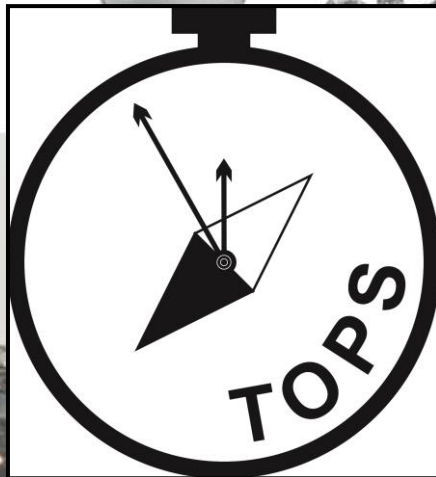
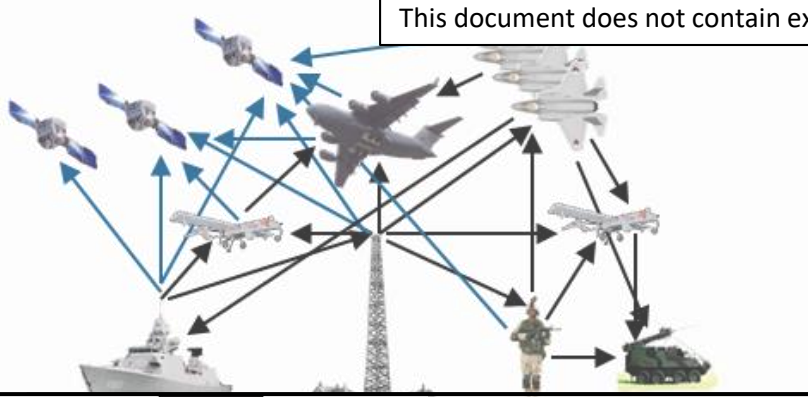
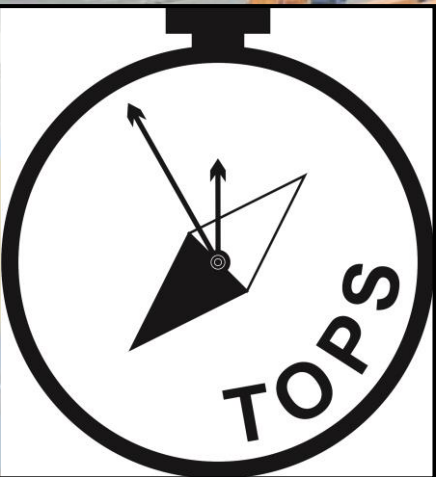


This document does not contain export-controlled technical data nor does it contain technical data related to a signed NDA or TA.

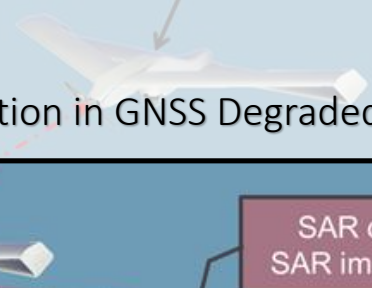


Timing, Orientation & Positioning Service (TOPS)



TNO Portfolio manager PNT
Danny J. Maat M.Sc.
September 29/30, Split-Croatia
SET-275 Symposium 'Cooperative Navigation in GNSS Degraded and Denied Environments'

SAR position not correct:
image of wrong target area



SAR orientation not correct:
SAR image in wrong orientation

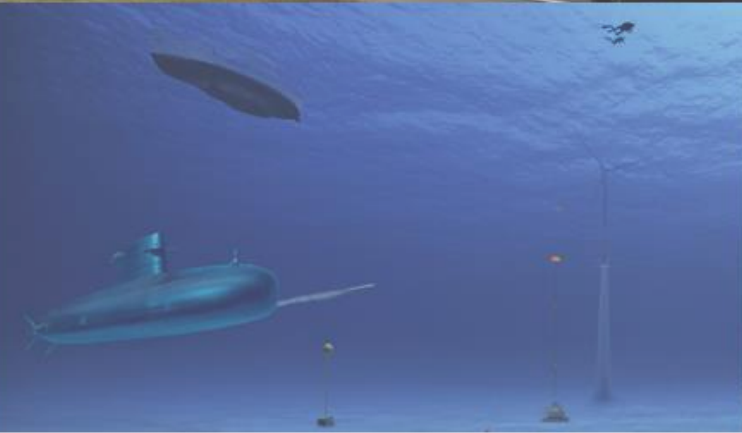
Real position

Real SAR observation

Dynamics not correctly estimated:
SAR image blur



**also true for other observation systems*



BACKGROUND OF ME IN A NUTSHELL

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TNO innovation
for life

- › 1989 – 1994: Graduated cum laude
master electrical engineer



 TNO The Hague
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2597 AK The Hague
The Netherlands

 Danny.Maat@TNO.nl

 +31 6 51 54 22 50

- › 1994 – 1996: Scantech B.V. / TU Delft
 - › Fuzzy logic in bar code decoding
 - › Patent NL9500597A

- › 1997 – now: **TNO**
 - › **Portfolio manager PNT since 2010**
 - › Program manager
 - › Project leader
 - › Technical project leader
 - › Quotation manager
 - › Software system architect

- › Research fields
 - › PNT
 - › Intelligent Autonomous Systems
 - › Bird Radar (spin out ROBIN Radar Systems)
 - › Semantic networks
 - › Expert Systems
 - › Nuclear, Biologic, Chemical & Damage Control



- › Reliable PNT undeniable for C2- and communication systems
- › PNT has foundational role in military domain (MilGPS)

Integrated Warfare Analysis

Assured PNT sources and applications are required in all Joint Force operations



- › Assured PNT **cannot** be delivered by Sat-NAV
 - › US DoD does not guarantee availability GPS
 - › MilGPS vulnerable for jamming
 - › **GNSS becomes more robust, but stay vulnerable**

Norway, Finland suspect Russia of jamming GPS

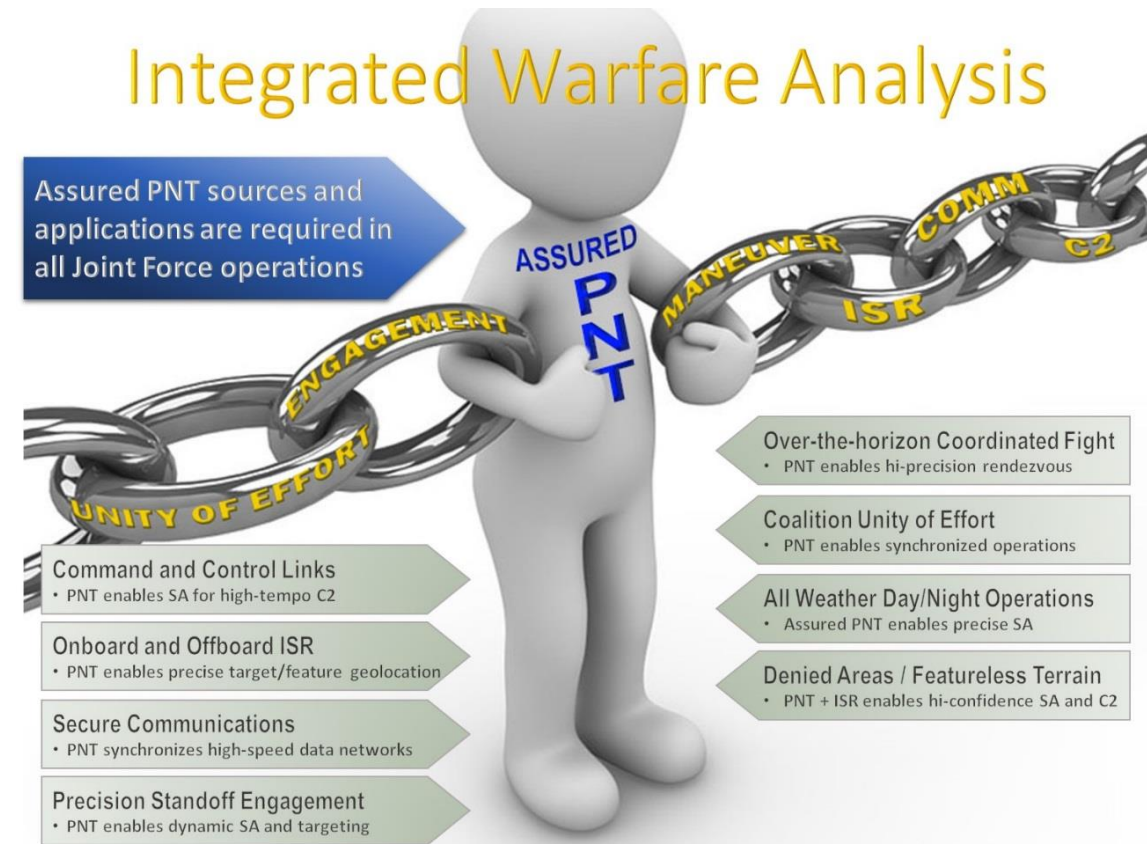


- › Challenges
 - › No single sensor system provides assured-PNT
 - › No single set operational conditions
 - › Different sensor options for every vehicle type



- › Solution has three parts:
 - › Sensors
 - › Sensor processing
 - › The fusion
- › Products delivered by industry
 - › Often knowledge about one sensor technology
 - › Black box
 - › Standardization
 - › Vendor lock-in
- › Why is sensor fusion difficult?
 - › Sensor have many types of error sources
 - › Sensor models and platform models not perfect
 - › Integration of multiple algorithms necessary

Integrated Warfare Analysis



Picture from NATO navigation Warfare (NAVWAR) Playbook, d.d. 22-02-2021

Integrated, robust & validated PNT-solution needed

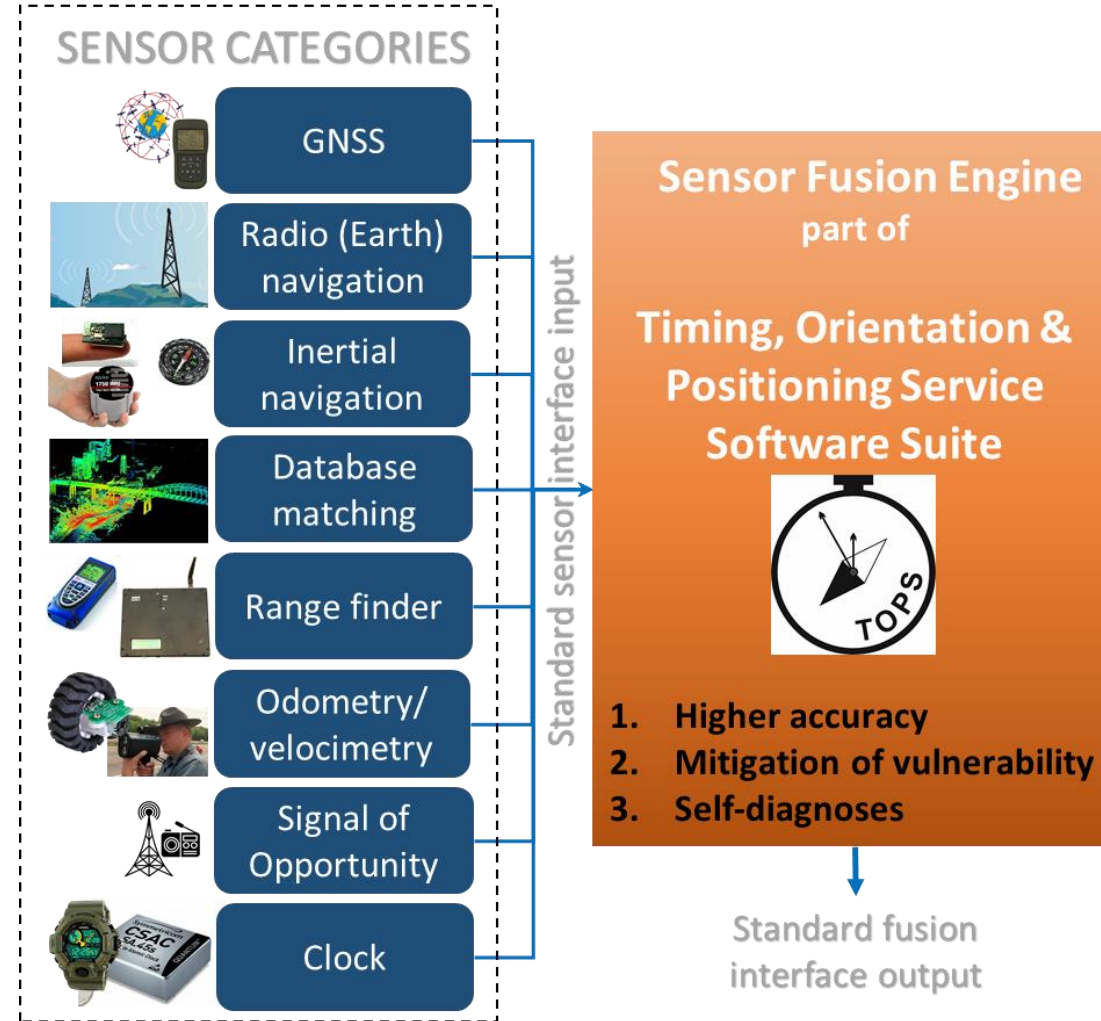
- › Minimize vulnerability (avoid single sensor dependency)
- › Complement strengths & create redundancies
- › Higher accuracy PNT estimates (over time)
- › Insight in PNT uncertainty

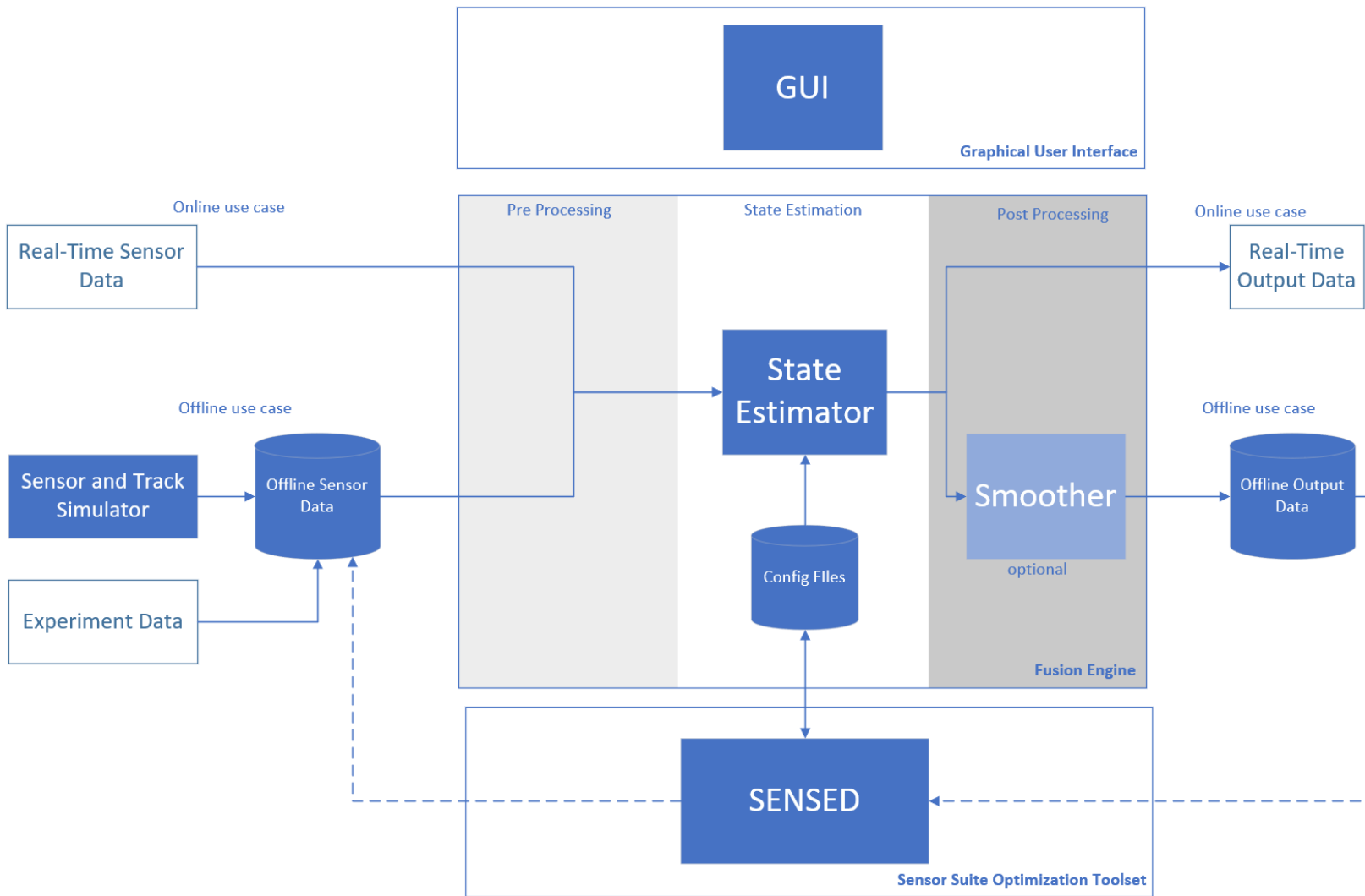
What can TNO do?

- › Determining which sensor to buy
- › Innovative sensor processing methods
- › Sensor fusion engine (online & offline)
- › Testing and validating

Why TNO?

- › Independent & not-for-profit research organization
- › In depth knowledge different technologies
- › Defence laboratory





› TOPS Software suite

- › Modular C++ sensor fusion framework
- › Single SW base to deploy and maintain
- › Focus on quality & performance

› Fusion engine

- › Highly configurable
- › Real-time (operational)
- › Off line analyzing
- › Pre processing (e.g. integrity)

› GUI

- › Research
- › Operational
- › Maintenance

› Sensor Suite Optimization Toolset

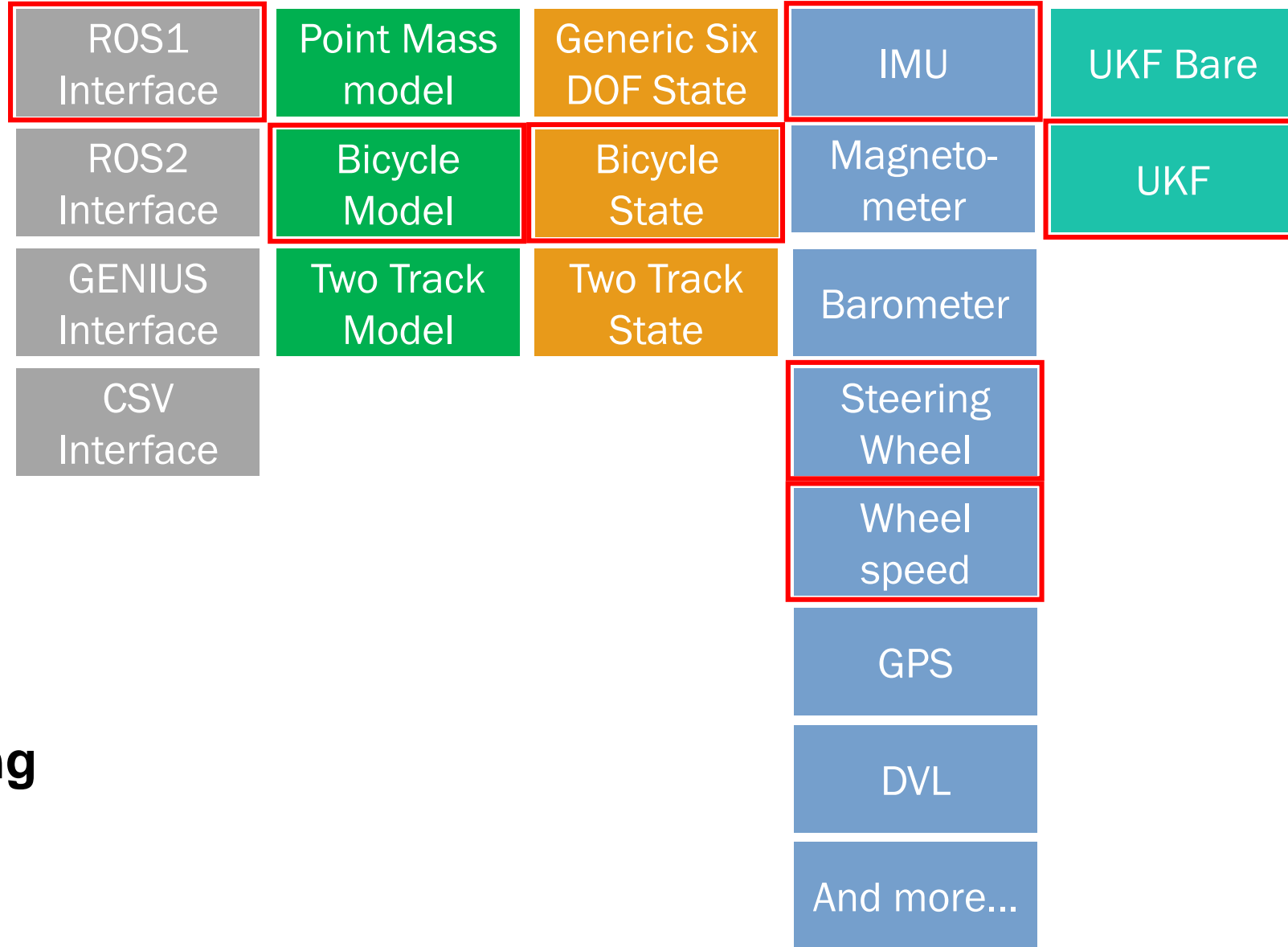
- › Simulation **EN**hanced **SE**nsor **D**esign
- › Which sensor to buy? Not trivial!

› Configurable based on needs

› Selectable predefined components

- › Filter interface
- › Plant model
- › State
- › Sensor model
- › Kalman filter

› **TOPS toolbox keeps growing**



- › Research tool
 - › Configuration & tuning
 - › Sensor analysis
 - › Run state estimator
 - › Results analysis
 - › Online/offline use case

› Maintenance tool

› Operational tool

The screenshot displays the TOPS GUI interface for the configuration file 'dnk_jvs_tt_scenic_vehil_100hz.cfg'. The interface is divided into several panels:

- Config Tree:** A tree view on the left showing configuration parameters such as 'DNK', 'initFilter', 'filterInterfaceCsv', 'state', 'kalmanFilter', 'plantModel', 'acc_in', 'acc_meas', 'gps', 'gyro', 'sw', 'magneto', 'amcl', 'uwb_f', 'uwb_r', 'ws_fl', 'ws_fr', 'ws_rl', 'ws_rr', 'disableSensor', 'wheelIndex', 'angularRate', 'measNoise', 'corrMeasNoise', 'adaptiveCovEstimation', 'learningRateCovEstimation', 'adaptiveCovEstimation_CorrMin', 'alphaCovEstimation_CorrMin', 'correlationWindow', 'correlationTime', 'minBound', 'maxBound', and 'smootherInterface'.
- Plot:** Two line plots showing sensor data over time (0 to 350 seconds).
 - Fig. 0-0:** Acceleration data in m/s/s. The y-axis ranges from -5 to 20. It shows three data series: acc_x (blue), acc_y (orange), and acc_z (green).
 - Fig. 1-0:** Angular rate data in rad/s. The y-axis ranges from -0.4 to 0.6. It shows three data series: pitch_rate (blue), roll_rate (orange), and yaw_rate (green).
- Data:** A panel on the right showing parameters like altitude (m), cov0-cov8, lat (rad), lon (rad), status (-), timestamp, x (m), and y (m). Below it, a list of datastores includes 'gps.csv', 'imu.csv', and 'out_state_tt.csv'.
- Console:** A log window at the bottom left showing system messages and performance metrics, including 'Finished filtering', 'Time elapsed = 24.0489 s', 'Filter iterations = 32227', 'Average cycle time = 0.746235 ms', and 'Average frequency = 1340.06 Hz'.
- Metrics:** A table at the bottom right summarizing performance metrics for the plots.

Plot	RefCurve	Curve	MSE	MAE
Fig. 0-0	acc_x (m/s/s)	acc_y (m/s/s)	0.351535	3.11719
	acc_x (m/s/s)	acc_z (m/s/s)	93.978	15.7266
Fig. 1-0	pitch_rate (rad/s)	roll_rate (rad/s)	0.000985002	0.21875
	pitch_rate (rad/s)	yaw_rate (rad/s)	0.0208105	0.498047

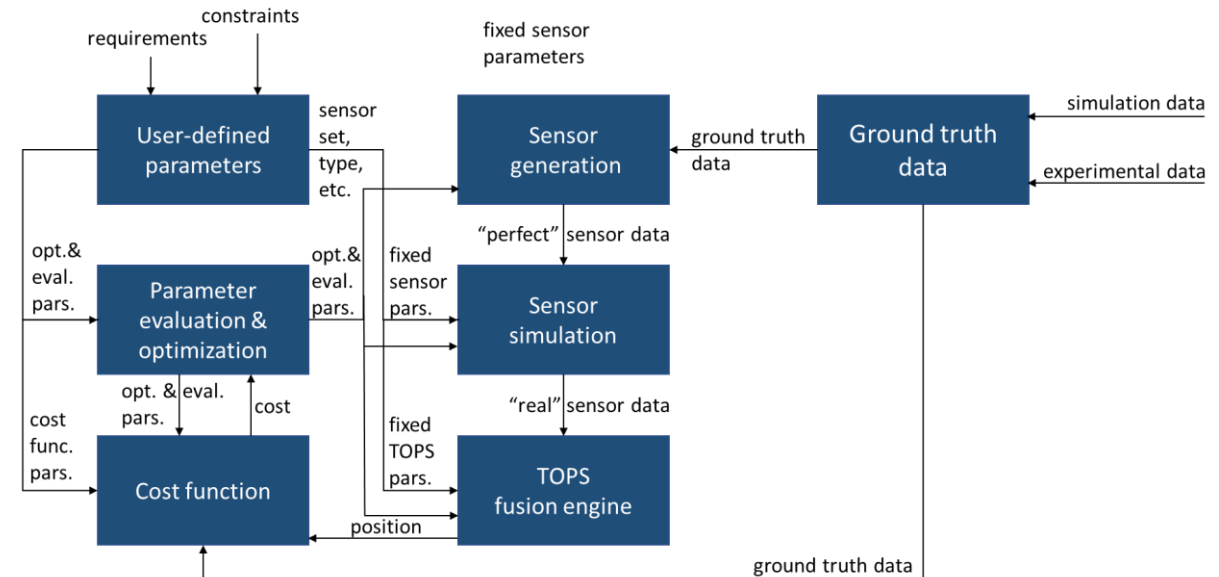
› Problem and functional gap: reasoning from requirement to sensors difficult

› Simulation **EN**hanced **SE**nsor **D**esigner

- › Sensor (suite) designer/optimizer with TOPS
- › Monte-Carlo-style verification

› Why SENSED?

- › Design & sensor optimizer
- › Optimize parameters for cost and requirements
- › Evaluate user-defined parameters
- › Sensitivity analysis



RESULTS LAND BASED USE CASE 1/2

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- › Subsidy project in cooperation with automotive TNO – Helmond
 - › Autonomous driving on bus depot
 - › Indoor/outdoor driving
 - › Development high fidelity vehicle model
 - › Research into GPS replacements
 - › UWB
 - › Lidar SLAM
 - › Laser scan matching
- › Differences military vs civil test case
 - › GPS-denied environment
 - › Off-road
 - › Operations at night time



- › TOPS sensor fusion suite
 - › Vehicle model
 - › IMU
 - › Steer angle
 - › Wheel speeds
- › 15 minute data set
- › Maximum error: 20 meter
- › **Very good!!**



CONCLUSION AND FUTURE DEV.

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- › TOPS proofs a successful framework, toolkit and service!
- › Operational service (white box) for Defence & Safety partners
- › TOPS continue to improve and functionality added
 - › Sensor fusion: platform model enhancements
 - › User-friendly GUI for operational (& maintenance) usage
 - › Indicator for sensor input and fusion output quality
- › Research & provision for new disruptive technologies
 - › Quantum sensors can boost gravity gradiometry
 - › Effect of new technology (TOPS - SENSED)
- › Cooperation and standardization
 - › NATO RTG (SET-309)
 - › Standardization sensor input and PNT-info output

ROS1 Interface	Point Mass model	Generic Six DOF State	IMU	UKF Bare
ROS2 Interface	Bicycle Model	Bicycle State	Magneto-meter	UKF
GENIUS Interface	Two Track Model	Two Track State	Steering Wheel	
CSV Interface			Wheel speed	
			Barometer	
			GPS	
			DVL	

