“Coupled Detection and Trajectory Estimation for Multi-Object Tracking”
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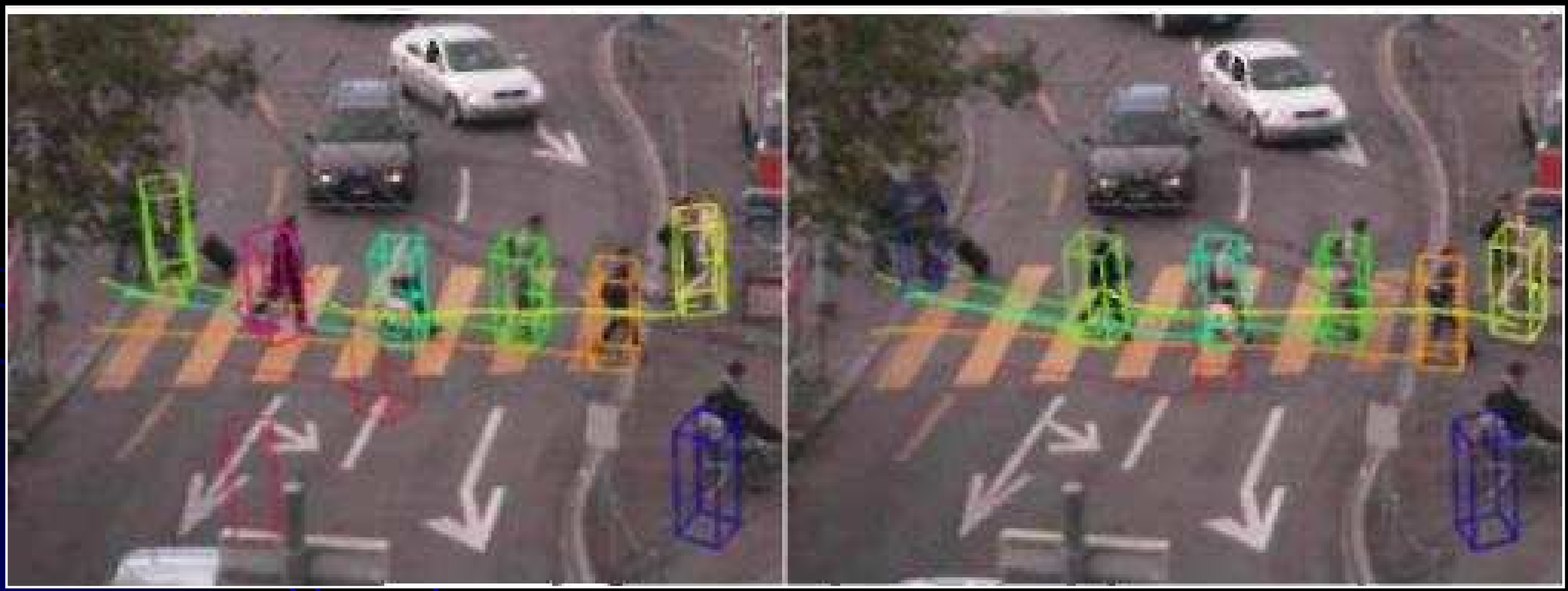
The Goal

The goal is multiply object tracking by detection with application on pedestrians.



Approach

Novel approach for multi-object tracking from monocular camera source, which considers object detection and space-time trajectory estimation as a coupled optimization problem.

Motivation

- Improve robustness by coupling object detection and tracking
  - Enhanced object model + feedback from trajectory estimation to detection
- Global optimization to resolve trajectory interactions
  - Incorporate real-world physical constraints

Experimental Results

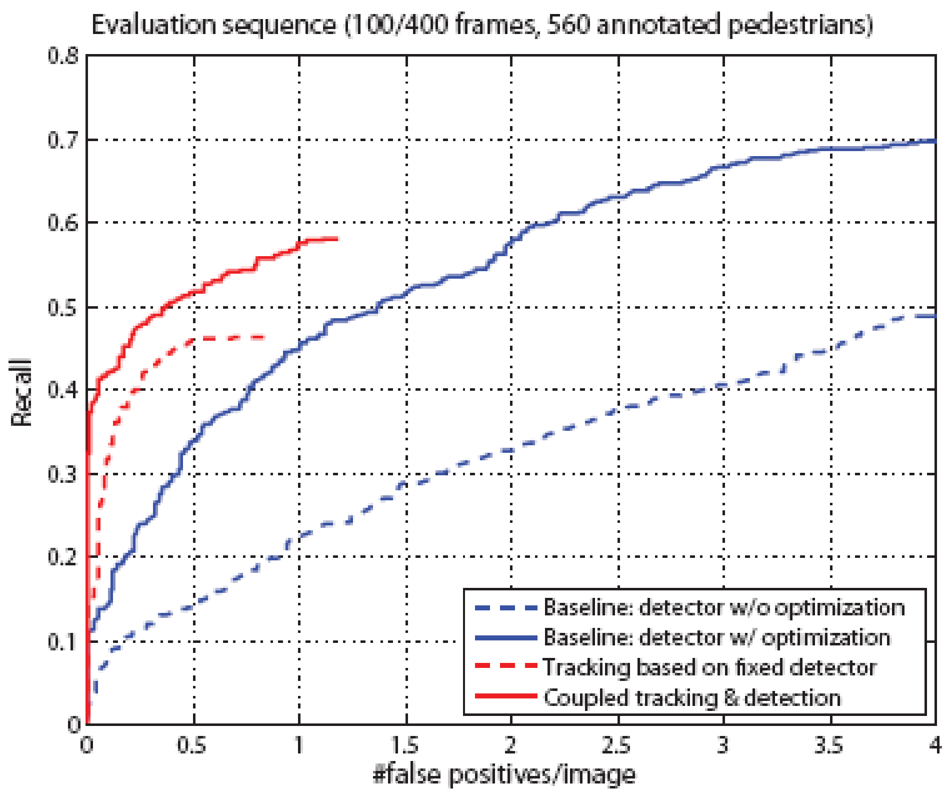


Figure 4. *Performance comparison of our coupled detection+tracking system compared to various baselines.*

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- Related Works
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  - Pedestrian Detection
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- Coupling between Detection and Trajectory Estimation
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Tracking

- Trajectory initialization
  - Background subtraction
  - Detection
  - Divine Intervention
- Target following
  - Mean – Shift tracking
  - Extended Kalman Filters
  - Particle Filters

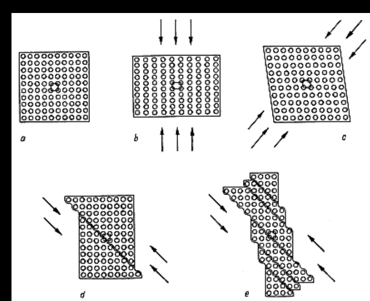
Common Challenges

- View point variation

- Illumination

- Scale

- Deformation



- Occlusion

Image adopted from Li Fei Fei

Intro of Detection into Tracking

A detector can be used for:

- To initialize targets or to re-initialize them in case of failure of tracking.
- The output of detector can be used directly as data source for tracking.

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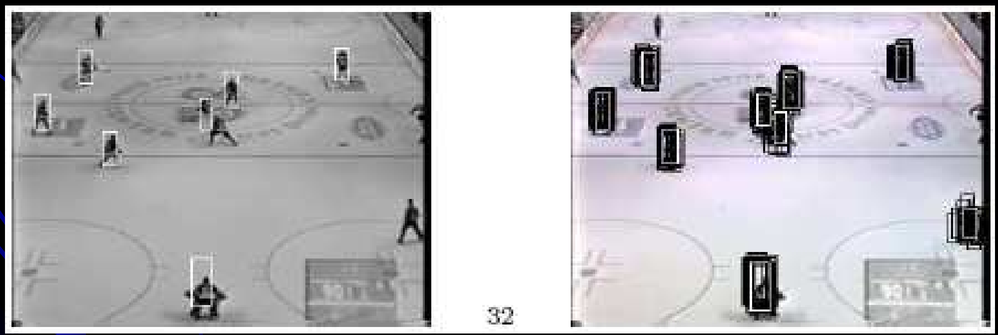
Related works

- K. Okuma, A. Taleghani, N. de Freitas, J. Little, and D. Lowe. A boosted particle filter: Multi-target detection and tracking. In ECCV'04.
  - Detection by Adaboost classifier.
  - Multi-target tracking by Mixture Particle Filters (variation of particle filter).



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Previous Works

- **Pedestrian detection** -

  B. Leibe, E. Seemann, and B. Schiele. Pedestrian detection in crowded scenes. In CVPR'05, 2005.

  B. Leibe, A. Leonardis, and B. Schiele. Robust Object Detection with Interleaved Categorization and Segmentation. In IJVC'05, revised in 2007.

  - B. Leibe and B. Schiele. Interleaved object categorization and seg-mentation. In BMVC'03
  - B. Leibe, A. Leonardis, B. Schiele, Combined Object Categorization and Segmentation with an Implicit Shape Model, ECCV'04 Workshop

- **Space-Time Trajectory Estimation** –

  B. Leibe, N. Cornelis, K. Cornelis, and L. Van Gool. Dynamic 3d scene analysis from a moving vehicle. In CVPR'07, 2007.

  (CVPR'07 Best Paper Award)

- **Optimization** –

  A. Leonardis, A. Gupta, and R. Bajcsy. Segmentation of range images as the search for geometric parametric models. IJCV, 14, 1995.

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Detection model

Constellation Model: Parts and Structure

Bastian Leibe, Aleˇs Leonardis, and Bernt Schiele

Robust Object Detection with Interleaved Categorization and Segmentation, in IJCV 2005.

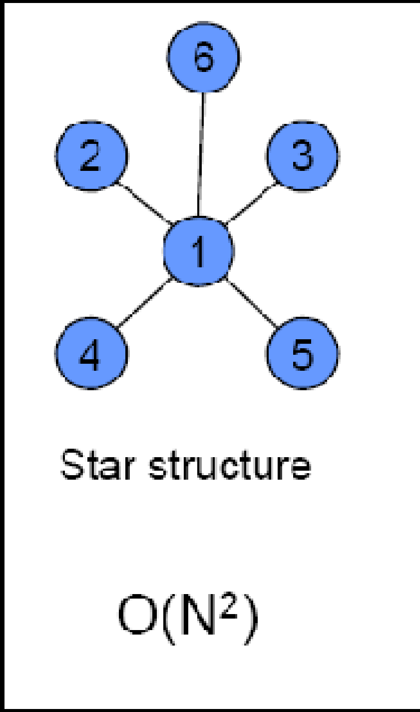


Image adopted from the course slides

Detection model - Training

Implicit Shape Model - *ISM*

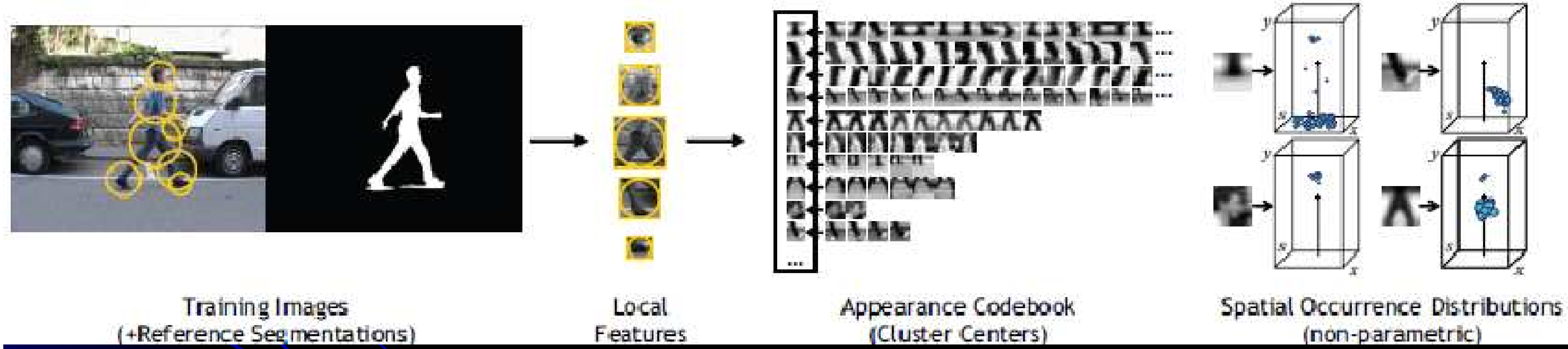
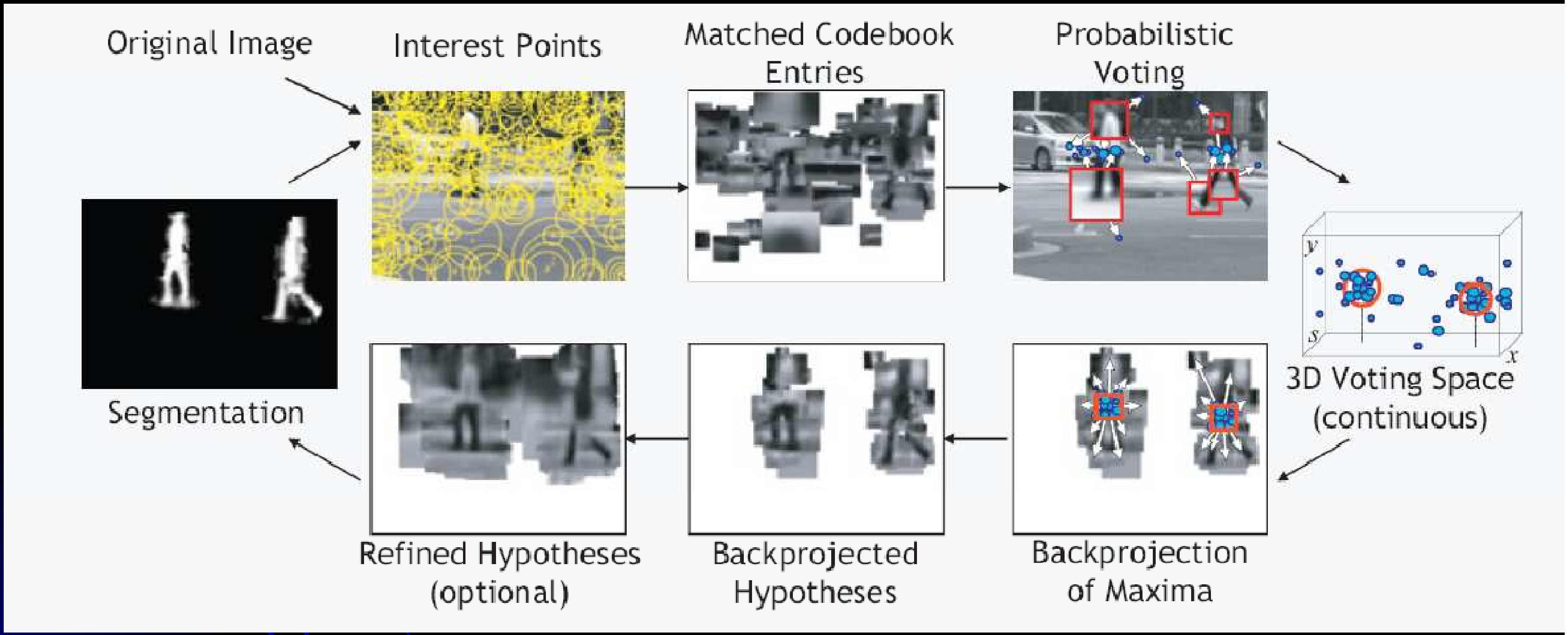


Image adopted from B.Leibe

Pedestrian detection – Hypothesis' Building Example



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MDL Hypothesis selection – in General

- **Problem**

  We have an over-complete set of hypothetical models. Who is the best?

- **Intuition**

  To prefer simple explanations to more complicated ones.

- **Solution**

  Minimum Description Length (MDL) (Rissanen 1984):

  the best encoding (model representation) is the one that minimizes the total description length for image, model, and error.

MDL Hypothesis selection - Solution

$$S_h \sim S_{data} - k_1 S_{model} - k_2 S_{error}$$

- S_{data} – number N of data points, which are explained by H .
- S_{model} denotes the cost of coding the model itself.
- S_{error} describes the cost for the error committed by the representation.
- κ_1, κ_2 are constants to weight the different factors

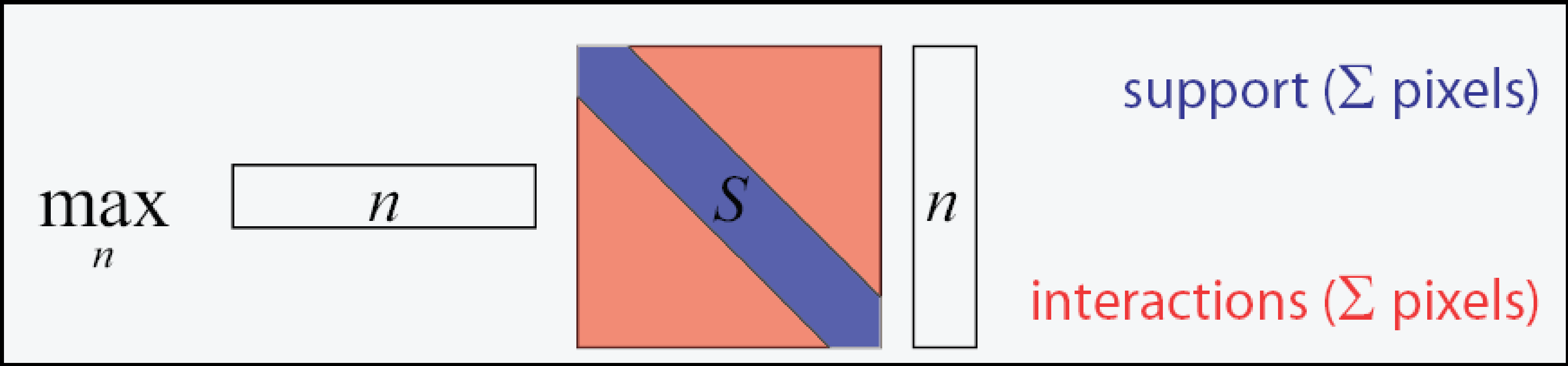
MDL Hypothesis selection – Solution of Quadratic Boolean Problem

- Optimal set of models :

$$\max\ n^T S n,\ S = \begin{bmatrix} s_{11} & . & . & s_{1N} \\ . & . & & . \\ . & & . & . \\ s_{N1} & . & . & s_{NN} \end{bmatrix}$$

  - $n = [n_1, n_2, \ldots, n_N]$ is a vector of indicator variables, such that n_i = 1 if hypothesis h_i is accepted, and n_i = 0 otherwise.
  - S is an interaction matrix.
  - diagonal elements s_{ii} are the merit terms, individual hypotheses.
  - the off-diagonal elements ($s_{ij} + s_{ji}$) express the interaction costs between two hypotheses h_i and h_j.

Implementation of MDL for Detection



Constraint:

Each pixel may at most belong to a single detection.

Image adopted from B.Leibe

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Space-Time Trajectory Estimation

- Trajectory growing
  - Collect detections in event cone
  - Evaluate under trajectory

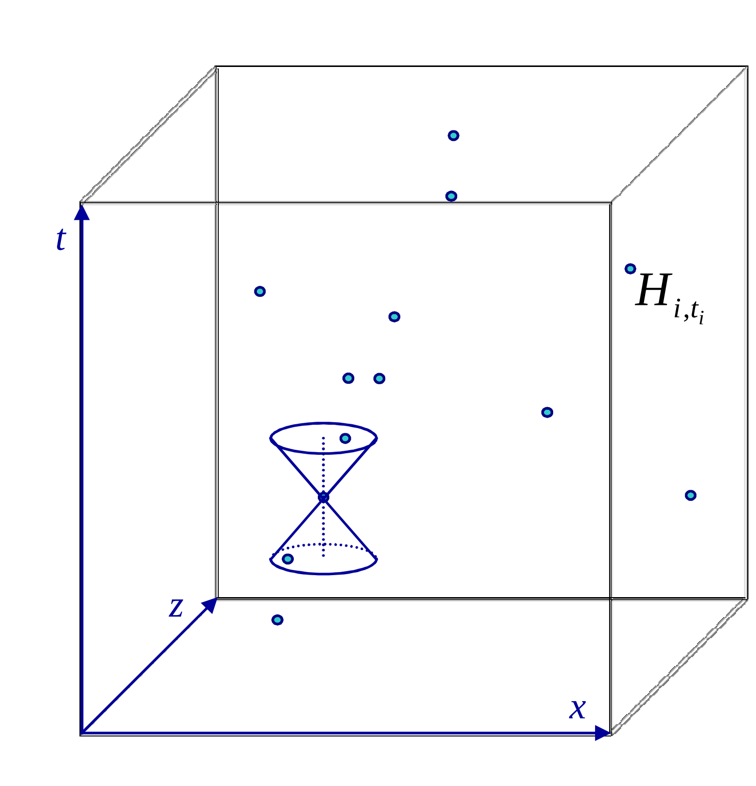
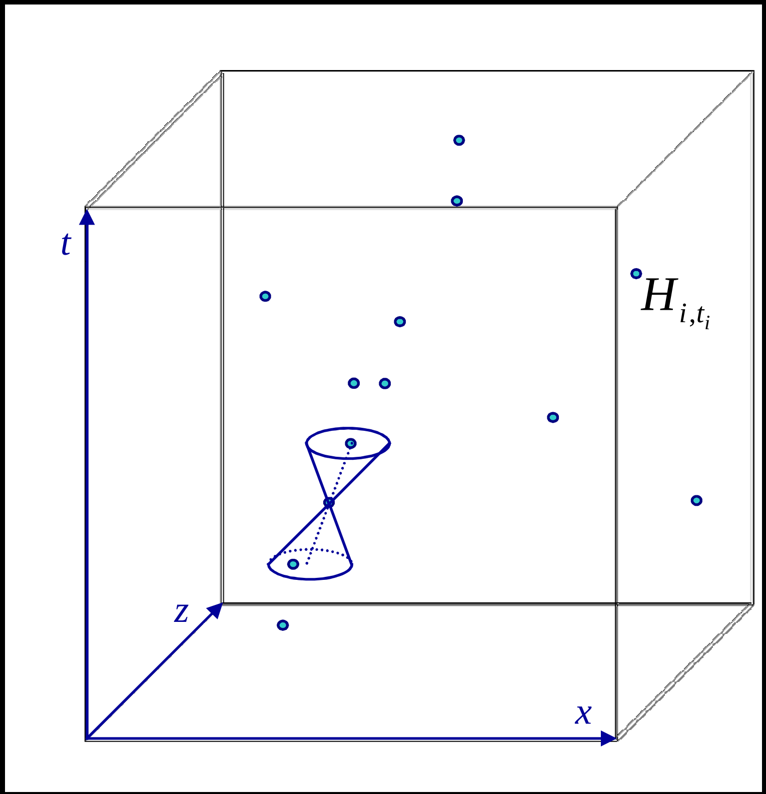


Image adopted from B.Leibe

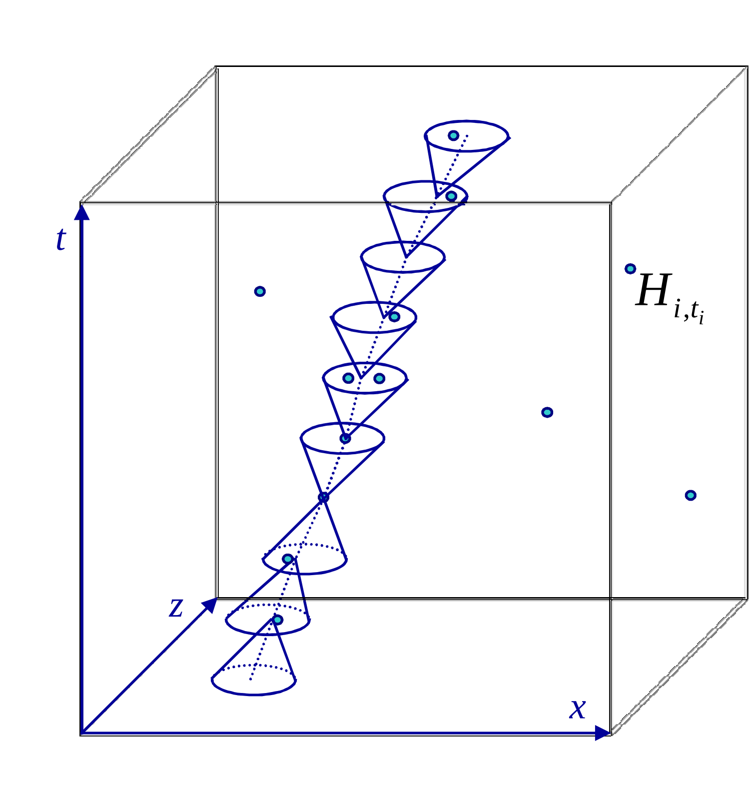
Space-Time Trajectory Estimation

- Trajectory growing
  - Collect detections in event cone
  - Evaluate under trajectory
  - Adapt trajectory



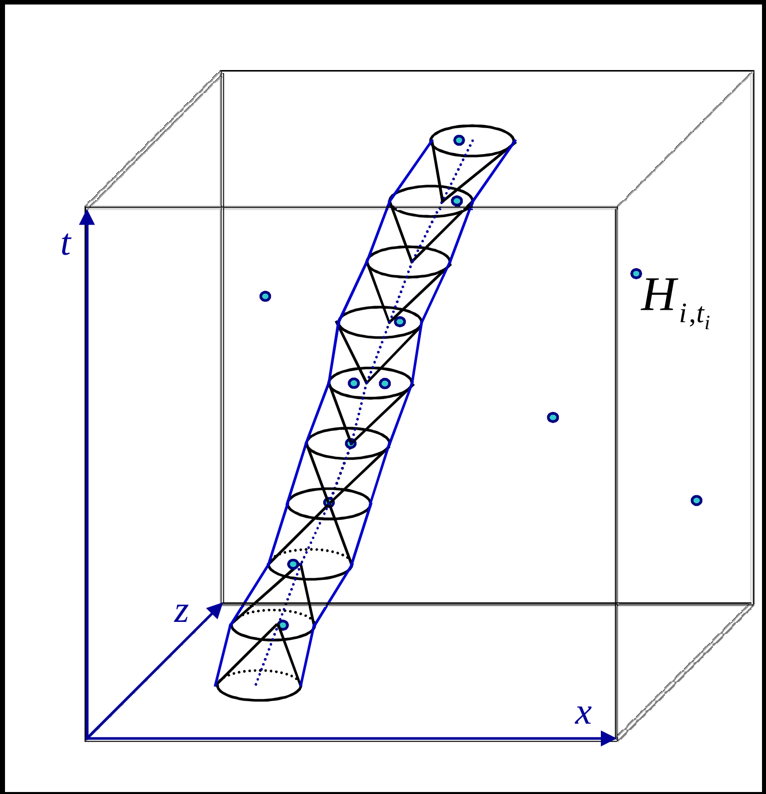
Space-Time Trajectory Estimation

- Trajectory growing
  - Collect detections in event cone
  - Evaluate under trajectory
  - Adapt trajectory
  - Iterate



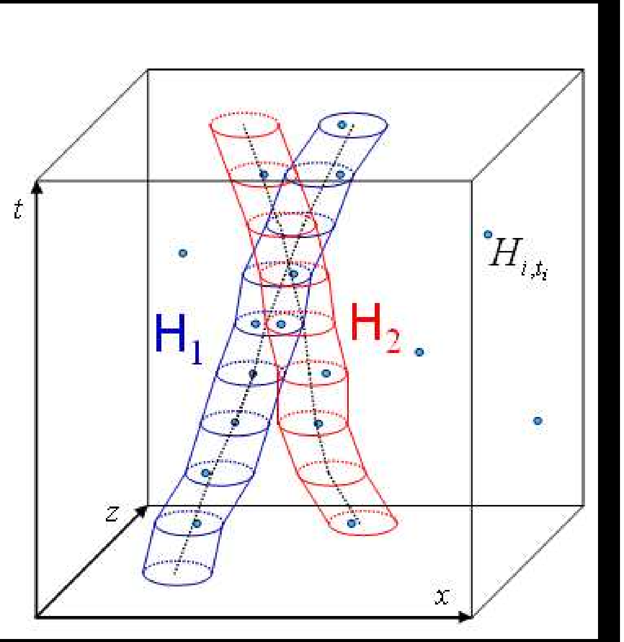
Space-Time Trajectory Estimation

- Trajectory growing
  - Collect detections in event cone
  - Evaluate under trajectory
  - Adapt trajectory
  - Iterate
  - Setting set as hypothesis



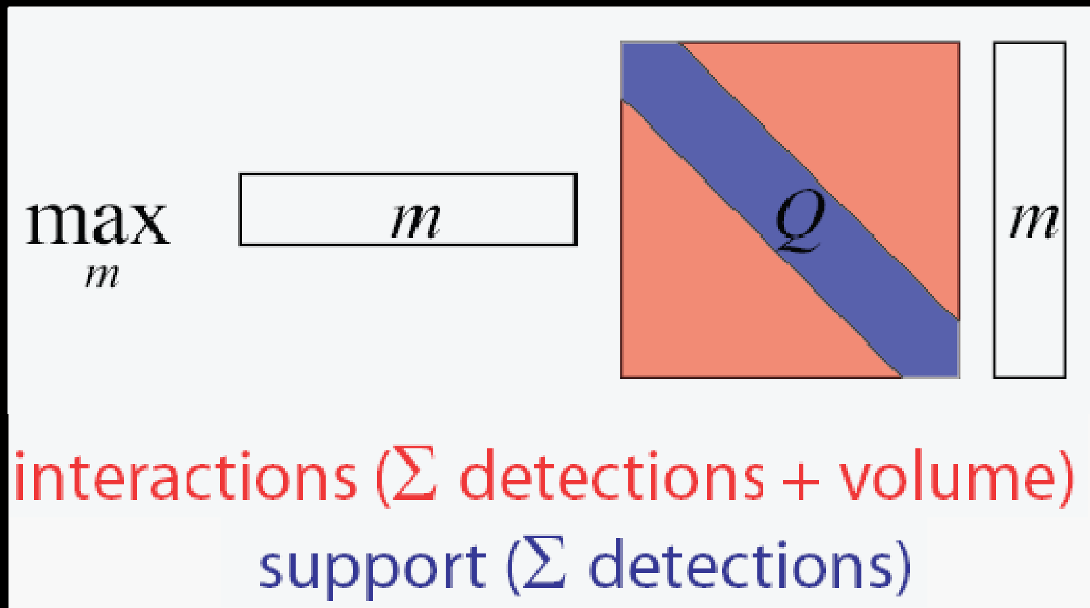
Implementation of MDL for Trajectory Estimation

- Trajectory selection
  - Start search from each detection.
  - Collect all resulting trajectories.
  - Perform hypothesis selection by solution of Quadratic Boolean Problem.



$$\max\ m^T Q m,\ Q = \begin{bmatrix} q_{11} & \cdot & \cdot & q_{1M} \\ \cdot & \cdot & & \cdot \\ \cdot & & \cdot & \cdot \\ q_{M1} & \cdot & \cdot & q_{MM} \end{bmatrix}$$

Implementation of MDL for Trajectory Estimation



Constraint:

- Each detection can at most belong to a single trajectory.
- No two trajectories may intersect at any point in time.

Image adopted from B.Leibe

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Coupling between Detection and Trajectory Estimation

- Basic idea:
  - Couple the two optimization problems into a single one.
  - Move support for current detections into coupling terms.
- Coupling terms:
  - Express support for certain trajectories from new detections.
  - Express spatial prior for detection locations from trajectories.

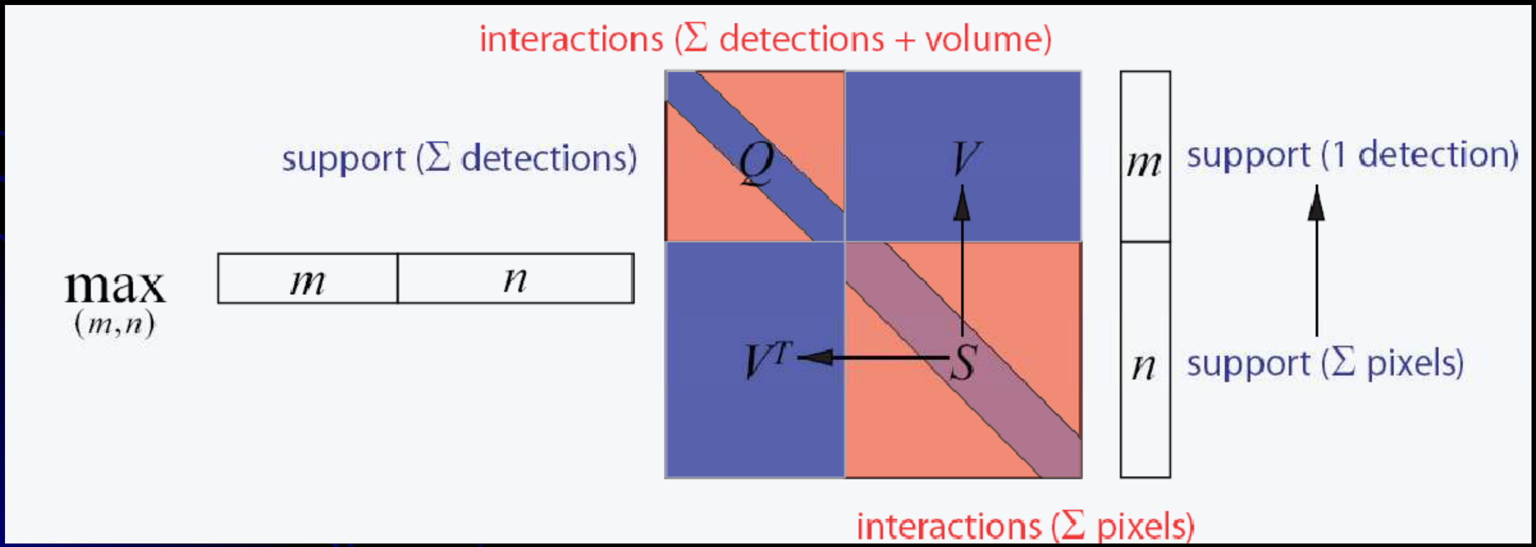

Image adopted from B.Leibe

Coupling between Detection and Trajectory Estimation

- The Problem: Asymmetric relationship
  - Trajectories rely on continuing detections for support.
  - But detections can exist without supporting trajectories (e.g. when a new object enters the scene).

Coupling between Detection and Trajectory Estimation

- Solution: Inserting of *virtual trajectories v* with interaction matrix *R.*
  - Enable detections to survive without contributing to an existing trajectory

$$\max_{(m,v,n)} \begin{bmatrix} m & v & n \end{bmatrix} \begin{bmatrix} \tilde{Q} & U & V \\ U^T & R & W \\ V^T & W^T & \tilde{S} \end{bmatrix} \begin{bmatrix} m \\ v \\ n \end{bmatrix}$$

  - W - Interaction between detections and virtual trajectories
  - V - Interaction between detections and real trajectories
  - U - Mutual exclusion between the two groups

Image adopted from B.Leibe

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Results and Discussion

- Videos:
  - Advantages
  - Limitations
- Conclusions

References

- B. Leibe, K. Schindler, L. Van Gool Coupled Detection and Trajectory Estimation for Multi-Object Tracking. In *ICCV'07*
- B. Leibe, A. Leonardis, and B. Schiele. Robust Object Detection with Interleaved Categorization and Segmentation. In IJVC'05, revised in 2007.
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Questions…