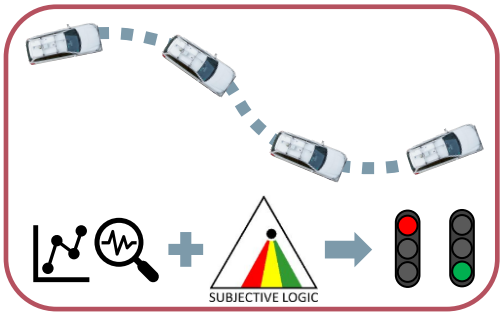
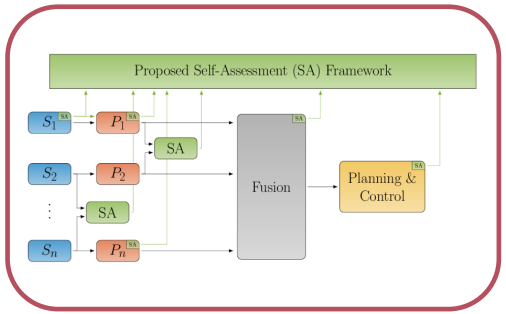
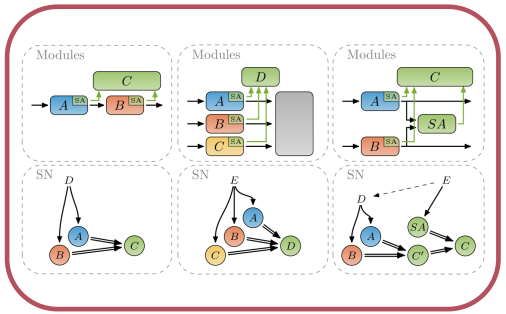






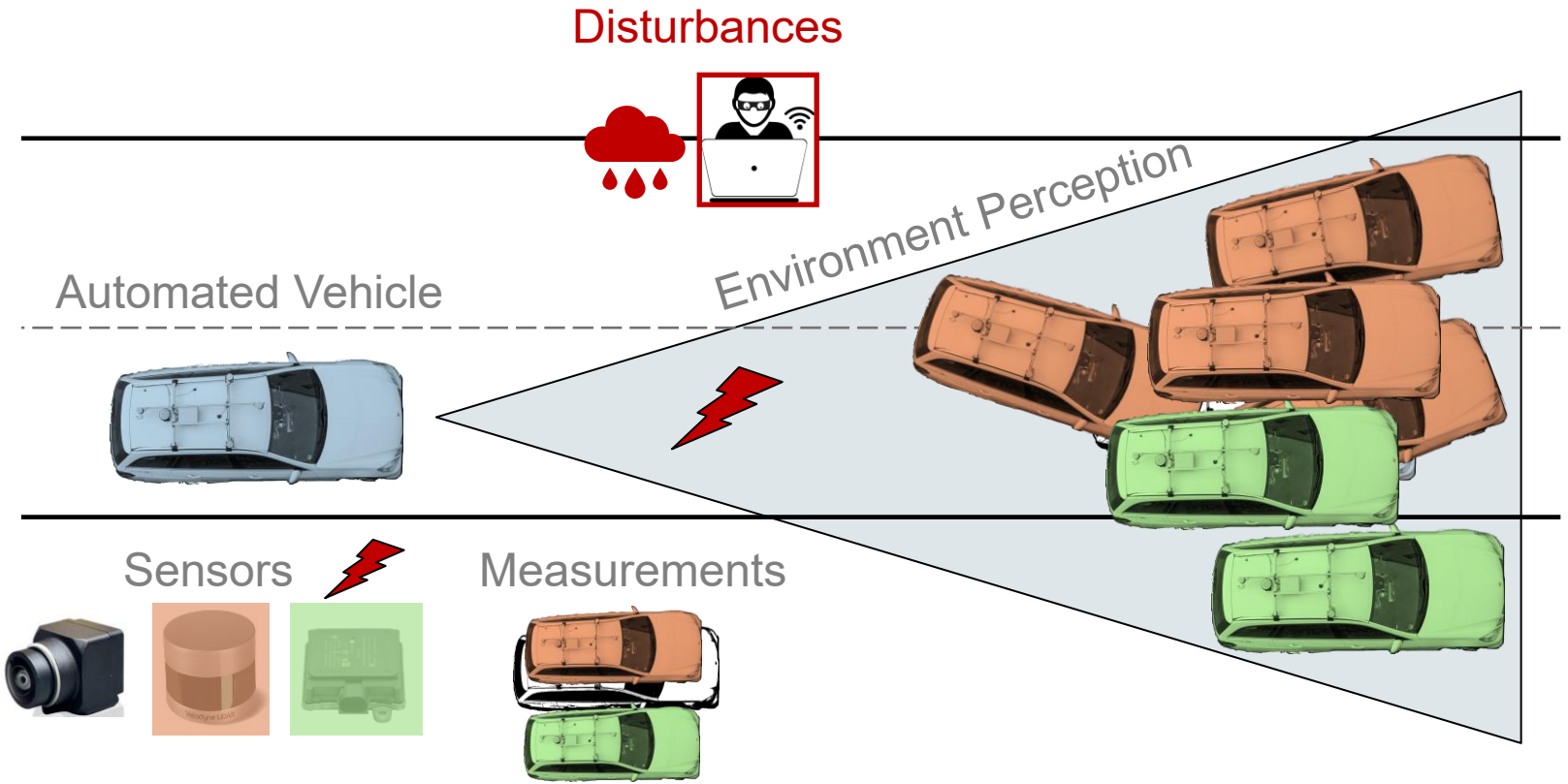
Toward a Unified Framework for Runtime Monitoring and Self-Assessment in Autonomous Driving Systems

Thomas Griebel

Ulm University, Germany
Institute of Measurement, Control, and Microtechnology

Motivation – Self-Assessment in Automated Driving

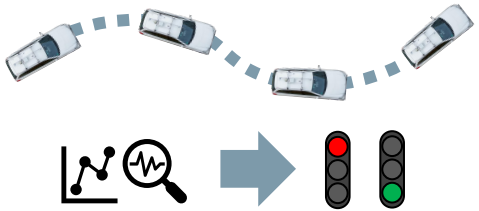
Example: Object Tracking



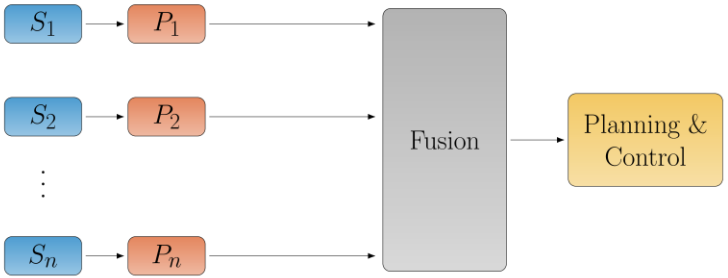
Motivation – Self-Assessment in Automated Driving

- Runtime Monitoring / self-assessment is a key element for safety and robustness
- **Goal:** Self-monitoring of the entire automated driving system

Self-Assessment



Autonomous Driving (AD) Stack



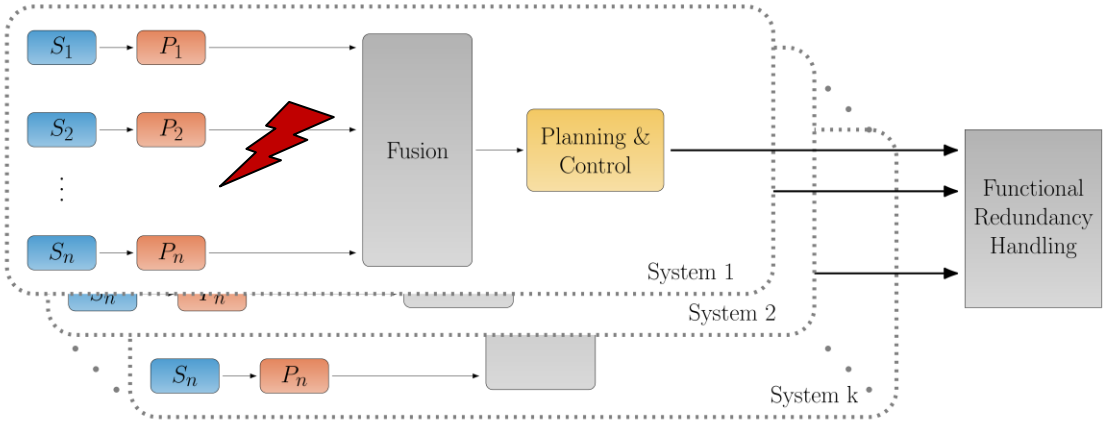
Classical Approach for Handling Functional Misbehavior

Problem:

Functional misbehavior in the AD stack

Classical Approach:

Redundancy



AD-Stack
- System 1
- System 2
- ...
- System k

State of the Art – Self-Assessment in Automated Driving and Its Limitations

State of the Art:

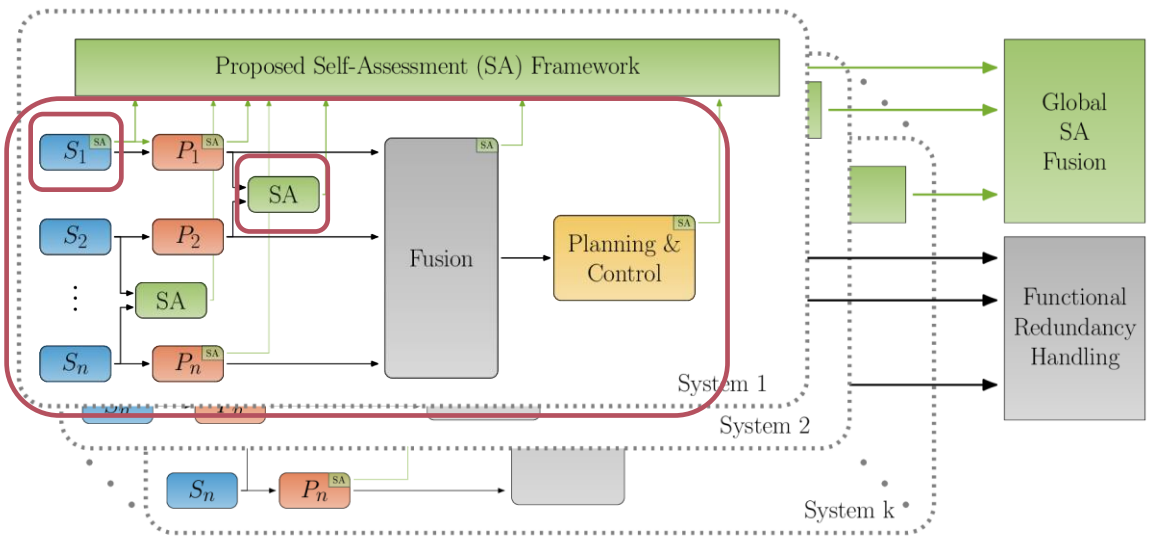
Self-assessment approaches are available at different levels:

- Module level
- Sub-system level
- System level

Objective and Research Gap:

Unified, overarching self-assessment framework

AD-Stack + Self-Assessment

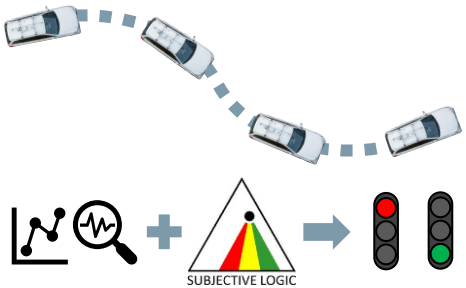


How can *modular* self-assessments be integrated and combined into a *unified*, *system-wide* statement?

Unified Interface for the Self-Assessment Framework

State of the Art – Self-Assessment Approaches

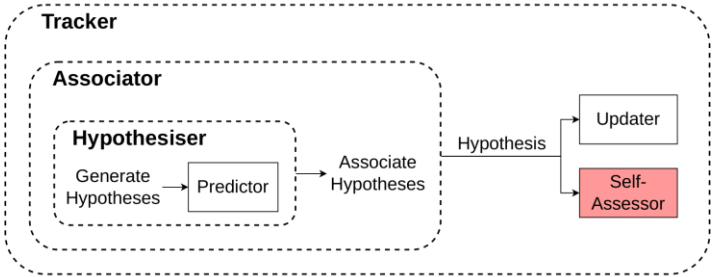
- Classical error detection mechanisms [1],[2] using individual tests and checks
- Self-assessment based on Subjective Logic [3],[4],[5]
  - Component-level verification of assumptions
  - Overall verification of all assumptions (fusion of components)

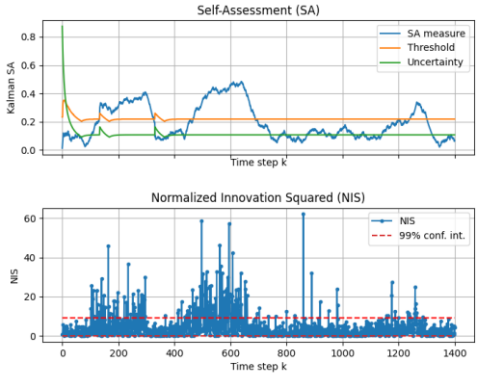


[1] Börner, M. and Isermann, R., “Supervision, fault detection, and sensor fault tolerance of passenger cars,” IFAC Proceedings Volumes, Volume 36, No. 5, Pages 319–326, 2003.
[2] Costa de Oliveira, F., Torres, F., and Garcia-Ortiz, A., “Recent Advances in Sensor Integrity Monitoring Methods - A Review,” IEEE Sensors Journal, Volume 22, No. 11, Pages 10256–10279, 2022.
[3] Griebel, T., Heinzler, J., Buchholz, M., and Dietmayer, K., “Online Performance Assessment of Multi-Sensor Kalman Filters Based on Subjective Logic,” 2023 26th FUSION, USA, IEEE, 2023.
[4] Griebel, T., Dehler, N., Scheible, A., Buchholz, M., and Dietmayer, K., “Self-Assessment for Multi-Object Tracking Based on Subjective Logic,” 2024 IEEE IV, 2024.
[5] 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 FUSION, IEEE, 2022.

Self-Assessment on Module Level

Self-Assessment and Monitoring Module for Tracking Algorithms: Implementation in the Stone Soup Framework [3],[4],[5]





GitHub

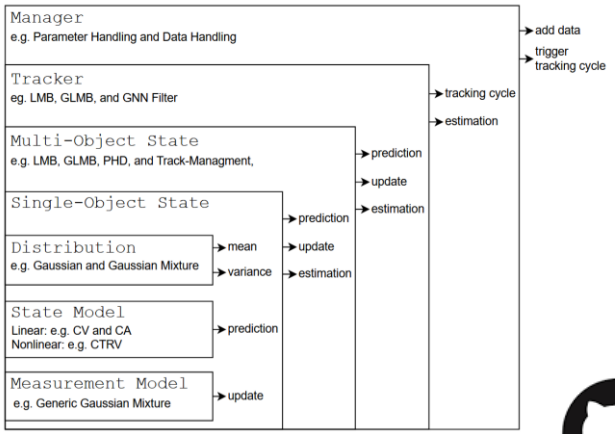
MRM

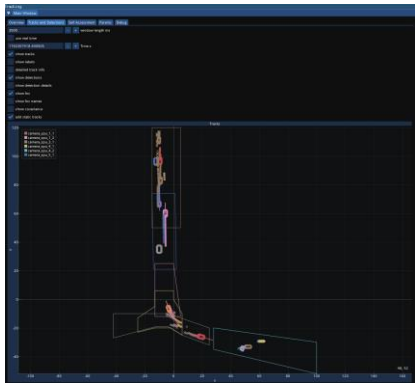
https://github.com/uulm-mrm/aduulm-stonesoup

[3] Griebel, T., Heinzler, J., Buchholz, M., and Dietmayer, K., “Online Performance Assessment of Multi-Sensor Kalman Filters Based on Subjective Logic,” 2023 26th FUSION, USA, IEEE, 2023.
[4] Griebel, T., Dehler, N., Scheible, A., Buchholz, M., and Dietmayer, K., “Self-Assessment for Multi-Object Tracking Based on Subjective Logic,” 2024 IEEE IV, 2024.
[5] 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 FUSION, IEEE, 2022.

Self-Assessment on Module Level

ADUULM-TTB: A Scalable, Generic, and Efficient Multi-Sensor Multi-Object Tracking Toolbox





GitHub

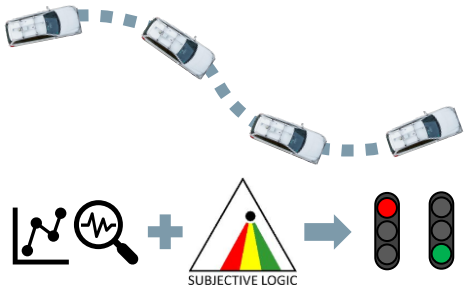
MRM

https://github.com/uulm-mrm/aduulm_ttb

Unified Interface for the Self-Assessment Framework

State of the Art – Self-Assessment Approaches

- Classical error detection mechanisms [1],[2] using individual tests and checks
- Self-assessment based on Subjective Logic [3],[4],[5]
  - Component-level verification of assumptions
  - Overall verification of all assumptions (fusion of components)



Interface Proposal for Self-Assessment:

Use of Subjective Logic

[1] Börner, M. and Isermann, R., “Supervision, fault detection, and sensor fault tolerance of passenger cars,” IFAC Proceedings Volumes, Volume 36, No. 5, Pages 319–326, 2003.
[2] Costa de Oliveira, F., Torres, F., and Garcia-Ortiz, A., “Recent Advances in Sensor Integrity Monitoring Methods - A Review,” IEEE Sensors Journal, Volume 22, No. 11, Pages 10256–10279, 2022.
[3] Griebel, T., Heinzler, J., Buchholz, M., and Dietmayer, K., “Online Performance Assessment of Multi-Sensor Kalman Filters Based on Subjective Logic,” 2023 26th FUSION, USA, IEEE, 2023.
[4] Griebel, T., Dehler, N., Scheible, A., Buchholz, M., and Dietmayer, K., “Self-Assessment for Multi-Object Tracking Based on Subjective Logic,” 2024 IEEE IV, 2024.
[5] 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 FUSION, IEEE, 2022.

Why Subjective Logic [6] ?

- Motivation: Perception is inherently subjective
- Accounts for uncertainties in information sources
- Enables the fusion of contradictory statements
- Provides a more expressive framework than classical probability theory

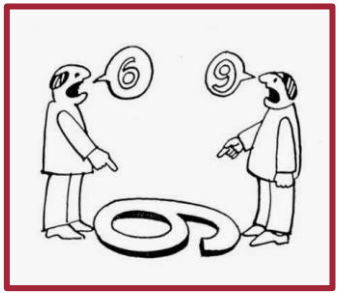
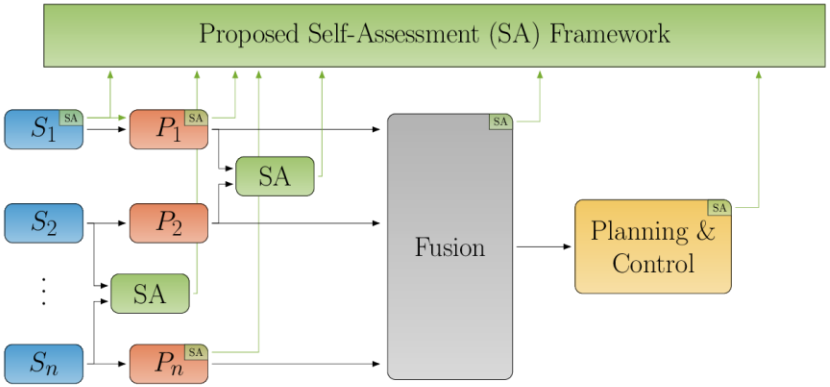


Figure „Sechs oder Neun" from https://leveragepoints.org/2017/10/31/alles-eine-frage-der-perspektive/

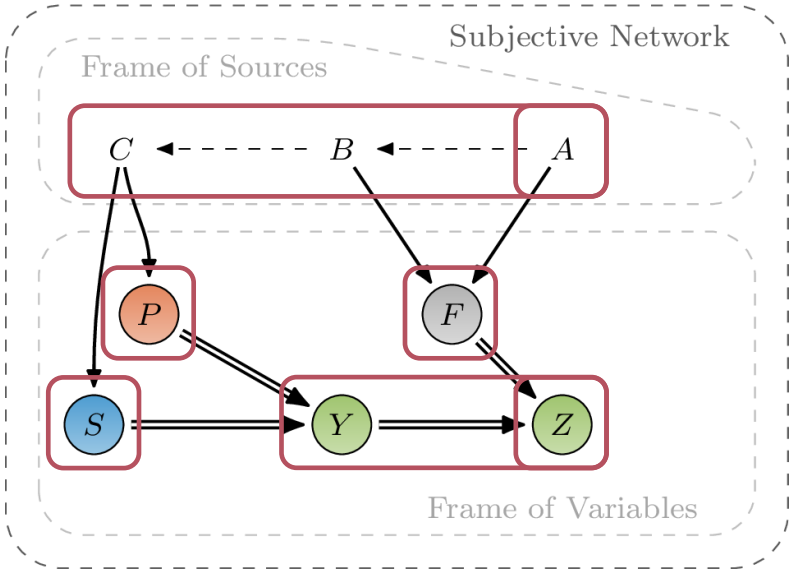
AD-Stack + Self-Assessment



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

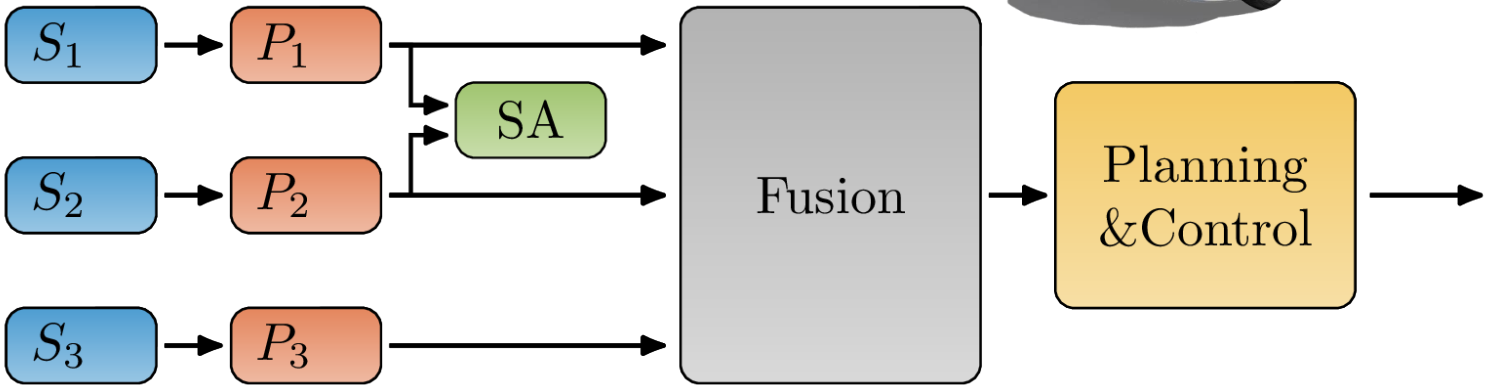
Subjective Networks [6]

- Decision-making process modeled as a graph
- **Goal:** Agent A aims to make a decision regarding variable Z
- **Components:**
  - Agents: A, B and C
  - Observations: S, P and F
  - Additional variables: Y and Z
- **Relations Between Components:**
  - Trust relations: Between agents (e.g., agent to agent)
  - Belief relations: Between agents and observations (e.g., agent to observation)
  - Conditional relations: Between variables (e.g., variable to variable)



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

Example AD Stack



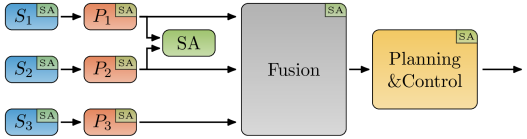
Prerequisites:

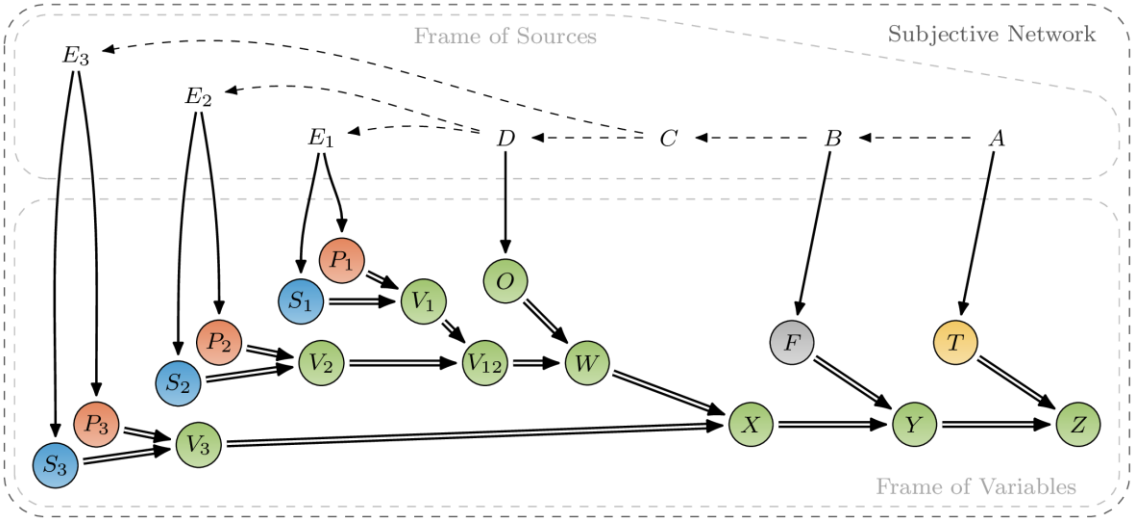
- Known system structure
- Self-assessment at the module level

Objective:

- Mathematical representation
- Self-assessment fusion → Statement about the overall system

Subjective Network of Our AD Stack



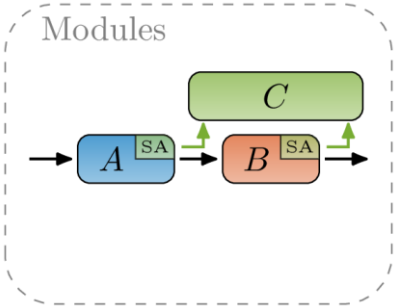


Next Steps:

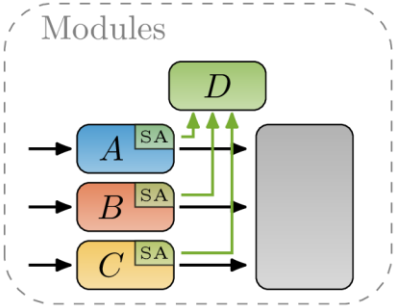
- Construction guide for arbitrary structures
- Decomposition into individual building blocks

Building Blocks for Constructing an AD Stack

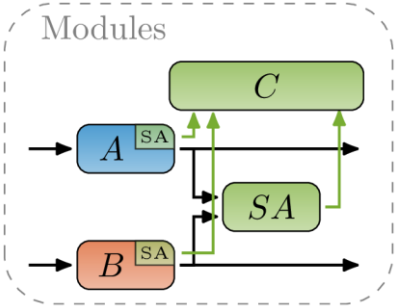
Series Connection:



Parallel Connection:



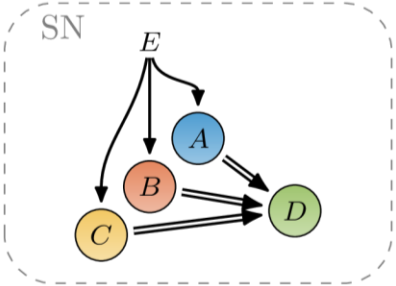
Concurrent Connection:



Building Blocks for Constructing an AD Stack

Series Connection:

Parallel Connection:



Concurrent Connection:

Redundancy:

- One module is sufficient
- ➢ Co-multiplication (OR operation)

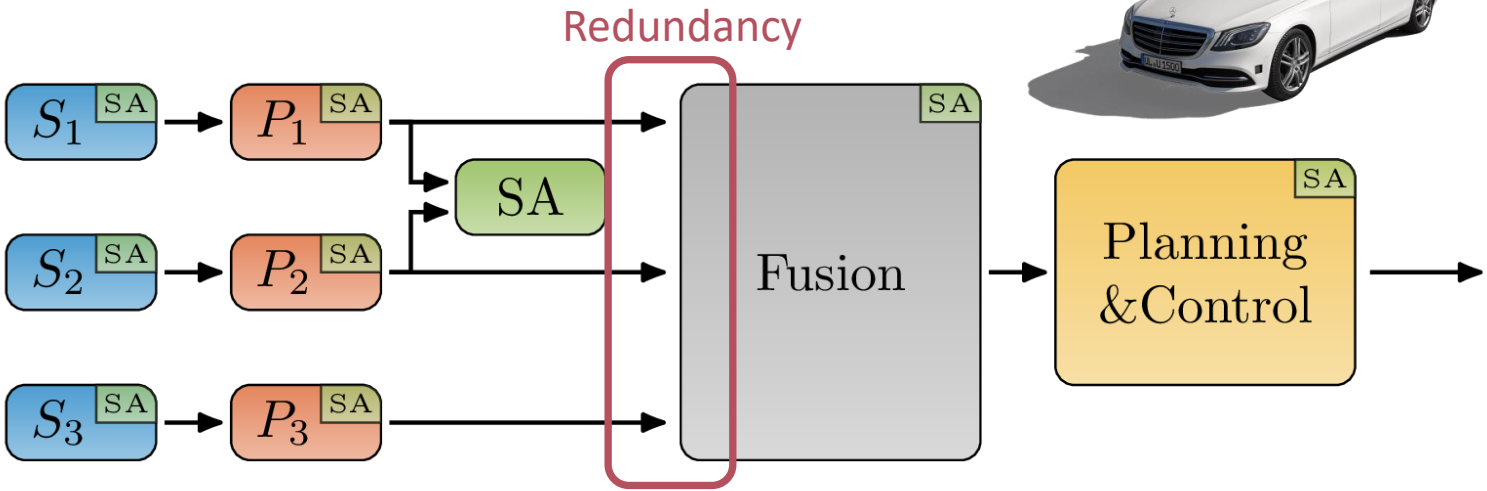
Compensation:

- The more, the better
- ➢ Cummulative/Average Fusion

Without Exception:

- All modules required
- ➢ Multiplication (AND operation)

Example AD Stack



Safety-Critical:

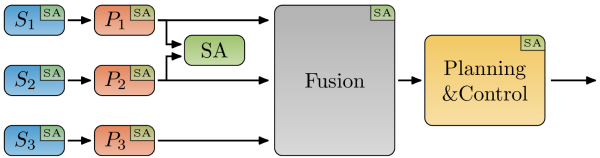
- Redundant interpretation
- Co-multiplication

Overall State-of-Health:

- Compensatory interpretation
- Cumulative Fusion

Application of the Self-Assessment Framework [7]

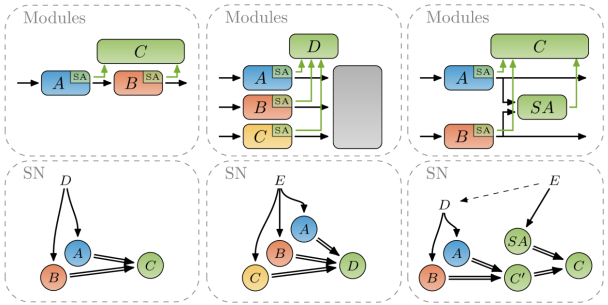
AD Stack



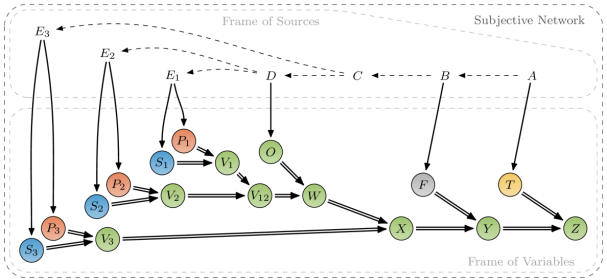
System-wide Self-Assessment Formula

$$\omega_Z^A = \begin{cases} \left(\left(\left(\omega_{V_1}^{E_1} \oplus \omega_{V_2}^{E_2} \right) \mathbin{\widehat{\oplus}} \omega_{SA}^{D} \right) \oplus \left(\omega_{S_3}^{E_3} \cdot \omega_{P_3}^{E_3} \right) \right) \cdot \omega_F^B \cdot \omega_T^A \\ \left(\left(\left(\omega_{V_1}^{E_1} \sqcup \omega_{V_2}^{E_2} \right) \mathbin{\widehat{\oplus}} \omega_{SA}^{D} \right) \sqcup \left(\omega_{S_3}^{E_3} \cdot \omega_{P_3}^{E_3} \right) \right) \cdot \omega_F^B \cdot \omega_T^A \end{cases}$$

Building Blocks

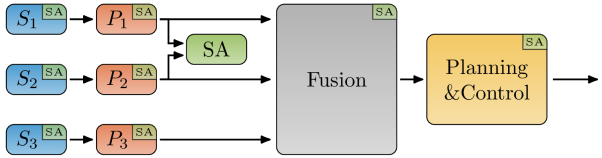


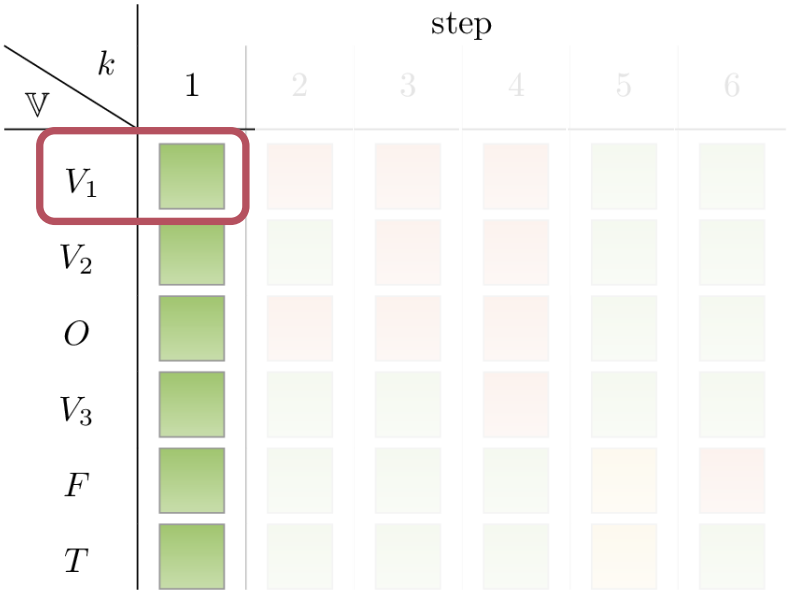
Subjective Network

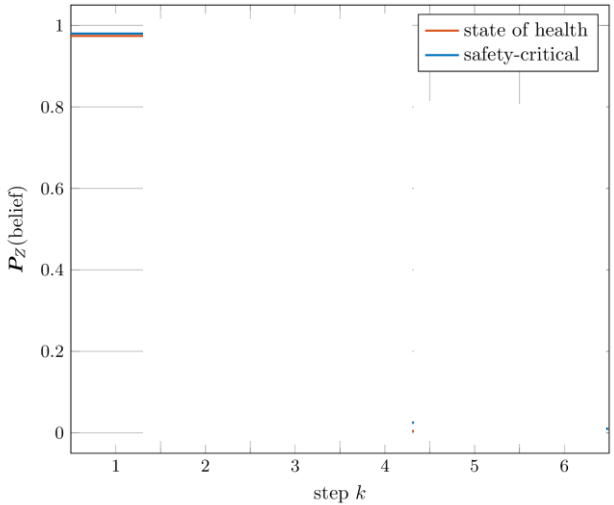


[7] Wodtko, Thomas; Griebel, Thomas; Buchholz, Michael; and Dietmayer, Klaus: A Unified Self-Assessment Framework for Autonomous Driving Stacks Using Subjective Logic. In: 16. Uni-DAS e.V. Workshop Fahrerassistenz und automatisiertes Fahren, 2025.

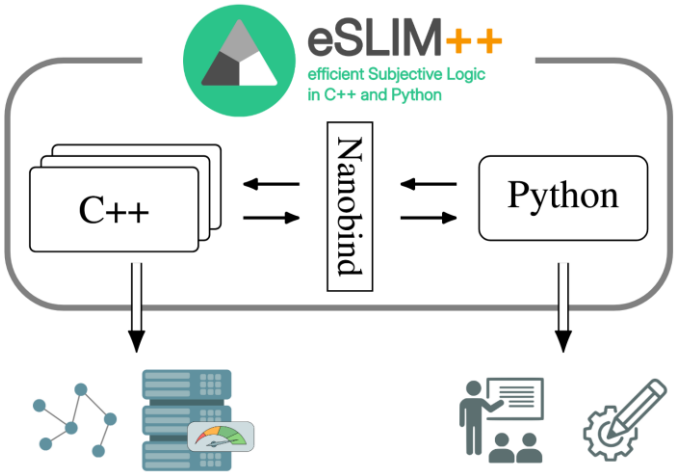
Evaluation of the Self-Assessment Formula







eSLIM++ - an Efficient Subjective Logic Implementation in C++ Providing Easy-to-Use Python Interfaces



eSLIM++
efficient Subjective Logic
in C++ and Python

GitHub

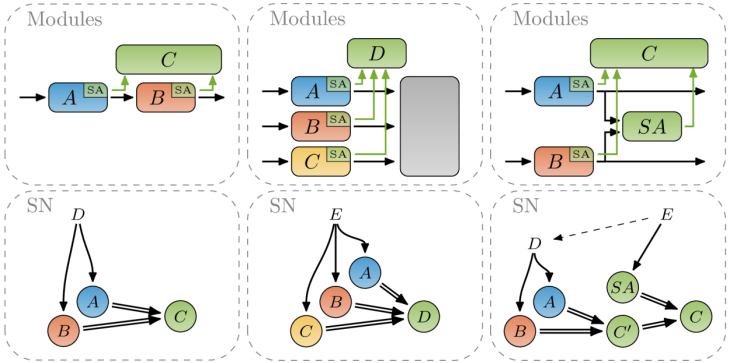
MRM

https://github.com/uulm-mrm/eslimpp

Conclusion and Outlook

Conclusion

- Framework for self-assessment in automated driving
- Unified interface: Subjective Logic
- Building blocks for general application



Outlook

- Additional self-assessments at the module level
- Integration with safety argumentation

Acknowledgement / Funding

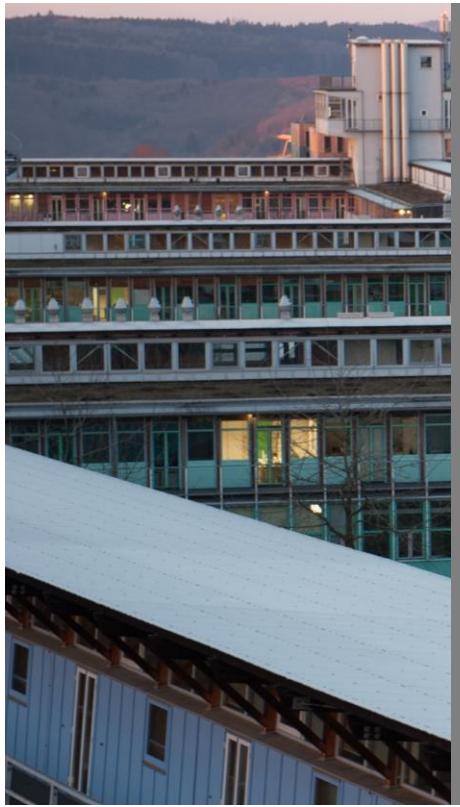
We gratefully acknowledge the funding of this work:

EVENTS has received funding under grant agreement No 101069614. It is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission. Neither the European Union nor the granting authority can be held responsible for them.

PODIUM project is co-funded by the European Union, under grant agreement No 101069547. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Commission. Neither the European Union nor the granting authority can be held responsible for them.

MRM Mess-, Regel- und Mikrotechnik

universität ulm



Toward a Unified Framework for Runtime Monitoring and Self-Assessment in Autonomous Driving Systems

Thomas Griebel

thomas.griebel@uni-ulm.de

MRM Mess-, Regel- und Mikrotechnik

References

- [1] Börner, M. and Isermann, R., “Supervision, fault detection, and sensor fault tolerance of passenger cars,” IFAC Proceedings Volumes, Volume 36, No. 5, Pages 319–326, 2003.
- [2] Costa de Oliveira, F., Torres, F., and Garcia-Ortiz, A., “Recent Advances in Sensor Integrity Monitoring Methods - A Review,” IEEE Sensors Journal, Volume 22, No. 11, Pages 10256–10279, 2022.
- [3] Griebel, T., Heinzler, J., Buchholz, M., and Dietmayer, K., “Online Performance Assessment of Multi-Sensor Kalman Filters Based on Subjective Logic,” 2023 26th FUSION, USA, IEEE, 2023.
- [4] Griebel, T., Dehler, N., Scheible, A., Buchholz, M., and Dietmayer, K., “Self-Assessment for Multi-Object Tracking Based on Subjective Logic,” 2024 IEEE IV, 2024.
- [5] 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 FUSION, IEEE, 2022.
- [6] Jøsang, A., "Subjective Logic: A Formalism for Reasoning Under Uncertainty," Heidelberg: Springer, 2016.
- [7] Wodtko, Thomas; Griebel, Thomas; Buchholz, Michael; and Dietmayer, Klaus: A Unified Self-Assessment Framework for Autonomous Driving Stacks Using Subjective Logic. In: 16. Uni-DAS e.V. Workshop Fahrerassistenz und automatisiertes Fahren, 2025.