Online Performance Assessment of Multi-Sensor Kalman Filters Based on Subjective Logic

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Online Performance Assessment of Multi-Sensor Kalman Filters Based on Subjective Logic

26th International Conference on Information Fusion – June 30th, 2023

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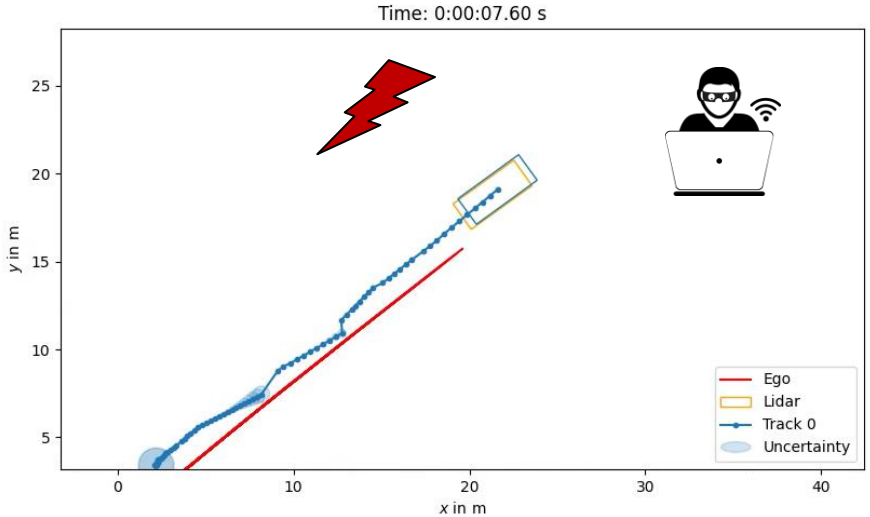
Institute of Measurement, Control, and Microtechnology

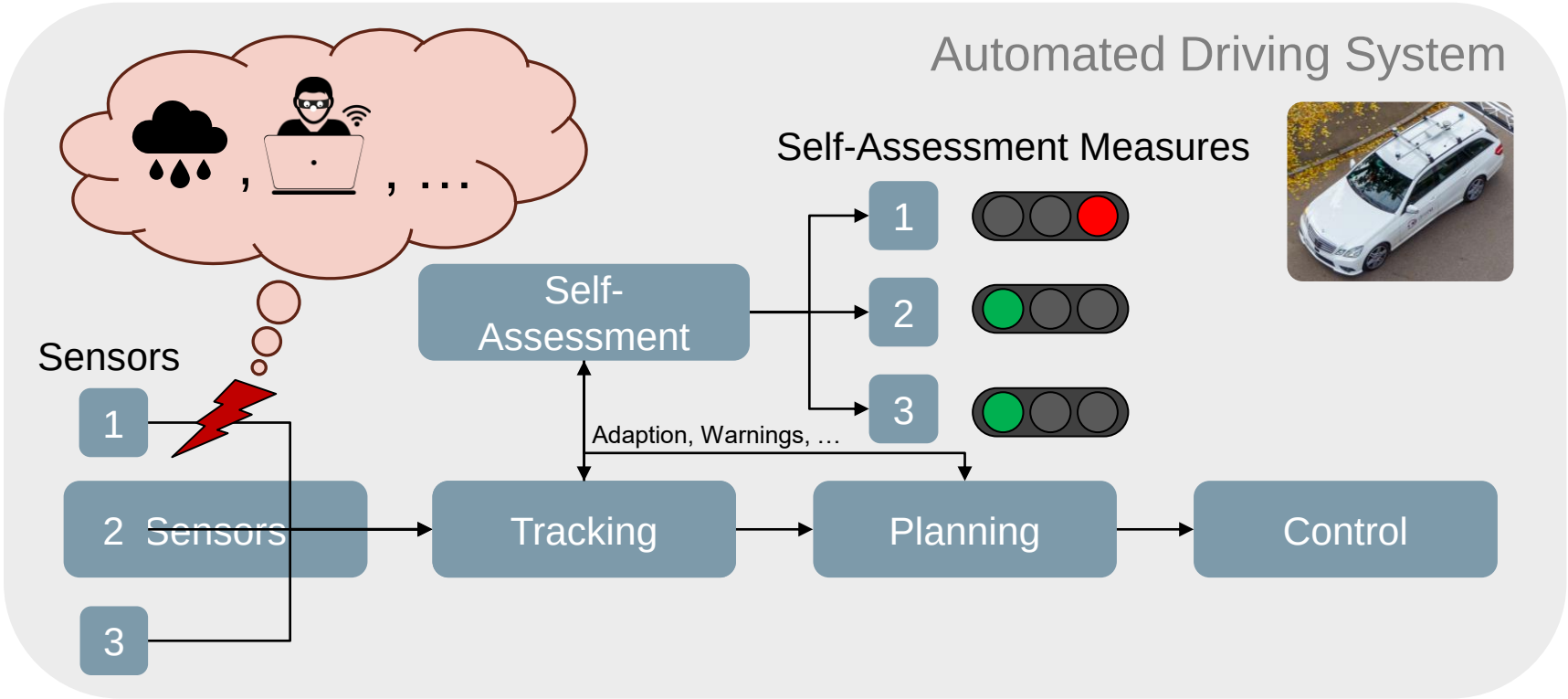
Motivation

Tracking:



Camera image:

Motivation – Self-Assessment in Tracking Algorithms



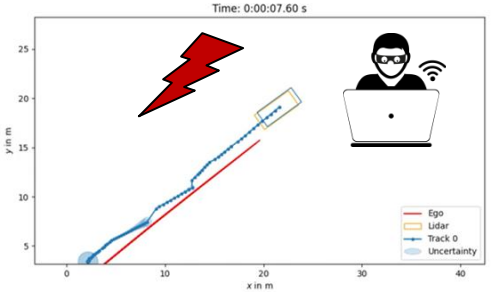
Motivation – Objective

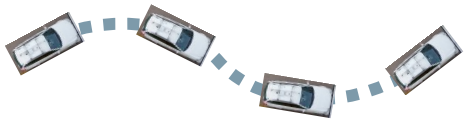
- External disturbances and manipulations of the sensors
  → Affecting the tracking performance

- Self-assessment in tracking should detect such disturbances
  - Issue appropriate warnings
  - Make adaptions

→ Development of a self-assessment module in tracking

Tracking:

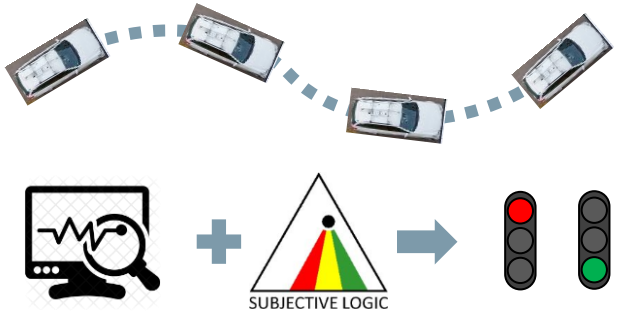




Tracking

Self-assessment

Related Work
Self-Assessment (SA) in Kalman Filtering



Classical approach for Kalman filtering:

- Single criteria or specific statistical tests, as the normalized innovation squared (NIS) [1]
- Only limited information about the reliability of the estimation results and algorithms is provided

Research gap and objectives:

- General, unified, and holistic concept and framework for SA in filtering and tracking algorithms
- Including multi-sensor overall assessment

SA with subjective logic [2] offers:

- Comprehensive SA module/methodology with components and overall assessment
- Modular structure → easily expandable
- Every statistical assumption can be checked
- Explicit consideration of statistical uncertainty
- Missing information can be modeled directly
- Dealing with small amounts of data

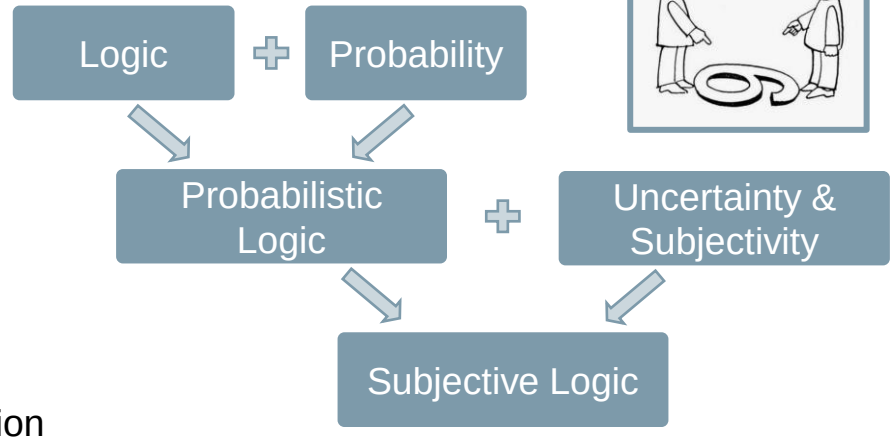
[1] Bar-Shalom, Y., Li, X. R., and Kirubarajan, T., "Estimation with Applications to Tracking and Navigation: Theory Algorithms and Software," John Wiley & Sons, 2004.
[2] Jøsang, A., "Subjective Logic: A Formalism for Reasoning Under Uncertainty," Heidelberg: Springer, 2016.

Subjective Logic [2] (SL)

- Perception is always subjective
- Modern extension of probabilistic logic for reasoning under uncertainty
- Explicitly includes the uncertainty about probabilities and subjective belief ownership
- Key structure in SL is the opinion representation

$$\omega_X = (\boldsymbol{b}_X, u_X, \boldsymbol{a}_X)$$

  - Belief $\boldsymbol{b}_X$: evidence collected
  - Uncertainty u_X: statistical uncertainty
  - Base rate $\boldsymbol{a}_X$: a priori knowledge



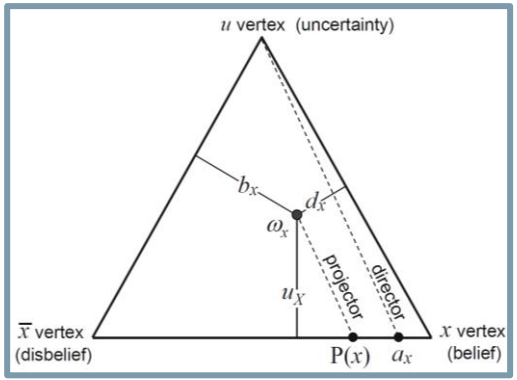
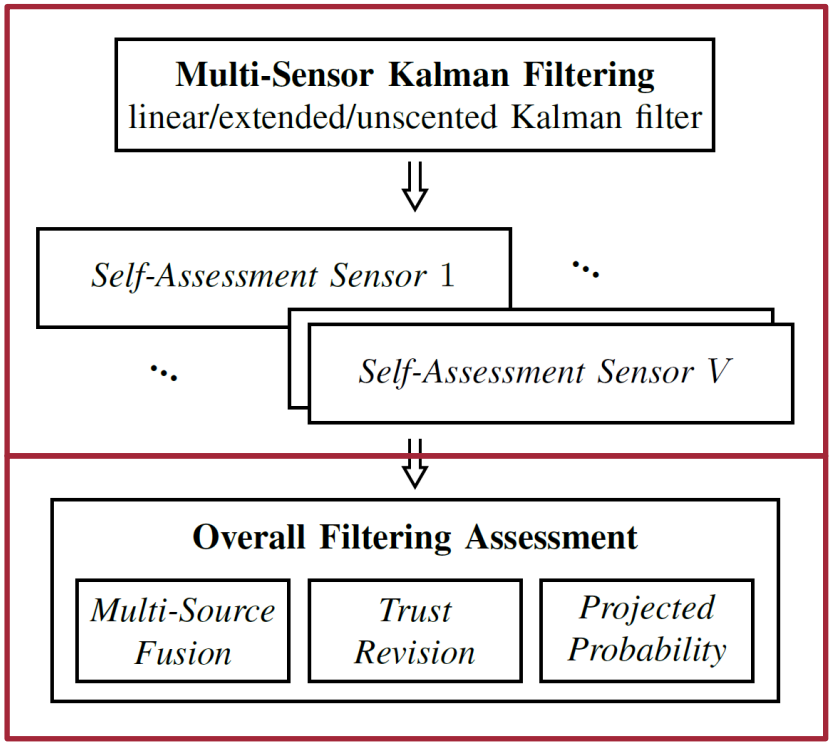


Figure „Sechs oder Neun" from https://leveragepoints.org/2017/10/31/alles-eine-frage-der-perspektive/

[2] Jøsang, A., "Subjective Logic: A Formalism for Reasoning Under Uncertainty," Heidelberg: Springer, 2016.

Our Contribution

- Extension of our SA approach based on SL [3],[4] towards nonlinear Kalman filtering
- Novel overall online assessment concept and framework based on SL for multi-sensor systems
- Framework allows for real-time evaluation of the performance of individual sensors, as well as the overall filtering performance
- Extensive evaluation in scenarios with challenging disturbance modes



[3] Griebel, T., Müller, J., Buchholz, M., and Dietmayer, K. "Kalman Filter Meets Subjective Logic: A Self-Assessing Kalman Filter Using Subjective Logic," 2020 IEEE 23rd International Conference on Information Fusion (FUSION), Rustenburg, South Africa, 2020.

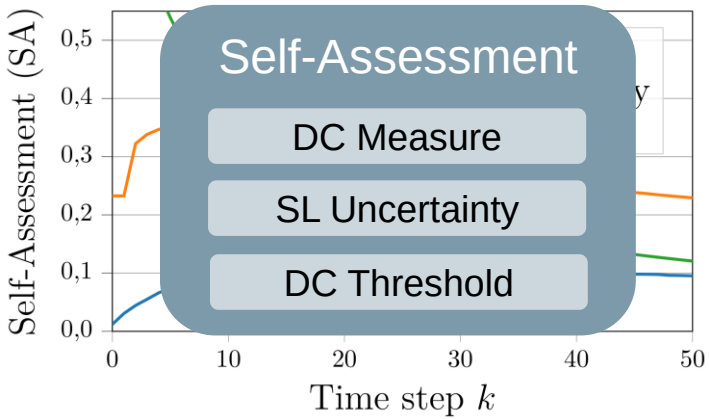
[4] Griebel, T., Müller, J., Geisler, P., Hermann, C., Herrmann, M., Buchholz, M., and Dietmayer, K. "Self-Assessment for Single-Object Tracking in Clutter Using Subjective Logic." 2022 25th International Conference on Information Fusion (FUSION). IEEE, 2022.

Single-Sensor SA Module for Kalman Filtering [3],[4]

- SA checks: Do the current measurements match the assumptions in the Kalman filter?
- Calculation of SA measures using the theory of SL

Tracking Assumptions	Self-Assessment Measures
Process and measurement noise: Normally distributed and white	Measurement opinion

- Single-sensor SA module consisting of:
  - Assessment measure based on degree of conflict [2] (DC)
  - Uncertainty measure from subjective logic
  - Threshold for the DC comparison measure (derivation given in [4])



[2] Jøsang, A., "Subjective Logic: A Formalism for Reasoning Under Uncertainty," Heidelberg: Springer, 2016.
[3] Griebel, T., Müller, J., Buchholz, M., and Dietmayer, K. "Kalman Filter Meets Subjective Logic: A Self-Assessing Kalman Filter Using Subjective Logic," 2020 IEEE 23rd International Conference on Information Fusion (FUSION), Rustenburg, South Africa, 2020.
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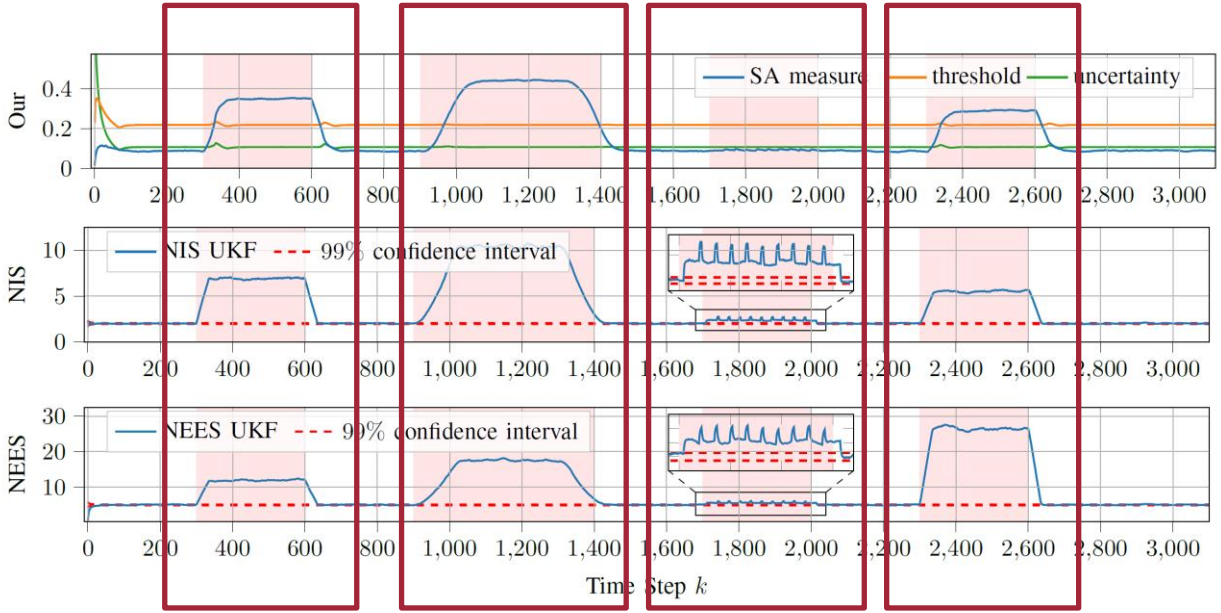
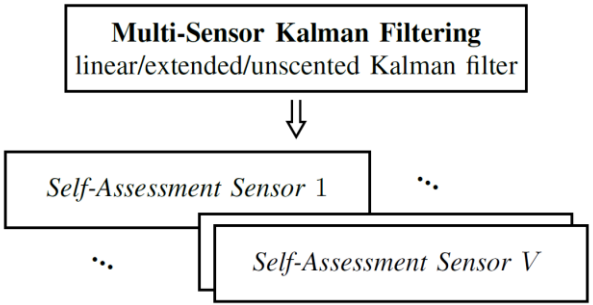
Single-Sensor SA for Nonlinear Kalman Filtering

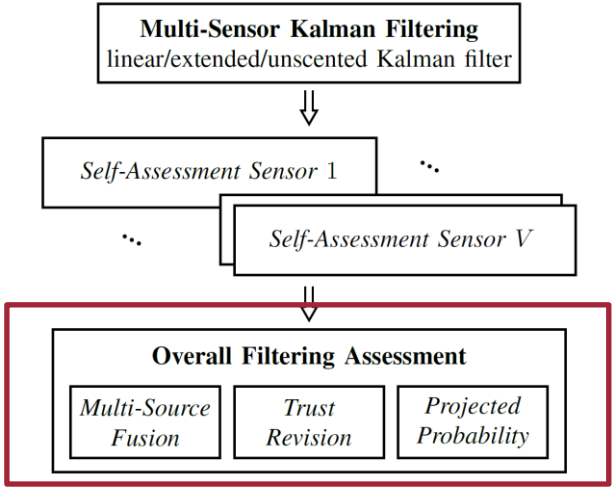


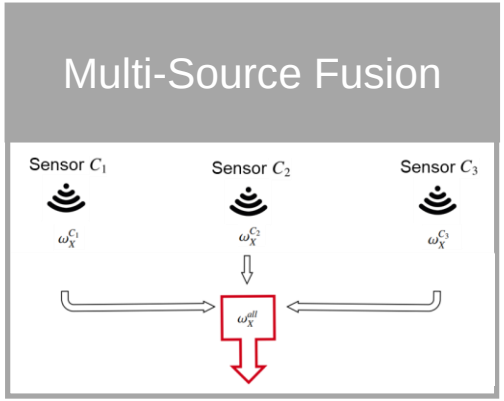


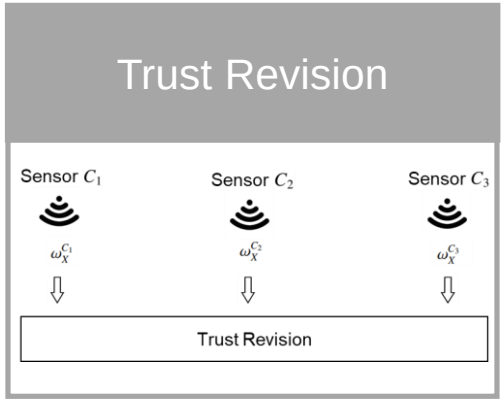
- Single-sensor nonlinear Kalman filter SA vs NIS and NEES
- Disturbances: Jump, drift, outliers in measurement noise and higher nonlinearity in transition

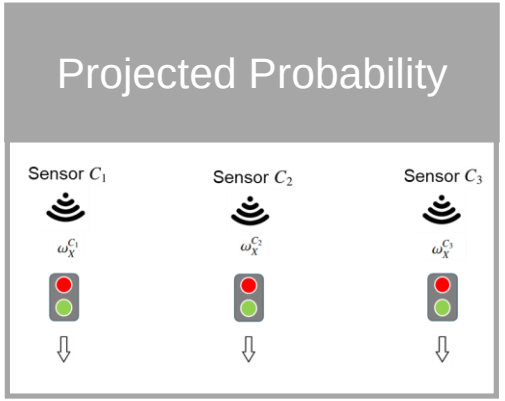
Multi-Sensor Overall Assessment

- Multi-sensor overall assessment directly utilizes the single-sensor SA modules
- Three different concepts are proposed
- Enables closed-form solutions in SL

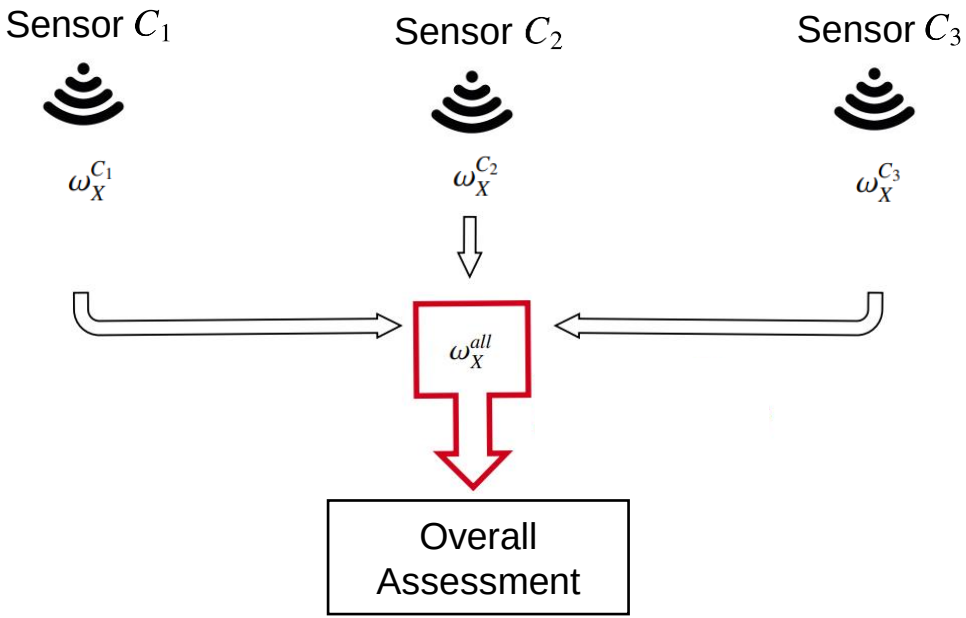








Multi-Sensor Overall Assessment
Multi-Source Fusion

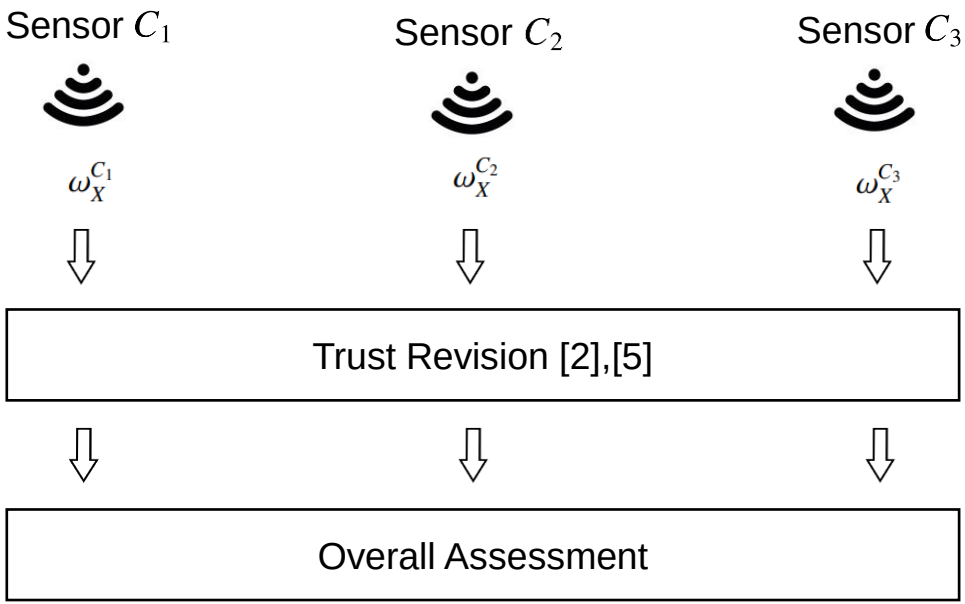


Fusion Operators [2]:

- Cumulative Belief Fusion (CBF)
- Averaging Belief Fusion (ABF)
  - Not all evidence reduces uncertainty
  - Uncertainties are averaged
- Weighted Belief Fusion (WBF)

[2] Jøsang, A., "Subjective Logic: A Formalism for Reasoning Under Uncertainty," Heidelberg: Springer, 2016.

Multi-Sensor Overall Assessment
Trust Revision



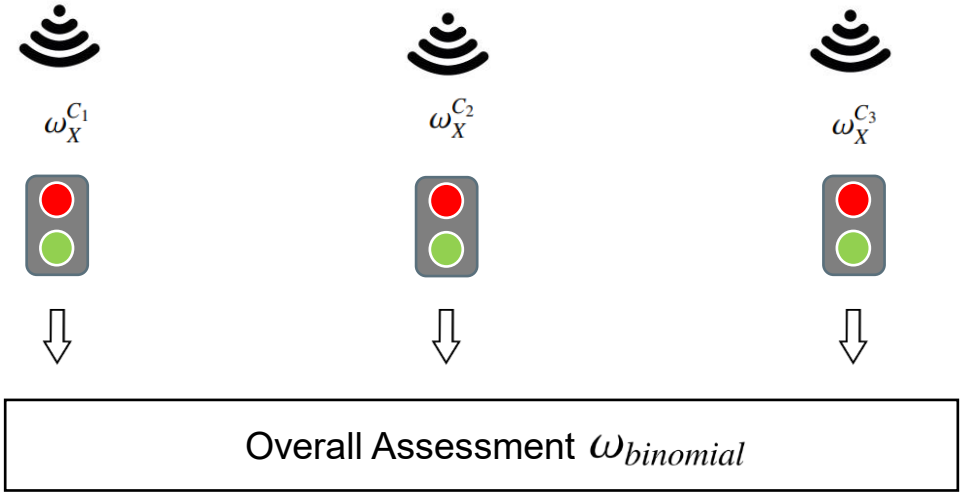
Trust Revision Concept [2],[5]:

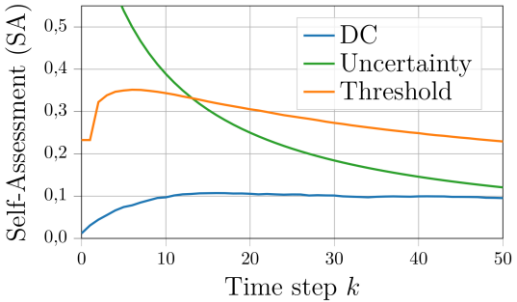
- Trust revision applied to the single-sensor SAs
- Additional consideration of trust and weighting for all single-sensor SA statements
- CBF operator is used for the fusion process afterward

[2] Jøsang, A. "Subjective Logic: A Formalism for Reasoning Under Uncertainty," Heidelberg: Springer, 2016.
[5] Jøsang, A. et al. "Multi-Source Trust Revision," 2017 20th International Conference on Information Fusion, Xi'an, China, 2017.

Multi-Sensor Overall Assessment
Projected Probability

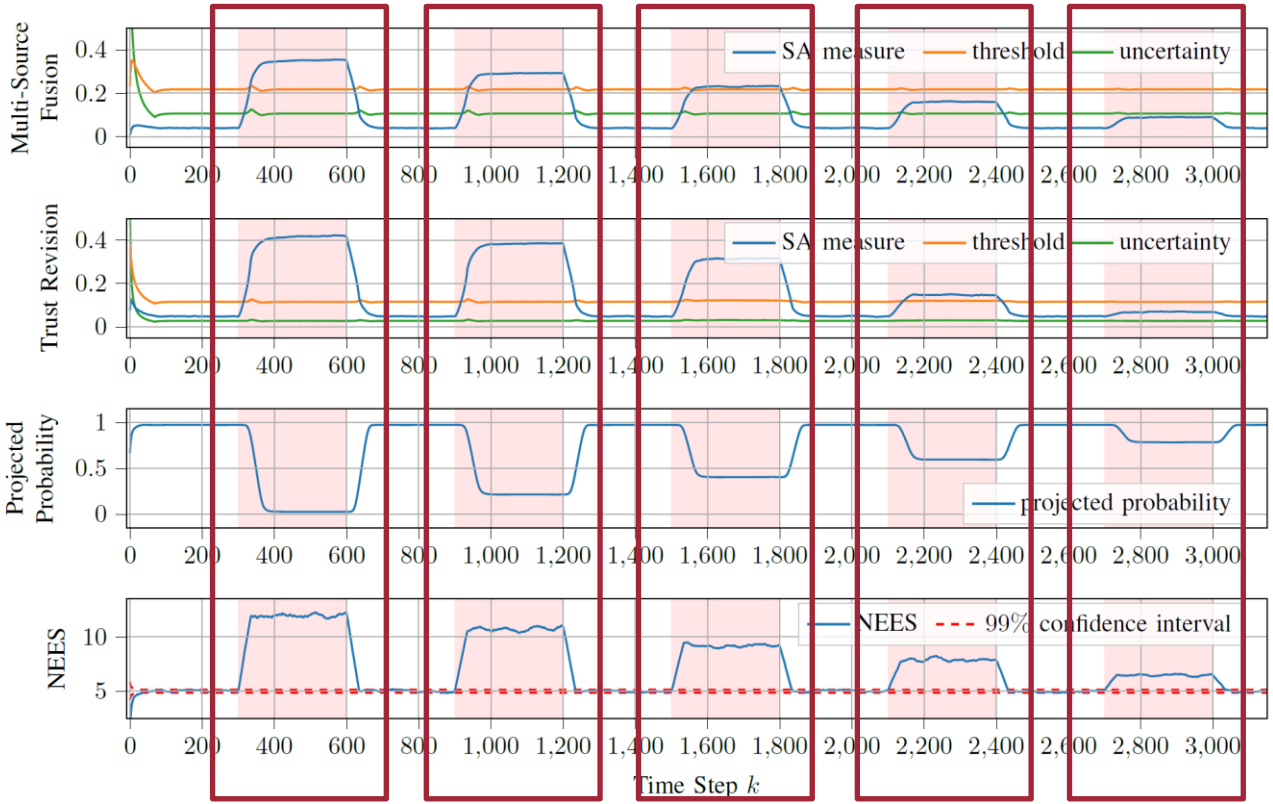
Sensor C_1 Sensor C_2 Sensor C_3





$$P_{binomial} = b + a \cdot u$$

Experiments – Multi-Sensor Overall Filtering Assessment

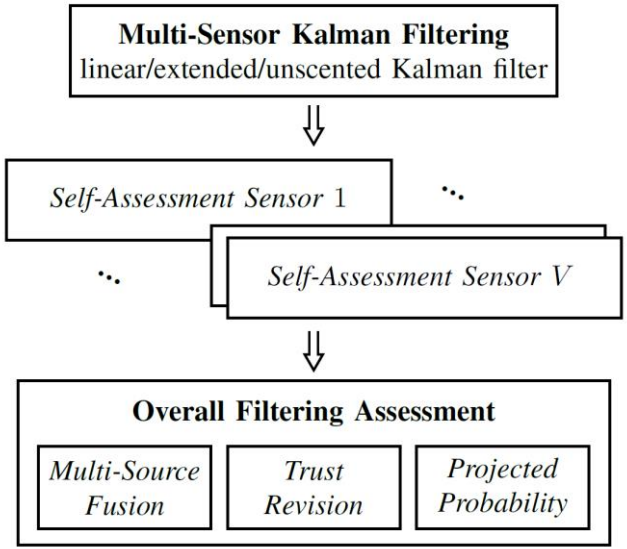


- Multi-sensor overall filtering assessment vs NEES
- Challenging nonlinear simulation scenario with 5 sensors
- Disturbances: Jumps in measurement noise of all 5 sensors simultaneously

Conclusion

Our Contribution:

- Extension of the SA approach based on SL towards nonlinear Kalman filtering
- Novel overall online assessment concept and framework based on SL for multi-sensor systems
- Evaluation in scenarios with challenging disturbance modes



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Conclusion

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- Novel overall online assessment concept and framework based on SL for multi-sensor systems
- Evaluation in scenarios with challenging disturbance modes

Future Work:

- Adaptive Kalman filtering based on SA
- Extension to multi-object tracking
- General, unified, and holistic concept and framework for SA in filtering and tracking algorithms

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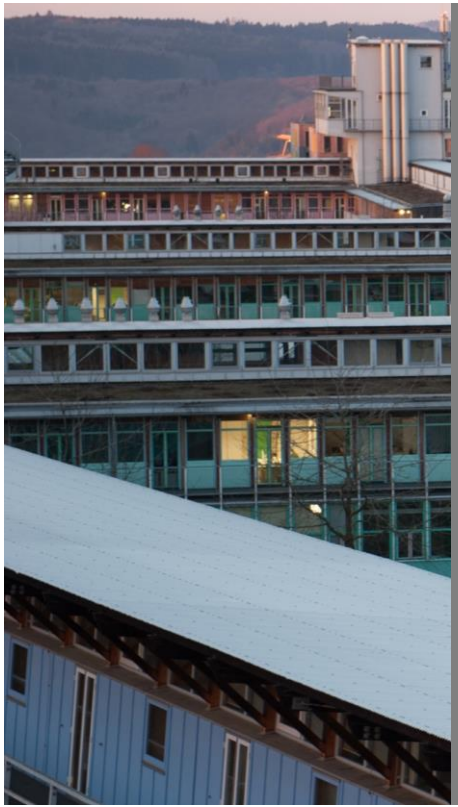

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Thank you for your attention!

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References

- [1] Bar-Shalom, Y., Li, X. R., and Kirubarajan, T., "Estimation with Applications to Tracking and Navigation: Theory Algorithms and Software," John Wiley & Sons, 2004.
- [2] Jøsang, A., "Subjective Logic: A Formalism for Reasoning Under Uncertainty," Heidelberg: Springer, 2016.
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