96
    - Point mesh, PCA, invalid motions, 10 Hz.
  - Isard & McCormic, ECCV'00
    - 2D b-spline, partitioned sampling, real-time.
  - Wu, Lin & Huang, ICCV'01
    - Data-glove + PCA, MC, view-dependent.
  - Stenger, Mendonça, Cipolla, CVPR'01
    - Accurate model, self-occlusion, UKF, 12 Hz.

Contributions

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- Construction of hand model from truncated quadrics
- Contour generation handling self-occlusion
- Application of Unscented Kalman filter
- Tracking 7 DOF with 12Hz using 2 cameras

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System Overview

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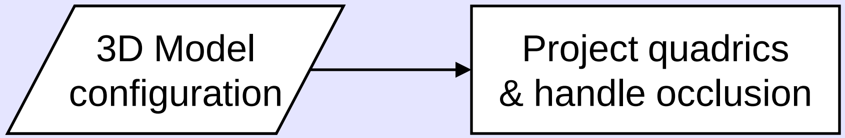
Model Projection



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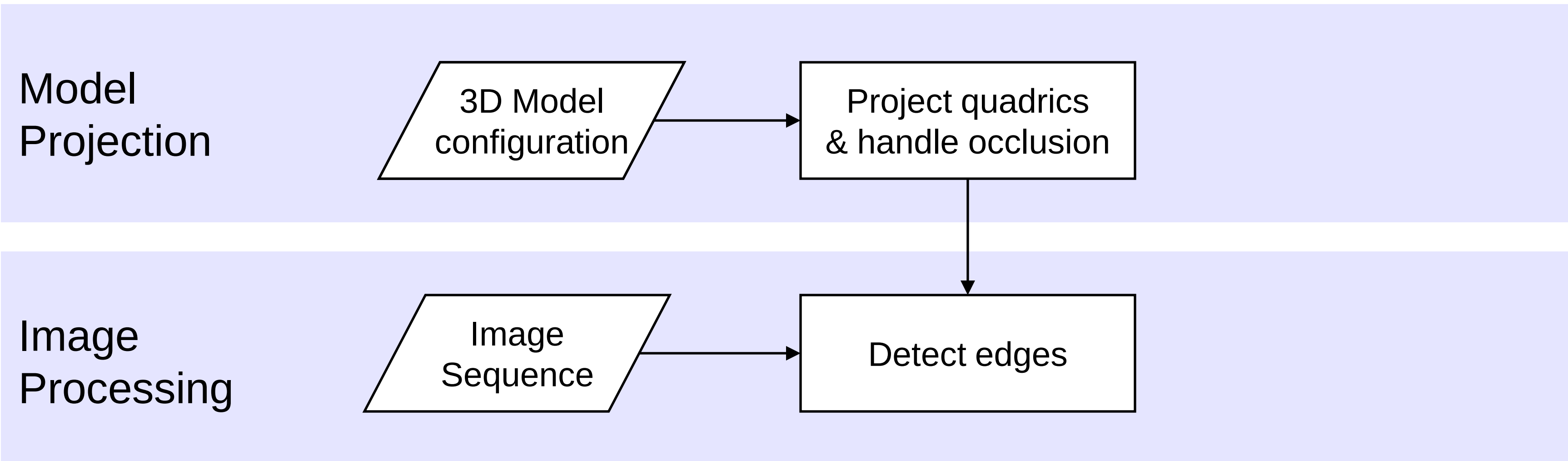

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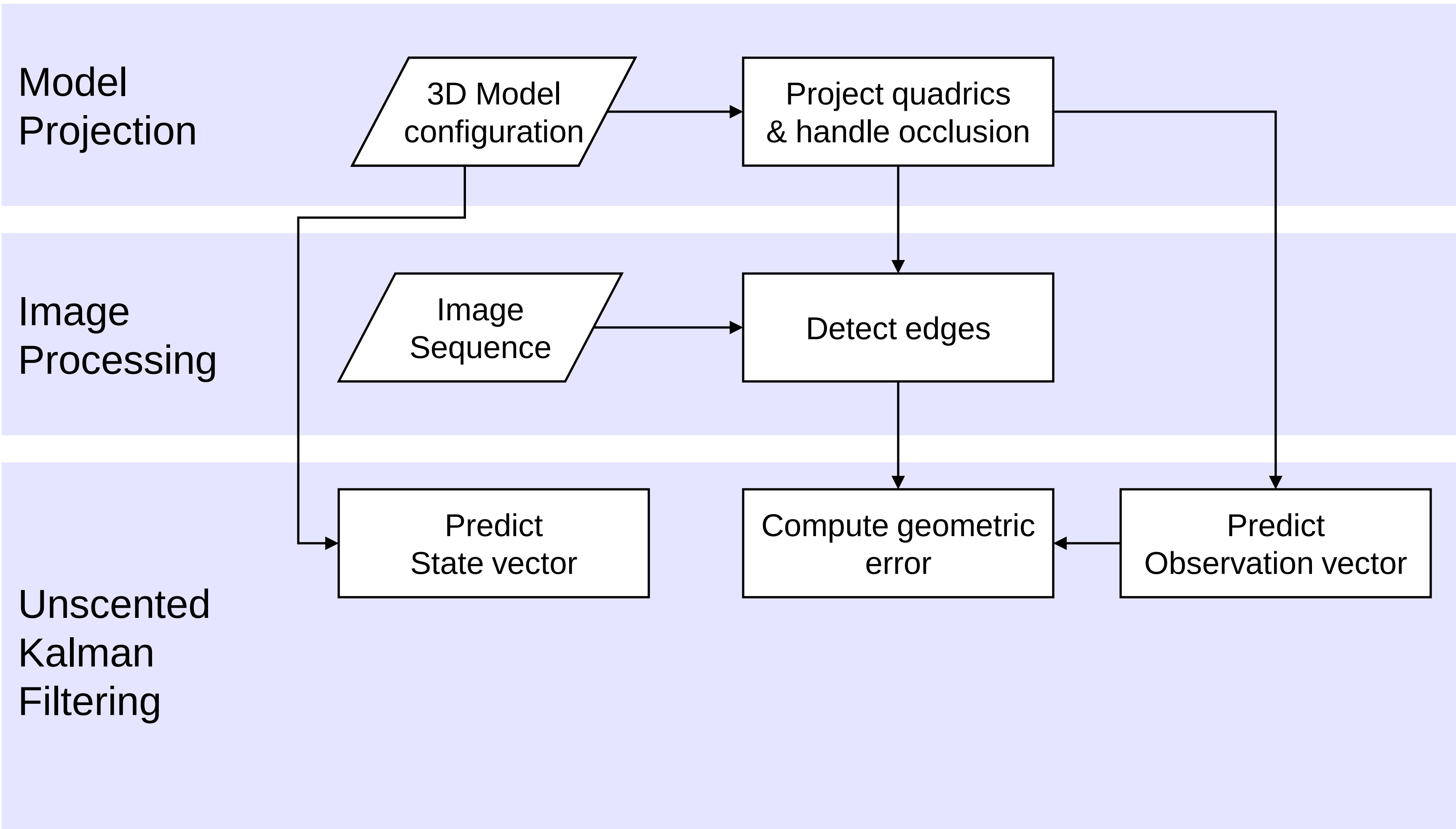

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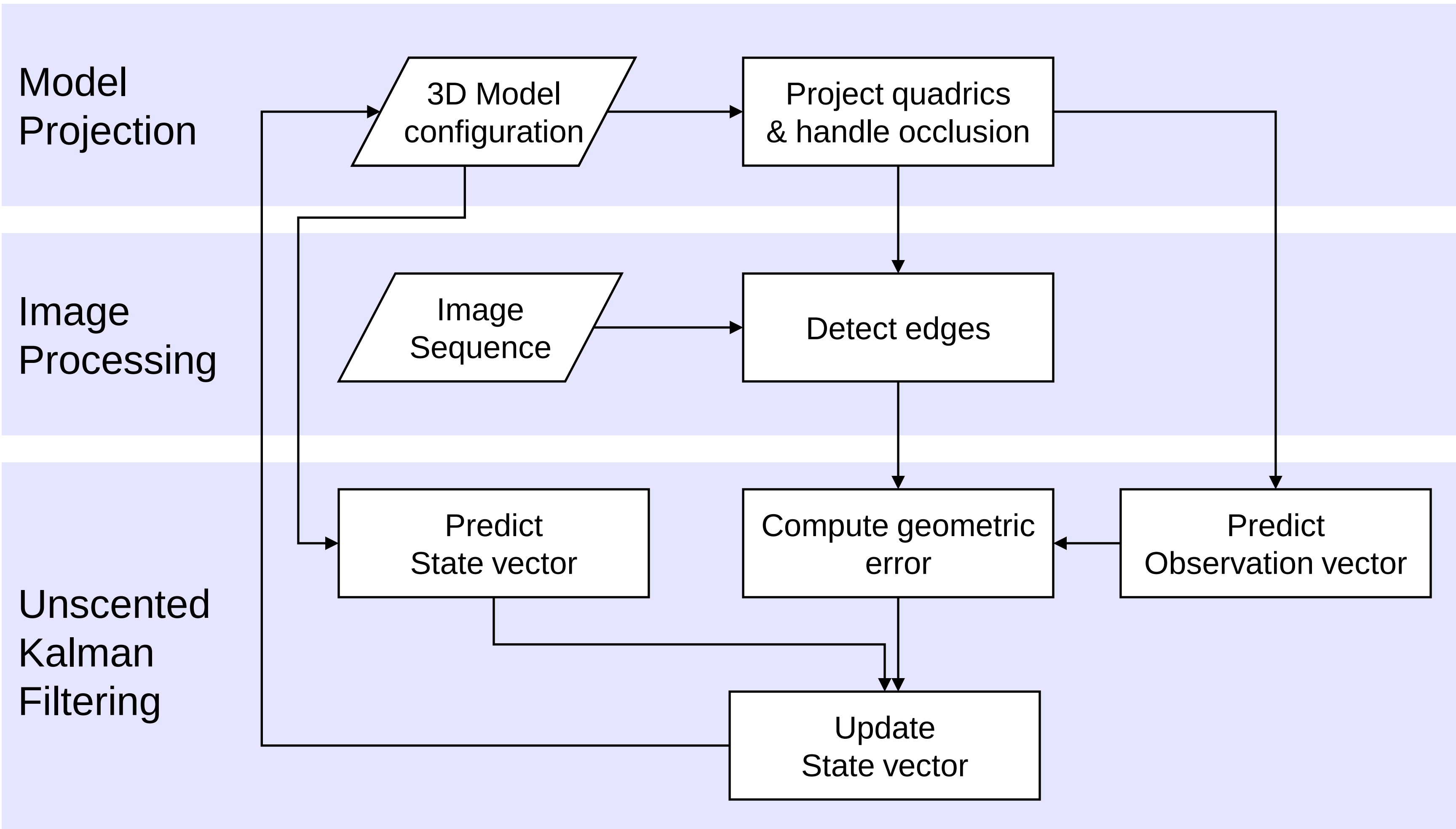


Quadrics

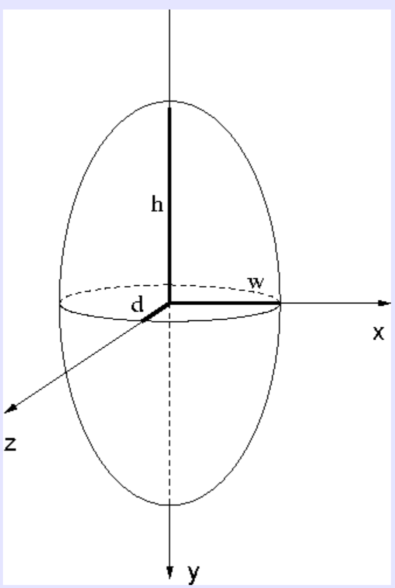
Quadric: Second degree implicit surface defined by points X satisfying $\mathbf{X}^T \mathbf{Q} \mathbf{X} = 0$.

$\mathrm{rank}(\mathbf{Q}) = 4$

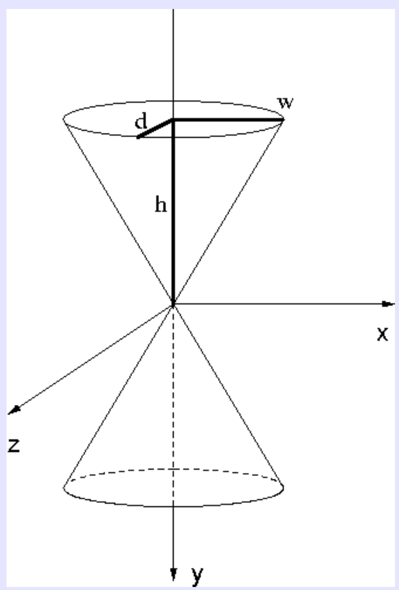
$\mathrm{rank}(\mathbf{Q}) = 3$

$\mathrm{rank}(\mathbf{Q}) = 2$

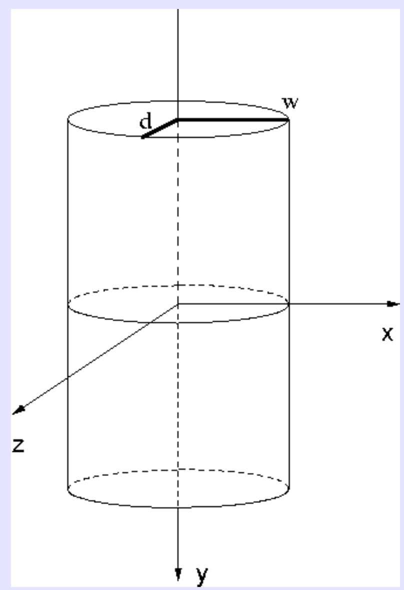
Ellipsoid



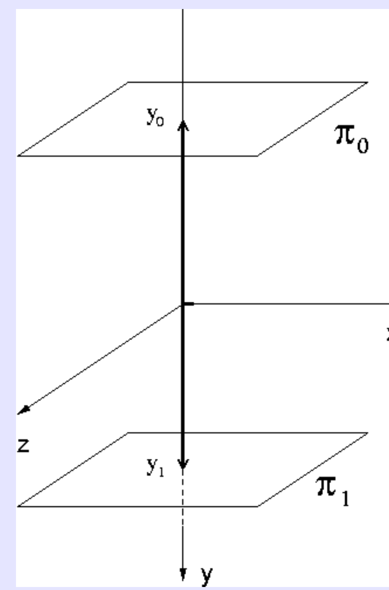
Cone



Cylinder



Pair of Planes



Shaping Quadrics

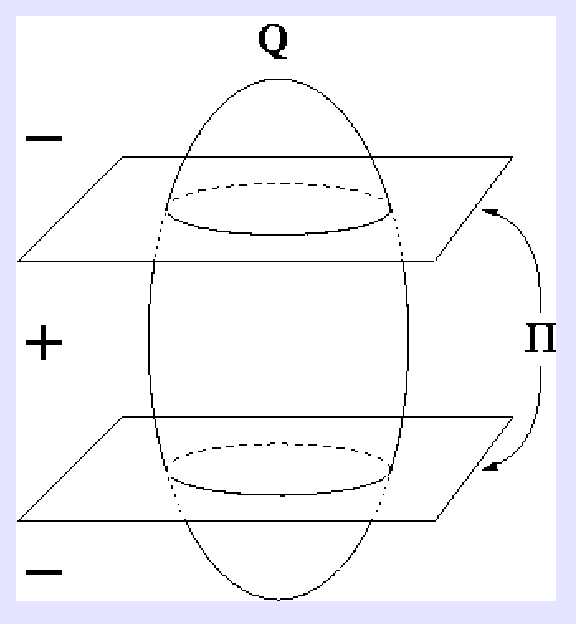
The shape of the quadric appear by factorizing **Q:**

$$\mathbf{Q} = \underbrace{\begin{bmatrix} \mathbf{R} & \mathbf{0} \\ \mathbf{t}^{\mathrm{T}} & 1 \end{bmatrix}}_{\text{Motion}} \underbrace{\begin{bmatrix} 1/a & 0 & 0 & 0 \\ 0 & 1/b & 0 & 0 \\ 0 & 0 & 1/c & 0 \\ 0 & 0 & 0 & 1/d \end{bmatrix}}_{\text{Shape}} \underbrace{\begin{bmatrix} \mathbf{R}^{\mathrm{T}} & \mathbf{t} \\ \mathbf{0}^{\mathrm{T}} & 1 \end{bmatrix}}_{\text{Motion}}$$

Clipping Quadrics

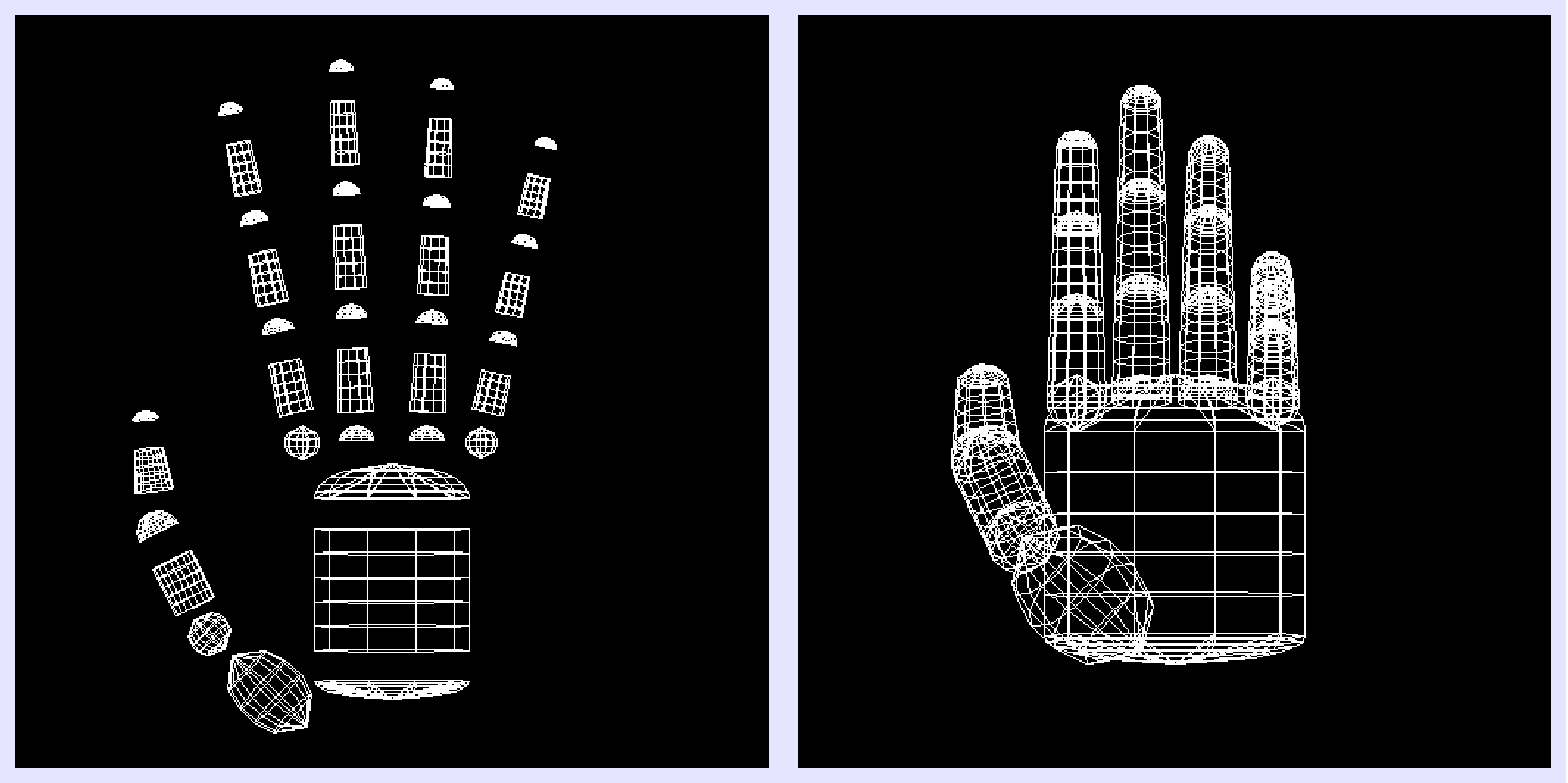
For modelling more general shapes truncate quadrics by finding points X which satisfy:

$$\mathbf{X}^T\mathbf{Q}\mathbf{X} = 0 \quad \text{and} \quad \mathbf{X}^T\Pi\mathbf{X} \geq 0$$



Hand Model

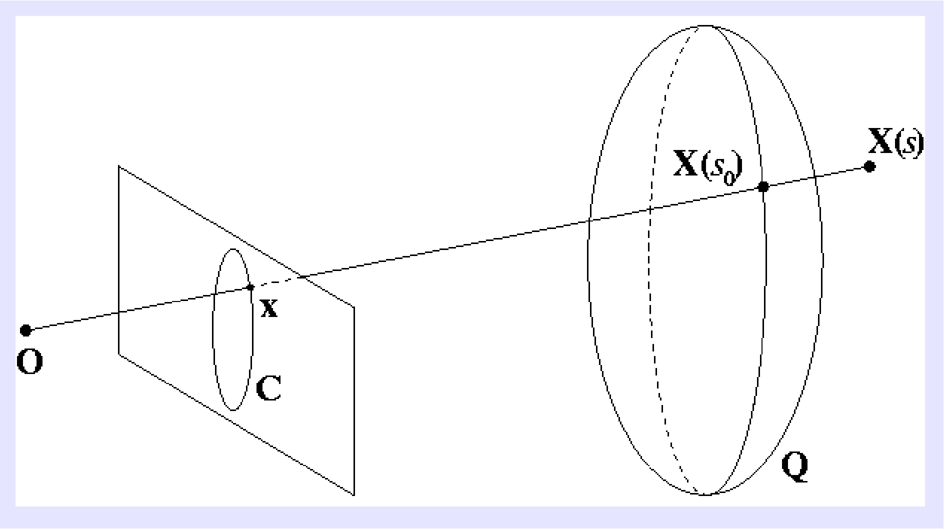
- 37 truncated quadrics
- 27 degrees of freedom (currently only 7 are tracked)



Projection of a Quadric

Assuming a normalized projective camera $\mathbf{P} = [\mathbf{I} \mid 0]$

Parameterize 3D points $\mathbf{X}(s) = \begin{bmatrix} \mathbf{x} \\ s \end{bmatrix}$



$$\mathbf{X}^T(s)\ \mathbf{Q}\ \mathbf{X}(s) = 0$$

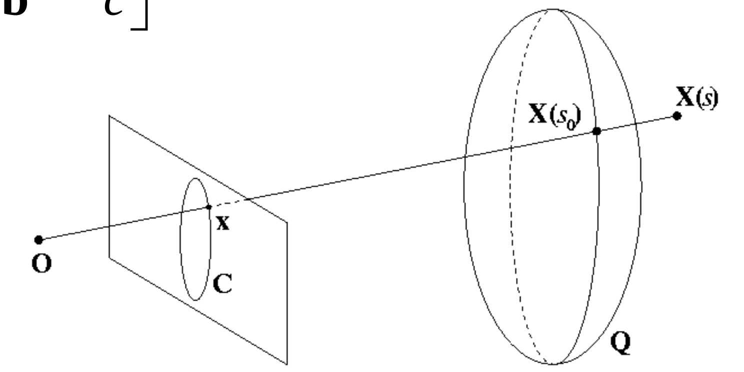
Projection of a Quadric (2)

$$\mathbf{X}^T(s)\ \mathbf{Q}\ \mathbf{X}(s) = 0$$

$$\mathbf{Q} = \begin{bmatrix} \mathbf{A} & \mathbf{b} \\ \mathbf{b}^{\mathrm{T}} & c \end{bmatrix}$$

$$\begin{bmatrix} \mathbf{x} & s \end{bmatrix} \begin{bmatrix} \mathbf{A} & \mathbf{b} \\ \mathbf{b}^{\mathrm{T}} & c \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ s \end{bmatrix} = 0$$

$$cs^2 + 2\mathbf{b}^{\mathrm{T}}\mathbf{x}s + \mathbf{x}^{\mathrm{T}}\mathbf{A}\mathbf{x} = 0$$



Condition for $\mathrm{X}(\mathrm{s})$ to be on the contour generator of Q:

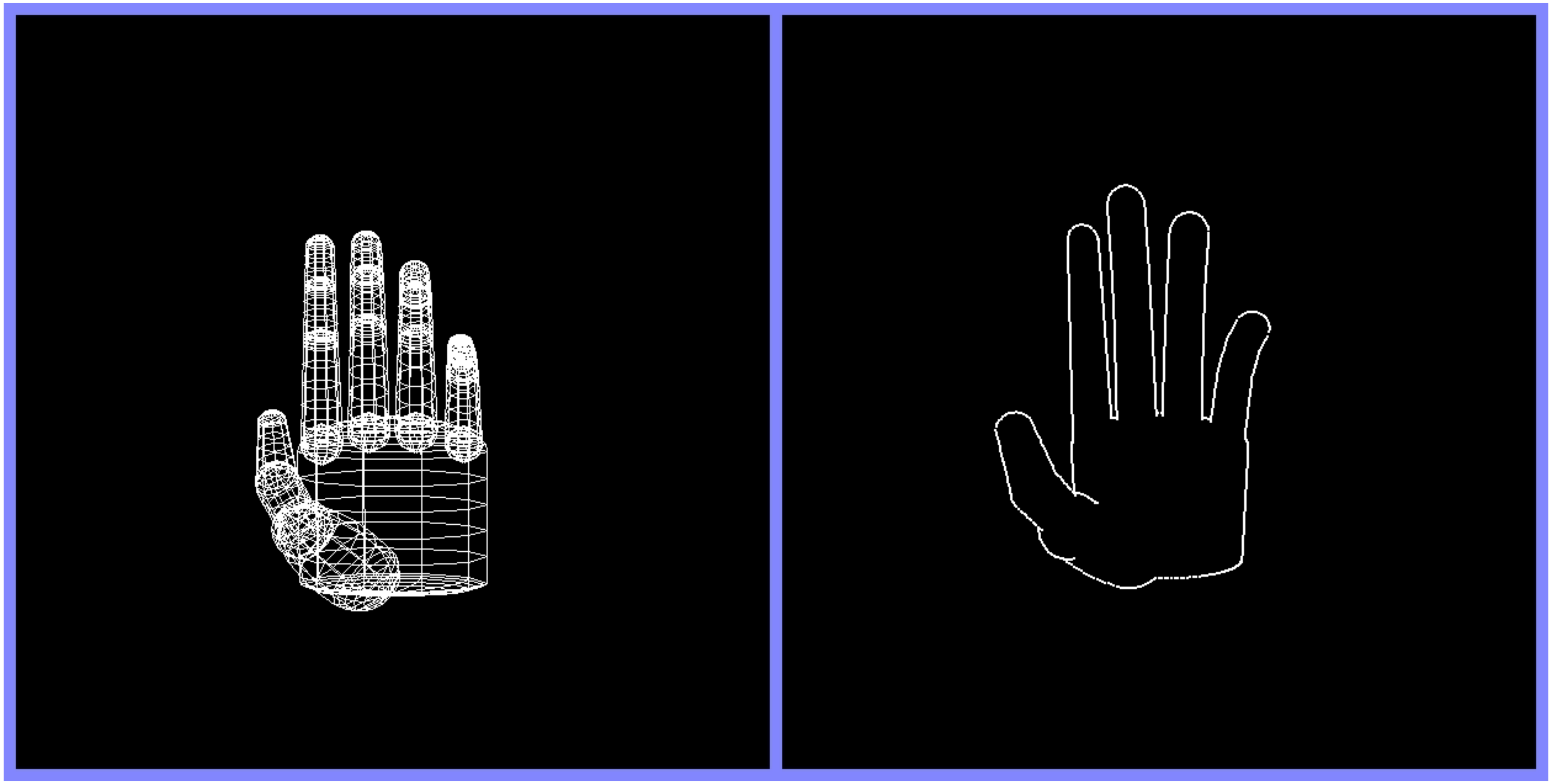
$$\Delta = 0 \Leftrightarrow \mathbf{x}^{\mathrm{T}}(c\mathbf{A} - \mathbf{b}\mathbf{b}^{\mathrm{T}})\mathbf{x} = 0$$

$$\mathbf{x}^{\mathrm{T}}\mathbf{C}\mathbf{x} = 0 \qquad \mathbf{C} = c\mathbf{A} - \mathbf{b}\mathbf{b}^{\mathrm{T}}$$

Projecting the Hand Model

3D model

Contours



Optimal Filtering

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- Given a state-space model

$$\mathbf{x}_k = \mathrm{f}\left(\mathbf{x}_{k-1}, \mathbf{v}_{k-1}\right)$$
$$\mathbf{z}_k = \mathrm{h}\left(\mathbf{x}_k, \mathbf{w}_k\right)$$

- Maximum likelihood estimator

$$\hat{\mathbf{x}}_k = \arg\min\left(-\log \mathrm{L}\left(\mathbf{x}_k \mid \mathbf{z}_k, \ldots, \mathbf{z}_0\right)\right)$$

- For linear models, Gaussian error model: Kalman filter

$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_{k|k-1} + \mathbf{K}_k\left(\mathbf{z}_k - \hat{\mathbf{z}}_{k|k-1}\right)$$

The Unscented Transform

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Method for computing statistics of a random variable after a nonlinear transformation (Julier & Uhlmann, 1995).

Given: n-dimensional random variable $\mathbf{x}_{k-1}$
with mean $\hat{\mathbf{x}}_{k-1}$ and covariance P_{k-1}

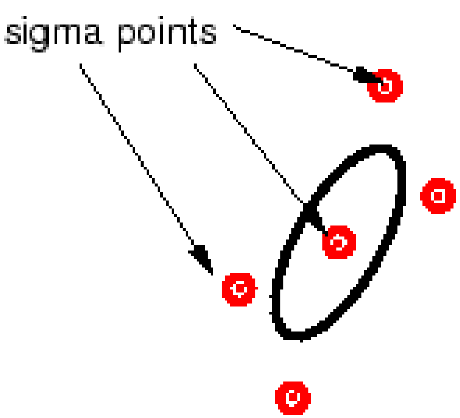
1. Compute $2n+1$ points with associated weights.
2. Apply the nonlinear transformation to each point.
3. Compute mean and covariance of the transformed points.

The Unscented Transform

1. Choose $2n$+1 points with associated weights

$$X_{k\text{-}1}^{i} = \begin{cases} \hat{\mathbf{x}}_{k-1} & i = 0 \\ \hat{\mathbf{x}}_{k-1} - \sigma_{k-1}^{i} & i = 1,\ldots,n \\ \hat{\mathbf{x}}_{k-1} + \sigma_{k-1}^{i} & i = n+1,\ldots,2n \end{cases} \qquad W_{k\text{-}1}^{i} = \begin{cases} 1/(n+1) & i = 0 \\ 1/2(n+1) & i = 1,\ldots,2n \end{cases}$$

where σ_{k-1}^{i} is the i^{th} column of the matrix $\sqrt{(n+1)\mathbf{P}_{k-1}}$



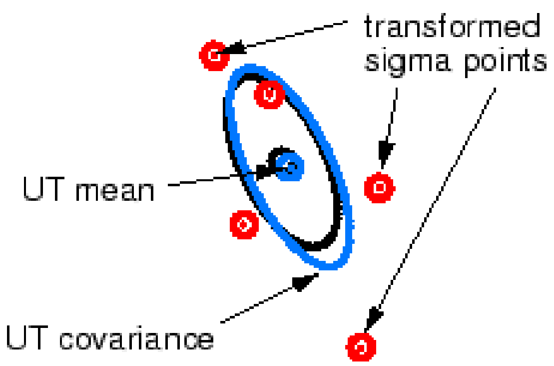
The set of points has the same mean, covariance and all higher odd central moments as the Gaussian distribution of $\mathbf{x}_{k-1}$.

The Unscented Transform

2. Apply the nonlinear transformation to each point

$$X_{k|k-1}^{i} = \mathrm{f}\left(X_{k-1}^{i}, k\right) \quad i = 0,\ldots,2n$$

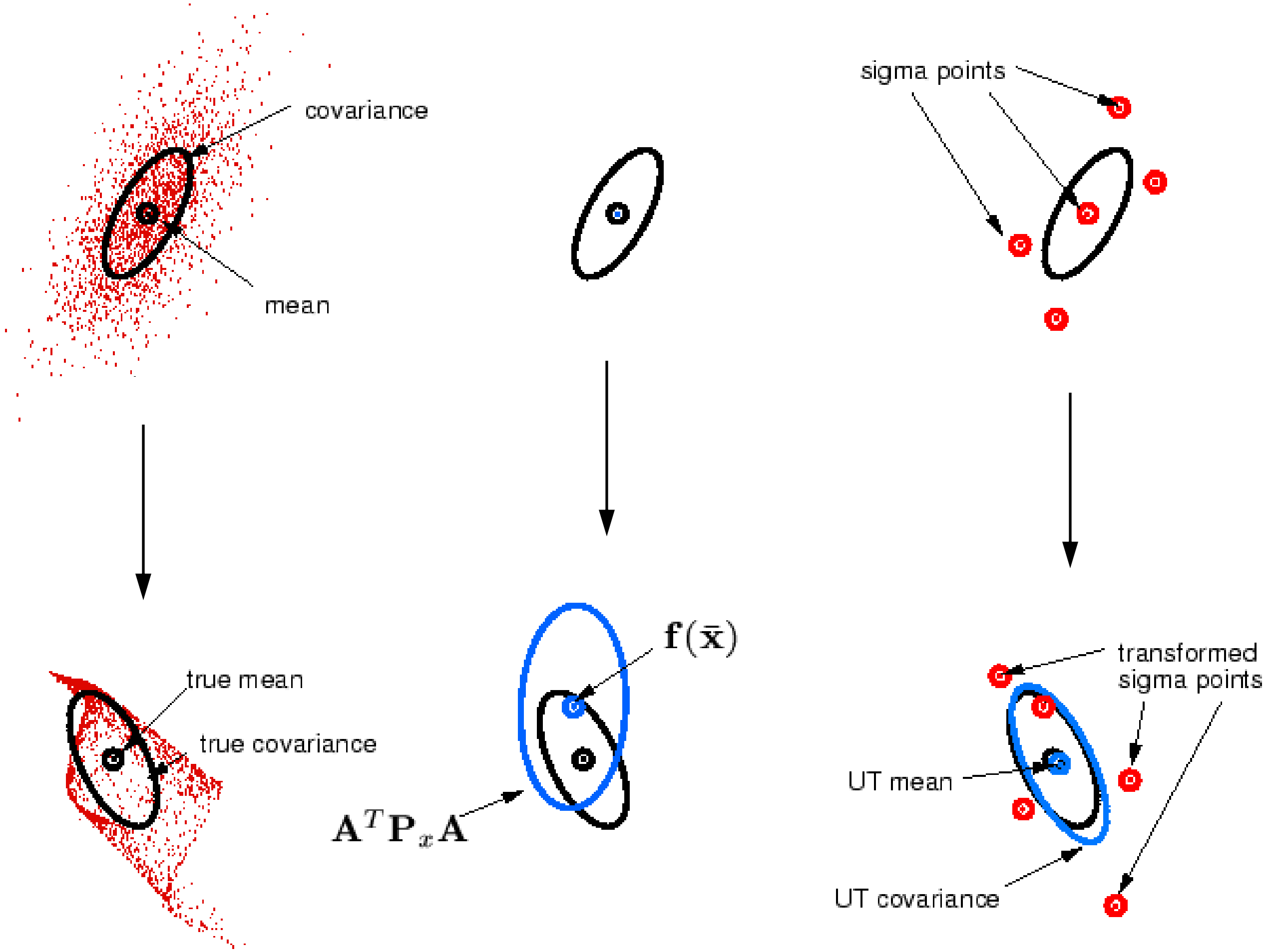
3. Compute mean and covariance of the transformed points.



This approximation is correct up to the second order.

Comparison

Actual (sampling) | Linearisation | Unscented Transform



Properties of the UT

- Approximates the distribution rather than the nonlinearity.
- Accurate to at least 2nd order (3rd order for Gaussian distributions).
- No Jacobian or Hessian matrices are needed.
- Efficient “sampling approach”.
- Assumes unimodal distributions.

Unscented Kalman Filter

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Prediction Step:

- Prediction of state (and error covariance matrix)

$$\hat{\mathbf{x}}_{k-1} \xrightarrow{\text{UnscentedTransform}} \hat{\mathbf{x}}_{k|k-1}$$

- Prediction of observation

$$\hat{\mathbf{z}}_{k-1} \xrightarrow{\text{UnscentedTransform}} \hat{\mathbf{z}}_{k|k-1}$$

Measurement Update Step:

- Compute innovation

$$\nu_k = \mathbf{z}_k - \hat{\mathbf{z}}_{k|k-1}$$

- Compute Kalman gain K_k
- Update state estimation (and error covariance matrix)

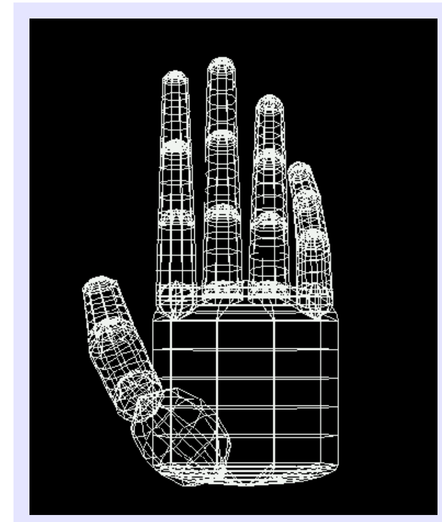
$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_{k|k-1} + \mathbf{K}_k \nu_k$$

State & Observation Vector

State Vector x_k:

- Global pose parameters (6 DOF)
- Configuration of joints (1 DOF)
- Velocity and acceleration

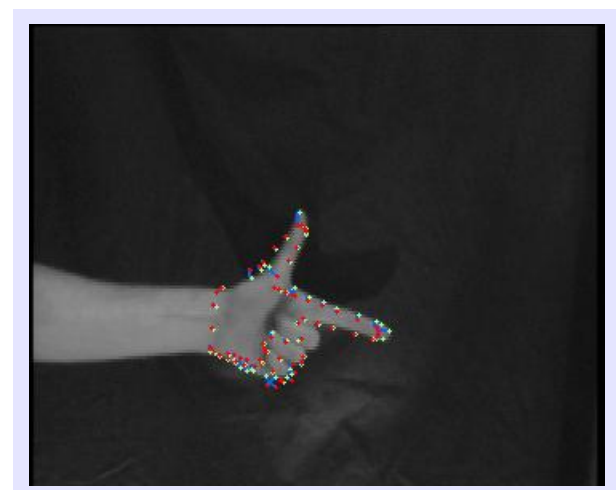
$$\mathbf{x}_k = \left[x_0, \ldots, x_l, \dot{x}_0, \ldots, \dot{x}_l, \ddot{x}_0, \ldots, \ddot{x}_l\right]^T$$



Observation Vector z_k:

- Local edge detection at contour points

$$\mathbf{z}_k = \begin{bmatrix} \mathbf{n}_0^{\mathrm{T}}\mathbf{s}_0 \\ \vdots \\ \mathbf{n}_m^{\mathrm{T}}\mathbf{s}_m \end{bmatrix}$$



Single View Tracking

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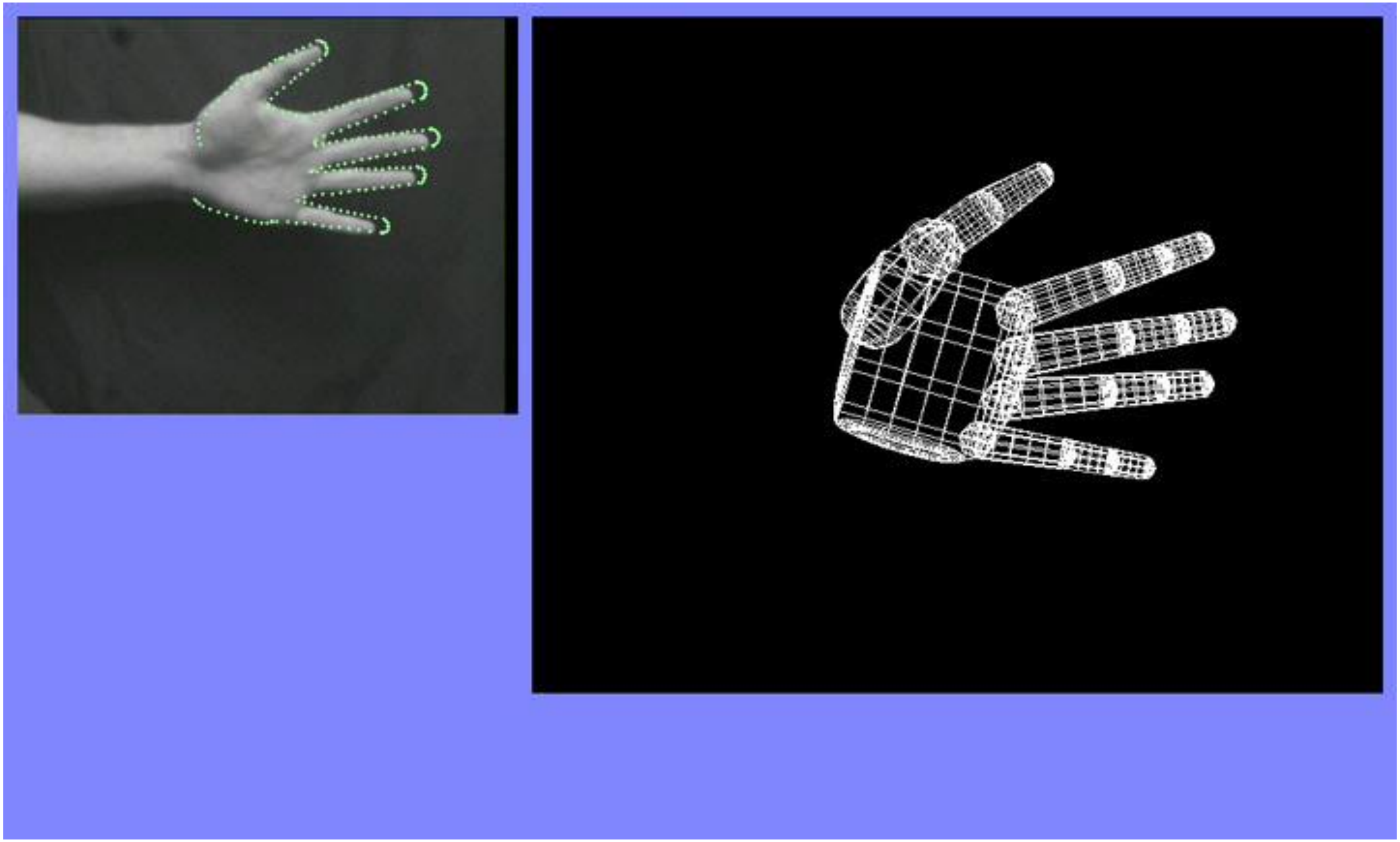
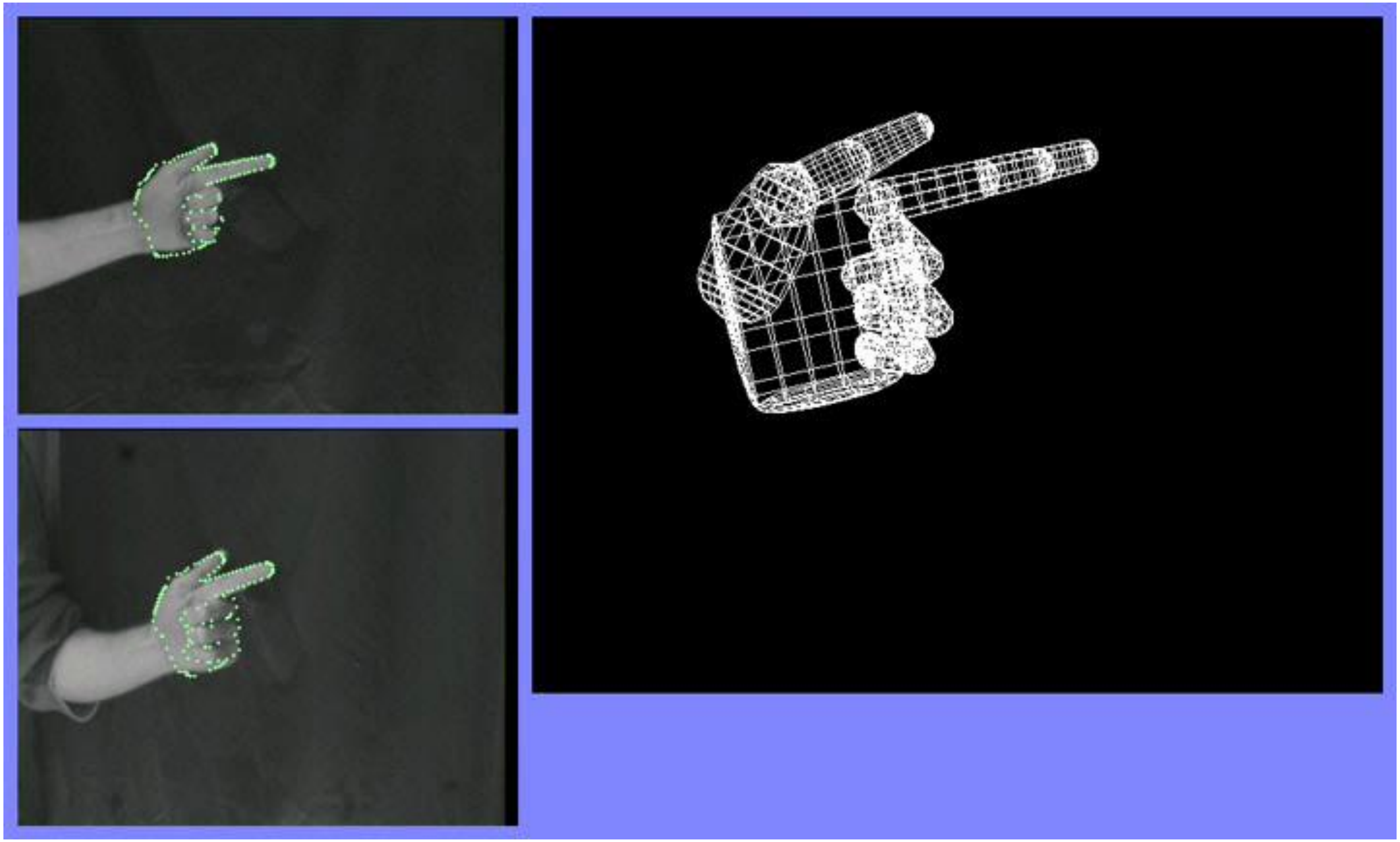
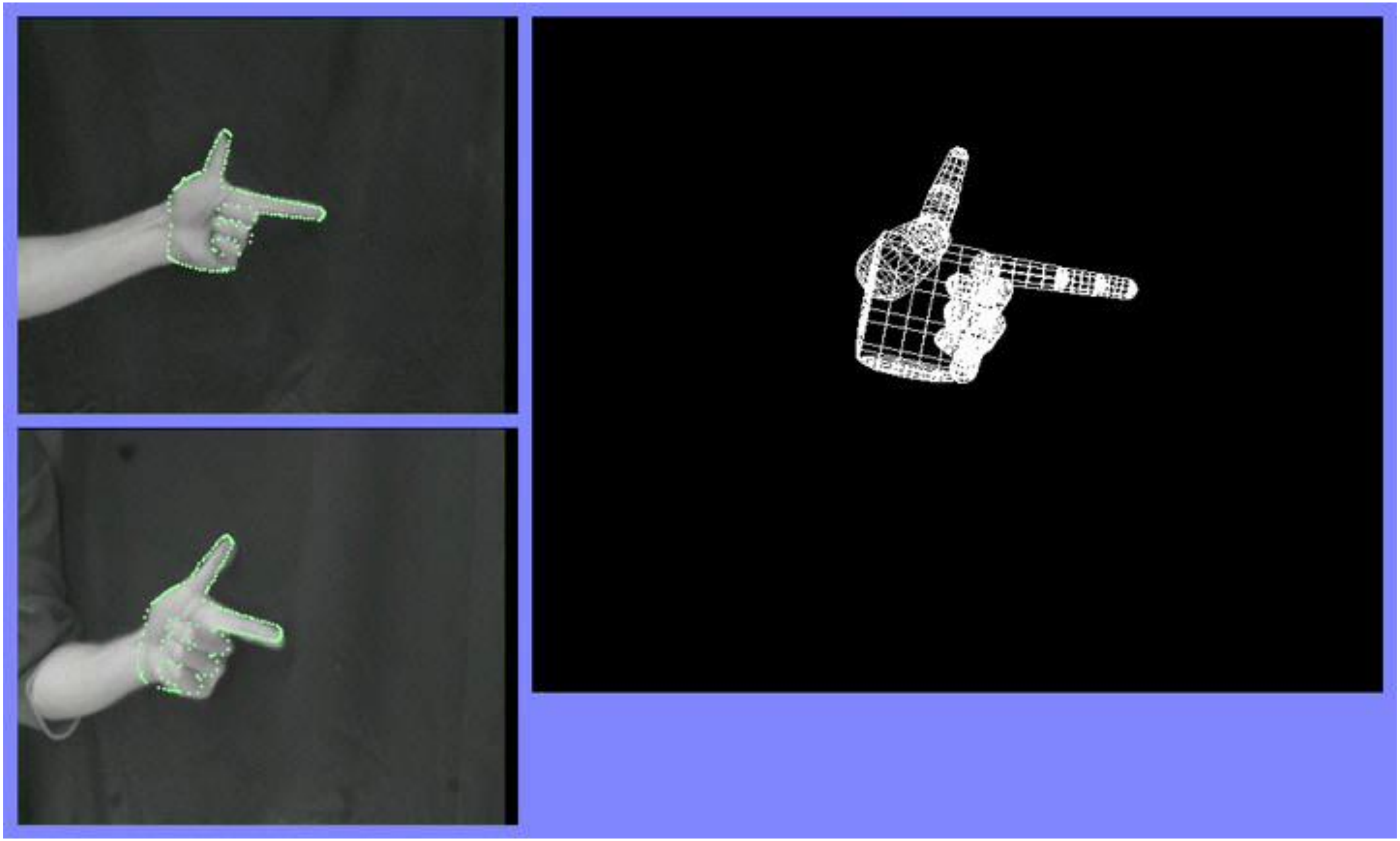


Stereo Tracking 1



Stereo Tracking 2



Conclusions & Future Work

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- Increase DOFs
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Thanks!