# Visual Odometry for Intelligent Vehicles

## Grupo Temático de Visión por Computador
## XXXV Jornadas de Automática


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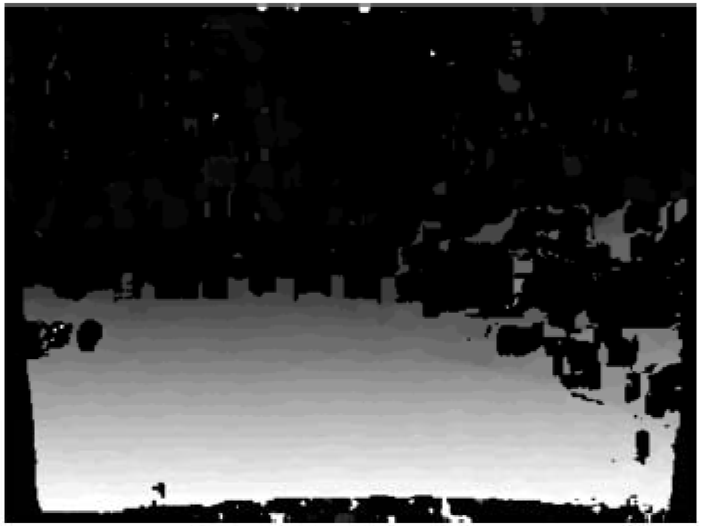
# Visual Odometry for Intelligent Vehicles

- The movement of the vehicle provides useful information for different applications --> visual odometry for intelligent vehicles
- This information can be known by means of a GPS, but there are some areas in urban environments where the signal is not available, as tunnels or streets with high buildings
- Visual odometry --> is based on a stereo-vision system where the feature road points are tracked frame to frame in order to estimate the movement of the vehicle, avoiding outliers from dynamic obstacles.
- The road profile is used to obtain the world coordinates of the feature points as a unique function of its left image coordinates. For these reasons it is only necessary to search feature points in the lower third of the left images.

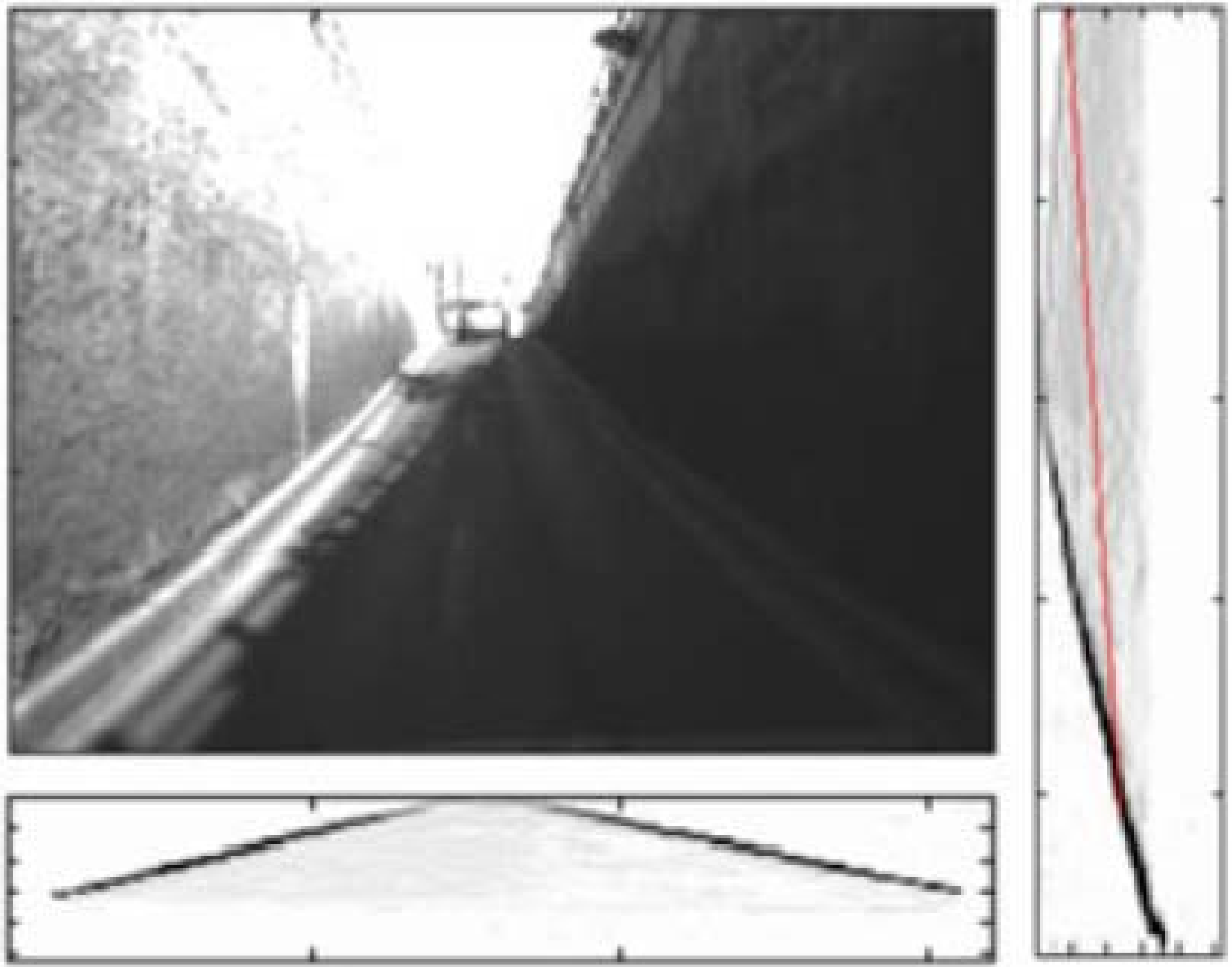
(a) Left image

(b) Disparity map

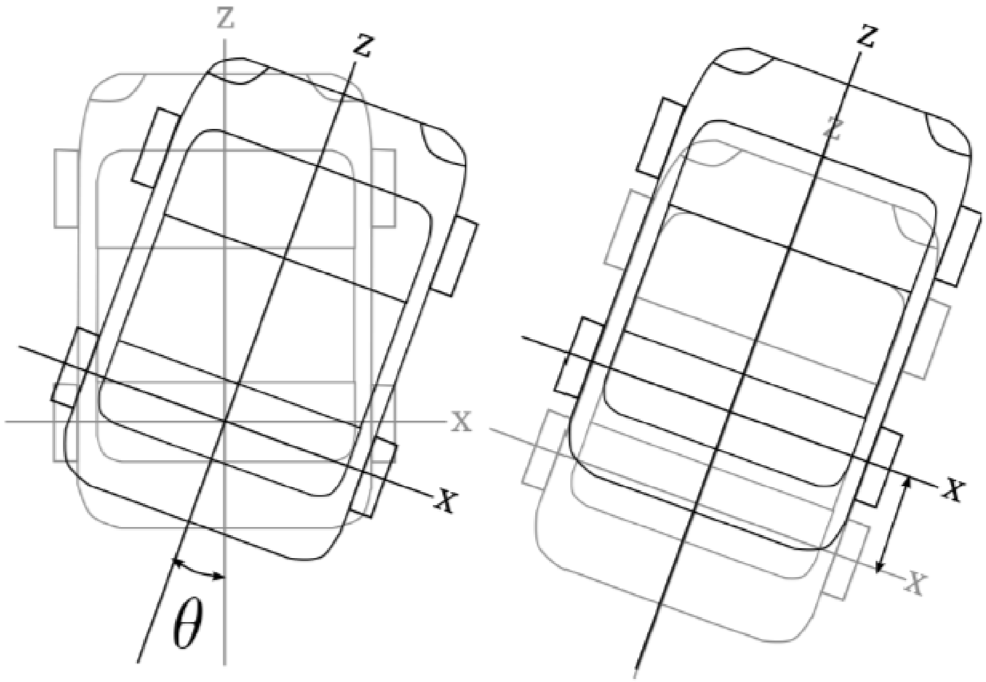
(c) Obstacles map



(d) Free map



# Visual Odometry for Intelligent Vehicles




Scheme of the movement of the vehicle. On the left, rotation stage. On the right, translation stage.



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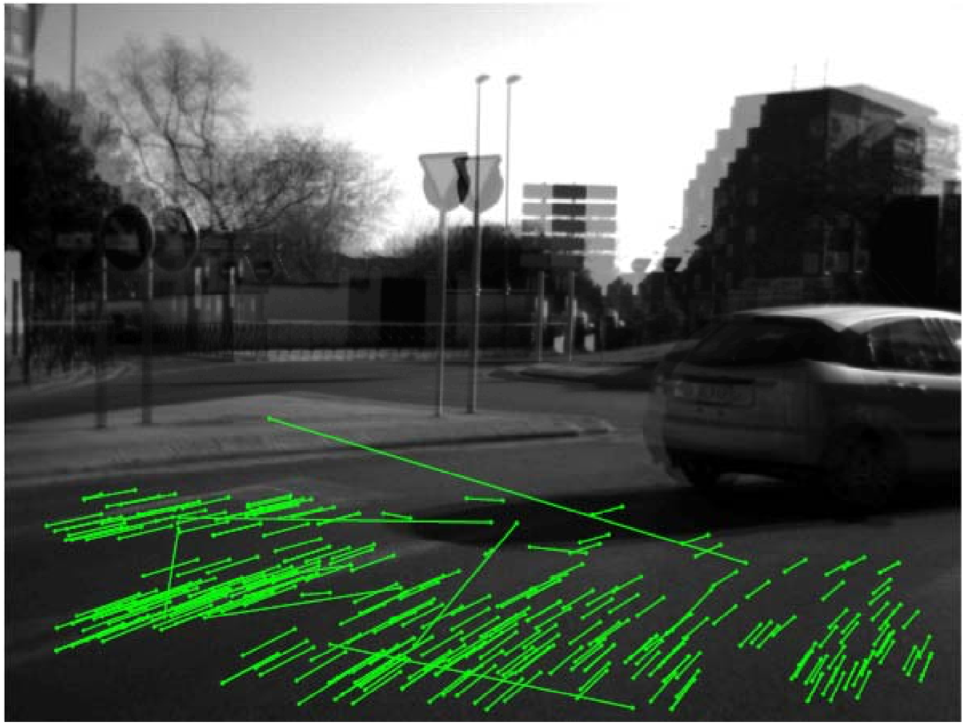
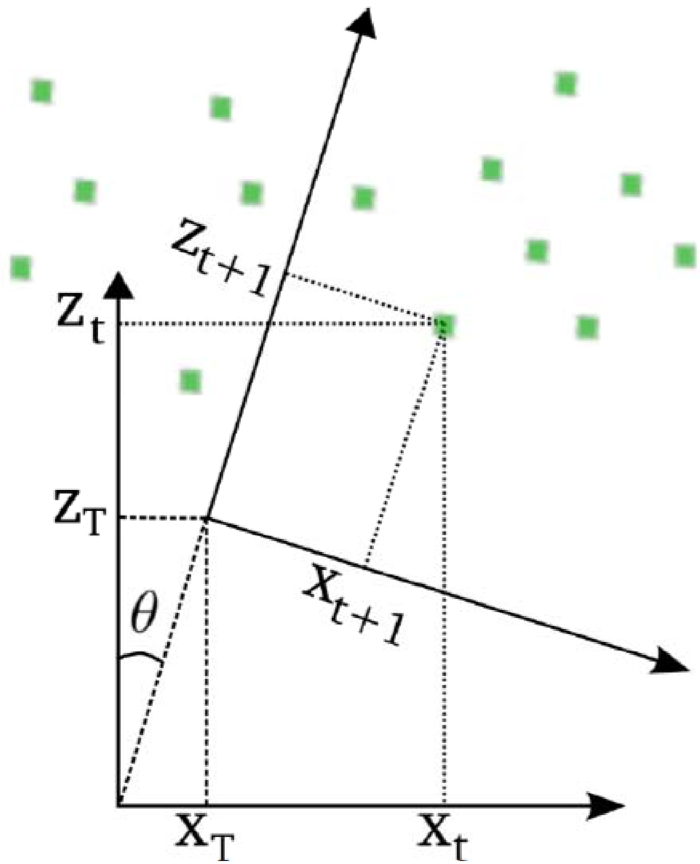


(a)




(b)



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# Extrinsic Parameter Self-Calibration and Nonlinear Filtering for In-Vehicle Stereo Vision Systems at Urban Environments

- **Visual odometry improvements -->** the continuous self-calibration of extrinsic parameters of a stereo vision system for safe visual odometry applications in vehicles at urban environments.
- The calibration method determines the extrinsic parameters of a stereo vision system based on knowing the geometry of the ground in front of the cameras.
- The slight changes of the road profile cause variations in the extrinsic parameters of stereo rig that are necessary to filter and maintain between tolerance values.
- Height, pitch and roll parameters are filtered, to eliminate pose outliers of the stereo rig that appear when a vehicle is maneuvering.

# Extrinsic Parameter Self-Calibration and Nonlinear Filtering for In-Vehicle Stereo Vision Systems at Urban Environments

- The reliable approach at urban environment is firstly composed of the calculation of the road profile slope, the theoretical horizon, and the slope of the straight line in the free map, to obtain the height (h), the pitch angle (θ), and the roll angle (ρ) of the vehicle through whole trajectory.
- Secondly, the nonlinear filtering is applied using Unscented Kalman Filter to improve the estimation of height, pitch and roll parameters.

This approach has been developed and tested initially in our Intelligent Vehicle

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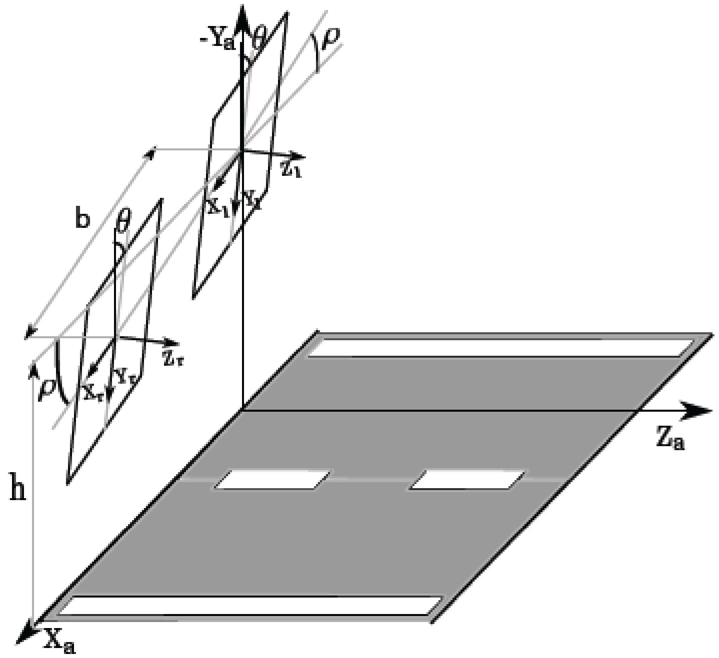
# 1. Public data set to test and compare our method

- In-vehicle stereo rig images have been extracted from the visual odometry benchmark of Karlsruhe Institute of Technology (22 stereo sequences).
- We have selected the sequence 7 to test our self-calibration method. The sequence 7 is captured by 2 Grayscale cameras, and is composed with 1100 stereo rig images, that have been acquired when a Volkswagen Passat B6 performs a trajectory of approximately 0.7 km in a residential environment.
- Cameras are mounted approximately level with the ground plane and are triggered at 10 frames per second. Images have a size of 1226 x 370 pixels.
- We can compare the result of our continuous self-calibration of extrinsic parameters with additional information of this dataset, which contains height, pitch and roll measurements of the vehicle provided by Inertial Navigation System (GPS/IMU OXTS RT 3003).

# 2. Self-calibration of extrinsic parameters

- The disparity map and the u-v disparity are used in order to distinguish between image points belonging to the ground and the ones which belong to the obstacles.
- Two self-calibration methods have been selected for obtaining the geometry of the road ground in front of the in-vehicle stereo rig, the first one uses Hough Transform (HT) and the second one RANSAC.




- These self-calibration methods allow both calculations of the road profile slope ($C_r$), the theoretical horizon ($v_{\Delta 0}$), and the slope of the straight line in the free map ($C$), that lead to both estimations of the height ($h$), pitch (θ) and roll ($\rho$) for each frame of stereo rig and considering constant in-vehicle yaw deviation.

## 2. Self-calibration of extrinsic parameters

- The aim is to obtain the homogeneous image coordinates (*$u_i$·S, v·S, S, 1*) of a world point P = (*X, Y, Z, 1*)

$$\begin{bmatrix} u_i S \\ vS \\ S \\ 1 \end{bmatrix} = M_{proj} \cdot M_{Translx} \cdot M_{Rotx} \cdot M_{Rotz} \cdot M_{Transly} \cdot \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

- The movement of the vehicle implies angle variations of the in-vehicle stereo rig related to ground reference, so:
  - Pitch angle rotates around axis X (perpendicular to moving of vehicle)
  - Roll angle rotates around axis Z (direction of vehicle moving forward)
  - Height oscillates around its constant value when vehicle is driving

- The disparity expression (Δ) for each world point P = (*X, Y, Z, 1*) →

$$\left\{ \begin{aligned} \Delta &= u_l - u_r = \frac{u_l S - u_r S}{S} = \\ &= \frac{\alpha \cdot b}{Z\cos\theta + (Y+h)\cos\rho\sin\theta + X\sin\rho\sin\theta} \end{aligned} \right.$$

- The value of *S* is a function of the world coordinates (*X, Y, Z*). So, in order to avoid the use of the world coordinates, S can be expressed as S = α·b/Δ

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# 2. Self-calibration of extrinsic parameters

$$\begin{bmatrix}X\\Y\\Z\\1\end{bmatrix} = M^{-1}_{Transly}\cdot M^{-1}_{Rotz}\cdot M^{-1}_{Rotx}\cdot M^{-1}_{Translx}\cdot M^{-1}_{proj}\cdot \begin{bmatrix} u\dfrac{\alpha b}{\Delta}\\ v\dfrac{\alpha b}{\Delta}\\ \dfrac{\alpha b}{\Delta}\\ 1\end{bmatrix}$$

Y=0

$$Y = -h + \frac{(v-v_0)b\cos\rho\cos\theta}{\Delta} - \frac{(u-u_0)b\sin\rho}{\Delta} + \frac{\alpha b\cos\rho\sin\theta}{\Delta} = 0 \Rightarrow$$

$$\Rightarrow (v-v_0) = \frac{\tan\rho}{\cos\theta}(u-u_0) - \alpha\tan\theta + \left(\frac{h}{b\cos\rho\cos\theta}\right)\Delta$$

We use the free map, the road ground part without obstacles of the disparity map. The straight line is $v = C\cdot u + d_{\Delta}$, where $C$ is the slope of the free map straight line.

$$C = \frac{\tan\rho}{\cos\theta} \Rightarrow \rho = \arctan\left(C\cdot\cos\theta\right)$$

**Roll angle**

In urban environments, $\cos\rho \approx 1$ and $\sin\rho \approx 0$

$$v = \frac{h}{b\cos\theta}\Delta + v_0 - \alpha\tan\theta$$

The theoretical horizon ($v_{\Delta 0}$) is the value of $v$ when the disparity is $\Delta = 0$

$$\theta = \arctan\left(\frac{v_0 - v_{\Delta 0}}{\alpha}\right)$$

**Pitch angle**

Straight line, named road profile $v = C_r\cdot\Delta + v_{\Delta 0}$

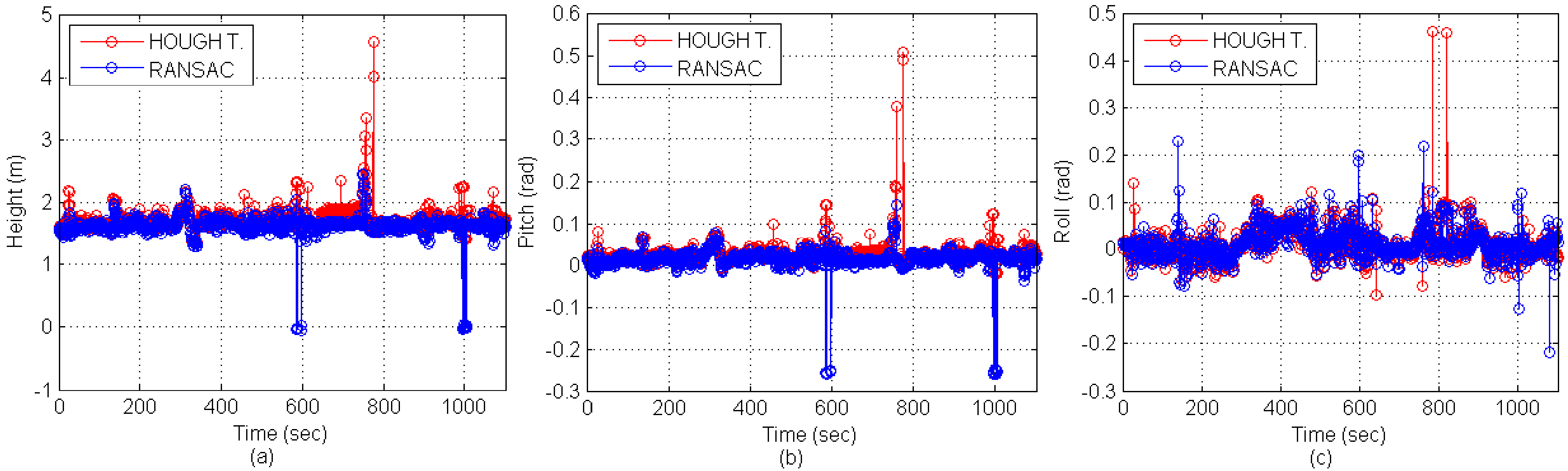
$$h = C_r\cdot b\cdot\cos\theta$$

**Height**

# 2. Self-calibration of extrinsic parameters

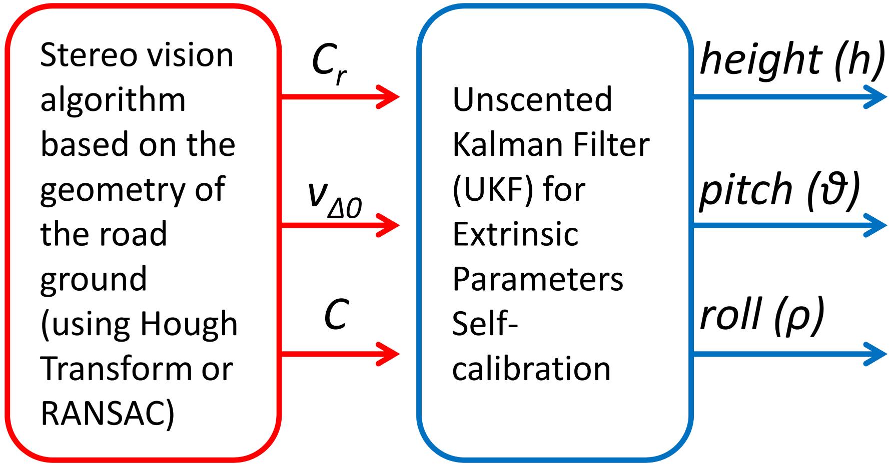
- The continuous estimation of the road profile slope ($C_r$), the theoretical horizon ($v_{\Delta 0}$), and the slope of the straight line in the free map ($C$) using Hough Transform or RANSAC allow:

  The continuous estimation of the height ($h$) (Fig. 2(a)), the pitch angle (θ) (Fig. 2(b)), and the roll angle ($\rho$) (Fig. 2(c)) of the vehicle through whole trajectory.



# 3. Nonlinear method for filtering extrinsic parameters

- Unscented Kalman Filter (UKF) estimates the state of discrete-time dynamic system, which is composed by observable variables (the road profile slope ($C_r$), the theoretical horizon ($v_{\Delta 0}$), and the slope of the straight line in the free map ($C$)), and hidden variables (the height ($h$), pitch ($\vartheta$) and roll ($\rho$)).




Block diagram with UKF measurement model

The state vector for UKF filtering of height, pitch and roll

$$x_k = \left(h_k \quad \theta_k \quad \rho_k\right)^T$$

# 3. Nonlinear method for filtering extrinsic parameters

- The prediction process --> $\hat{x}_{k+1} = f(\hat{x}_k, v_k)$

  but we unknown the complex dynamic model of vehicle that has been used in experiments, so we simplify the prediction process considering previous state estimation and $v_k \sim N(0, R_v)$ represents a process noise distributed as a Gaussian with mean zero and covariance matrix $R_v$ -->

$$R_v = \begin{bmatrix} 0.01 & 0 & 0 \\ 0 & 1 \cdot 10^{-8} & 0 \\ 0 & 0 & 0.01 \end{bmatrix}$$

  where covariance values are small due to urban environment, since we don't expect large changes in process update. So, slightly changes are considered around former estimated state in process update.

- The measurement model --> $\hat{y}_k = h(\hat{x}_k, w_k)$

  The observations of the true state are transformed by the measurement model, and perturbed by a random sample of the observation noise $w_k \sim N(0, R_w)$

$$R_w = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

  Covariance values are higher to eliminate the outliers of the measurements

# 3. Nonlinear method for filtering extrinsic parameters

- UKF algorithm allows continuously the utilization of a nonlinear measurement model to filter outliers of extrinsic parameters.
- The UKF filter estimates height, pitch and roll nonlinear signals, which are perturbed by outliers that come from road geometry estimation of the ground in front of the vehicle: (i) the road profile slope ($C_r$), (ii) the theoretical horizon ($v_{\Delta 0}$), and (iii) the slope of the straight line in the free map ($C$).

$$\left\{ \begin{array}{l} \theta = \arctan\left(\dfrac{v_0 - v_{\Delta 0}}{\alpha}\right) \\ h = C_r \cdot b \cdot \cos\theta \\ \rho = \arctan(C \cdot \cos\theta) \end{array} \right\}$$

**Extrinsic parameters**

$b$ = 0.54 m, $v_0$ = 183.1104 pixels, and $\alpha$ = 707.0912 pixels

$$\left\{ \begin{array}{l} v_{\Delta 0} = 183.1104 - (707.0912 \cdot \tan\theta) \\ C_r = \dfrac{h}{0.54\cos\theta} \\ C = \dfrac{\tan\rho}{\cos\theta} \end{array} \right\}$$

**Measurement model**



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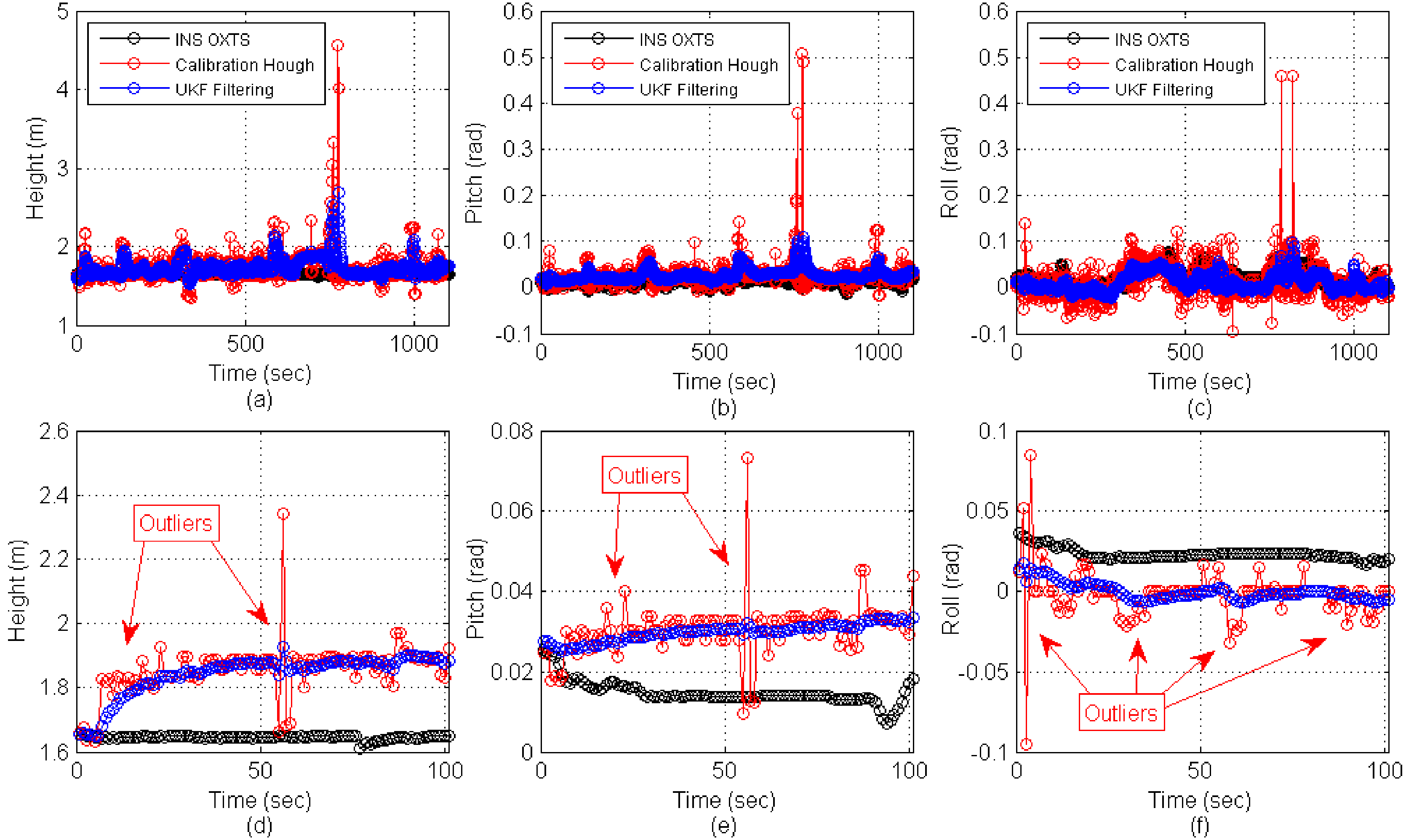
## **4. Results:** (a) *h*, (b) θ, (c) *ρ* UKF filtering through whole sequence of 1100 frames using continuous estimations of $C_r$, $v_{\Delta 0}$, *C* parameters by Hough Transform method, and (d) *h*, (e) θ, (f) *ρ* details from 100 frames



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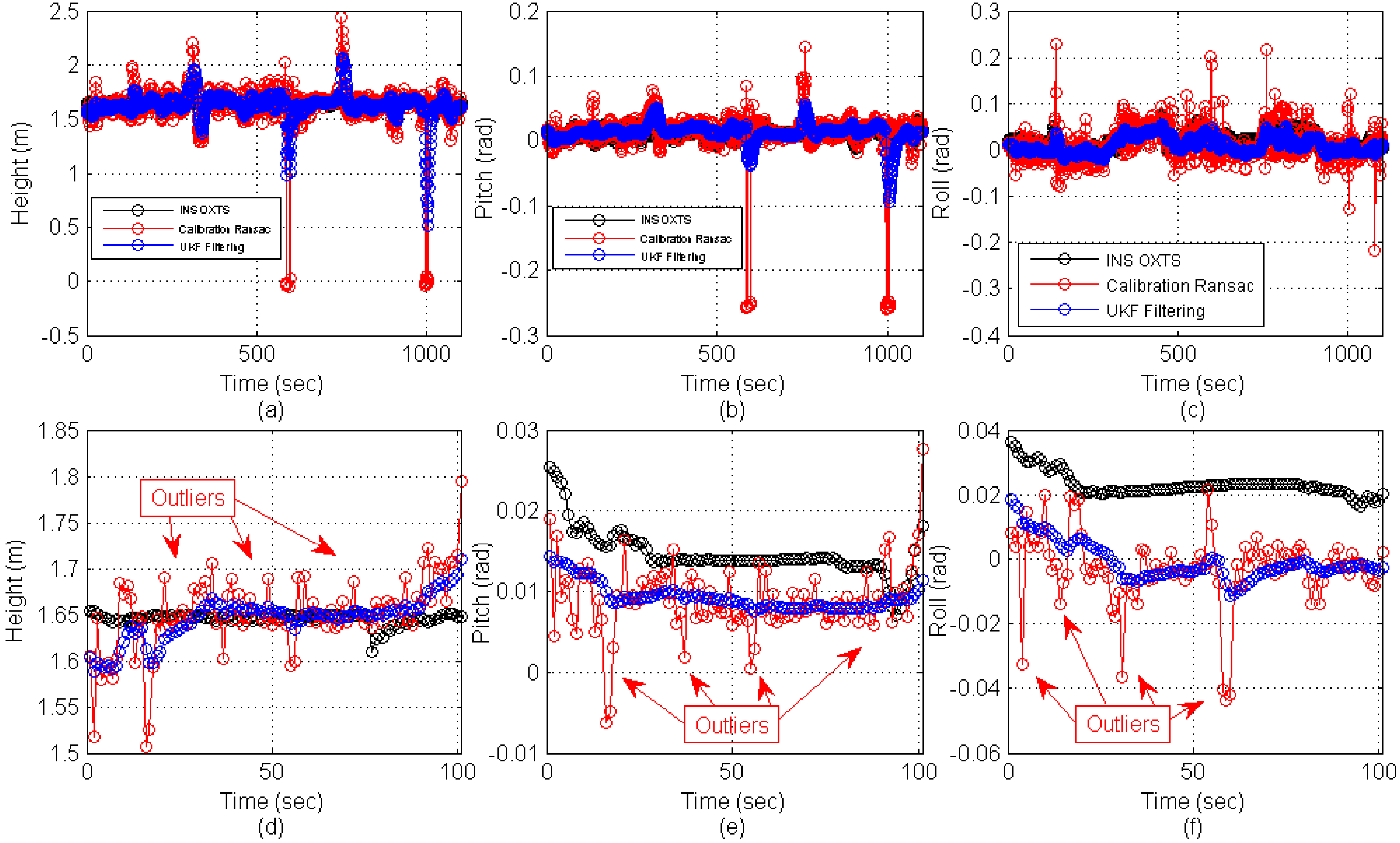
# 4. Results: (a) $h$, (b) θ, (c) $\rho$ UKF filtering through whole sequence of 1100 frames using continuous estimations of $C_r$, $v_{\Delta 0}$, $C$ parameters by RANSAC method, and (d) $h$, (e) θ, (f) $\rho$ details from 100 frames



# 5. Conclusions

- Extrinsic parameters have been estimated continuously for the self-calibration of in-vehicle stereo rig, as an essential task for Intelligent Transportation Systems in urban environments (such as visual odometry).
- Extrinsic parameter results have demonstrated the feasibility of the geometry estimation of the ground in front of the vehicle using RANSAC method.
- The accuracy improvement of the height, pitch angle and roll angle measurements, by means of the elimination of outliers, have been accomplished using nonlinear UKF filtering based on nonlinear measurement model.
- These results have been validated through time-domain comparison with high-accuracy measurements, which have been provided by an in-vehicle INS device.


# Thanks for your attention