Kalman Enhanced Trailer Pose Estimation

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Motivation

• Articulated vehicles are commonly used in transportation scenarios
  – Complex kinematics
  – Difficult handling

• Problem: How to control (passive) trailers?

• State estimation for articulated vehicles
  → Where is the trailer?
Motivation

- Pose estimation between truck and trailer
- Support for one- and two-axle-trailers
- Assistance systems (e.g. parking support)
Existing 2-D Approach

yaw angles $\gamma$ and $\kappa$
Sensor Setup [BZW06]

- Camera facing backwards
- Three/one artificial marker(s)
Initial 2-D Solution [BZW06]

- Geometric model: Accumulation of affine transformations (translations and rotations)
- Triangle shaped pattern (increased accuracy)
- Plane constraint: vehicle is moving on a flat surface (assumption)
- Artificial optical markers (AprilTags)
  
- Active & passive component
Laboratory Model

scale 1:16
Reconstruction scheme [BZW06]
Generalization of the Approach

• On uneven ground, errors are caused by inadequate modelling
  ➔ Removal of the planarity assumption

How can we model the pose estimation problem in 3-D?
Angles in 3-D
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Camera/Marker-Setup
Extension to 3-D Pose Estimation

• Naive extension of the method results in a parametrization that requires:
  – 2 yaw angles $\gamma, \kappa$ (as in in 2-D)
  – 2 pitch angles $\theta_1, \theta_2$
  – 2 roll angles $\phi_1, \phi_2$

• We are only interested in 4 of these angles:
  $\gamma, \kappa, \theta = \theta_1 + \theta_2, \phi = \phi_1 + \phi_2$
Idea of our Approach

1. Estimate the 6-D pose (translation & rotation) of the trailer relative to the truck

2. Decompose the computed transformation into the four angles relevant for kinematics
Sample Input Images
Projection onto the Image Plane
Imaging Process

- Positions of marker features are described as:
  \[ P^i = \{ p^i_j | p^i_j = (x^i_j, y^i_j)^T \in \mathbb{R}^2, j \in \mathbb{N} \} \]
- The corresponding world coordinates are:
  \[ P^w = \{ p^w_j | p^w_j = (x^w_j, y^w_j, z^w_j)^T \in \mathbb{R}^3, j \in \mathbb{N} \} \]
- The projection \( \Pi \) is a mapping function:
  \[ P^c \rightarrow P^i \]
Inverting the Projection

• Estimation of the trailer’s pose
• Optimization problem:
  Minimize re-projection error
• Formulated as a non-linear optimization problem

• Goal: Rotation & translation from camera to trailer/model (fitting process)
Obvious: Point correspondences

- Takes 2-D/3-D point correspondences to estimate the camera‘s pose
- However: Point correspondence solving (like solvePNP) re-estimates the vehicle in every frame, ignoring temporal coherence and motion models of the truck/trailer system in the process
- This is sub-optimal and leads to non-robust results
Solution: Extended Kalman Filter

• Allows the estimation of the state of a
dynamic system based on noisy measurements

• System state:
\[ x = \left( s^T, q^T, v^T, \omega^T \right)^T \in \mathbb{R}^{13} \]

• Motion model: linear
Kalman Motion Model

\[
f(x_{t+1}) = \begin{pmatrix}
    s_t + \Delta t \cdot v_t \\
    q_t \cdot Q(\Delta t \cdot \omega_t) \\
    v_t \\
    \omega_t
\end{pmatrix} + \xi
\]
Solution: Extended Kalman-Filter

- Measurement model:
  \[ h_i(x) = \Pi(T_{w\rightarrow c}(p_i^w)) + \epsilon \]

- The measurement model computes the reprojection of the \( i \)-th marker corner point

- \( T_{w\rightarrow c} \) transforms a point from world- to camera-coordinates

- \( \Pi \) represents the imaging process

- Extension to work on manifolds
Angle Decomposition

• The Kalman filter yields a pose estimate consisting of a translation \( t \in \mathbb{R}^3 \) and a rotation \( R \in \mathbb{R}^{3\times3} \)

• The pitch and roll states \( \theta \) and \( \phi \) can easily be extracted by decomposing \( R \) into three Euler angles

• After a ground projection, the yaw angles \( \gamma \) and \( \gamma \) using methods mathematically derived in previous work [FZP14]
Evaluation

- Required: An instrumented vehicle that is able to precisely measure the required (two-axle) trailer state
- Problem: No reference system available
- „Solution“: Ray-traced computer generated rendering of the scene
Virtual Evaluation

- Idea: Simulation
- Easy regression and component analysis
- Different depth of simulation: single component errors
- Great scalability
- *Software-in-the-loop*
Evaluation Setup

- Dimensions taken from laboratory model
- Simulated test track using continuous functions
- Camera resolution 640x480
- Frame rate 25 Hz
- Test length 80 seconds/2000 frames
- Artificial noise to simulate image disturbances
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Track configuration

\[ u_\gamma(t) = 30 \cdot \sin \left(\frac{t}{6}\right) \]

\[ u_\kappa(t) = 15 \cdot \cos \left(\frac{t}{6}\right) \]

\[ u_\theta(t) = 80 \cdot \left( G_{25,2}(t) - G_{25,4}(t) \right) \]

\[ u_\phi(t) = -40 \cdot \left( G_{60,2}(t) - G_{60,6}(t) \right) \]

\[ G_{\mu,\sigma}(t) = \left( \sigma \sqrt{2\pi} \right)^{-1} \cdot \exp \left( -0.5 \cdot \left( \frac{t-\mu}{\sigma} \right)^2 \right) \]
Evaluation results
Evaluation results

avg $|\epsilon_\beta|$ [Deg]

Var $|\epsilon_\beta|$ [Deg]

- 3-D with Kalman filter
- 3-D [FZP14]
- 2-D [BZW06], [FEKZ14]

evaluation with noise
evaluation without noise
Conclusion

• The Kalman filter extension allows to make use of both the temporal coherence in the image sequence as well as the motion model of the truck/trailer system.

• The 3-D Kalman extension is superior to both the 3-D and the 2-D approach.

• The system supplies data to a kinematic-based driver assistance system.
Questions?

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