Timing, Orientation & Positioning Service (TOPS)

Modular sensor-fusion framework to achieve accurate and reliable time and position information

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ABSTRACT

Today, our society is largely dependent on the Position, Navigation & Timing (PNT) information provided by Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS), GLONASS, Beidou and Galileo. These systems can provide accurate global position estimates and timing information. Timing information is often used for synchronization between systems. However, due to the nature of the weak signal strength of GNSS systems they are vulnerable to (intentional) disruption. Especially in military context, jamming and spoofing form a significant threat to operational efficacy. Often there is no automated solution to recognize these threats while providing accurate PNT information when GNSS is unavailable or compromised.

Subsequently the philosophy is that armed forces should not rely on any single sensor solution for their PNT information. Rather, multiple sensors should be used to complement each other's strengths and create redundancies. It is recognized that multiple suppliers within the industry will provide sensors for a single military platform. Depending on the supplier a level of processing and/or fusion will be done by the sensor itself.

This paper proposes a modular sensor-fusion framework, Timing, Orientation & Positioning Service (TOPS), that can combine sensor information to achieve accurate PNT information. To assure the availability of a navigation solution under GNSS denied conditions, TOPS can combine a wide variety of alternative navigation (Alt-NAV) sensors, such as Inertial Navigation Systems (INS), land-based radio navigation systems, database matching navigation systems, odometry and velocimetry based systems, etc. Two example scenarios are provided where TOPS was employed, one concerning a land based vehicle and the other an Autonomous Underwater Vehicle (AUV).

1.0 INTRODUCTION

Navigation technology is foundational for modern warfare to the extent that not being able to maintain time, position and orientation equates to defeat. The combination of an INS with GNSS, conventionally GPS, have been a backbone for military navigation systems in the past decades. However, such systems suffer acute fundamental shortcoming; GNSS relies on weak radio signals which are easy to jam and are even spoofable in some cases, such as for Open Signal GPS. On the other hand, all INS solutions suffer from integration drift and must be periodically corrected by using an Earth fixed reference.

As a result, research and development efforts have been focused on improving the robustness of military grade INS/GNSS based navigation solutions. One can think of applying Controlled Reception Pattern Antennas (CRPA) to improve the sensitivity for the GNSS signals through directional sensitivity or by boosting of the GPS signal power at the satellite. Additionally, methods are developed for signal authentication and signal integrity monitoring in order to make a navigation solution less susceptible to spoofing and meaconing. Nevertheless, the use of RF signals remains a fundamental vulnerability for satellite based navigation solutions.

In order to assure the availability of a navigation solution under GNSS denied conditions, a multitude of alternative navigation sensors are applied that measure Earth fixed features. One can think of sensing the Earth's magnetic field with a magnetic sensor, or detect static objects/features in the environment with acoustic, visual or radar systems in order to aid the continuity of a navigation solution. Many of these alternative sensing techniques require active signals and/or are susceptible to external disturbances. Due to large differences in the environments where navigation solutions are needed, manufacturers integrate navigation solutions with different combinations of navigation sensors, often using their own sensor technology as a basis. Here some issues arise;

First, not every manufacturer has access to the best sensor technology for each of the navigation sensors used in their integrated navigation solutions. This leads to suboptimal navigation solutions and a vendor lock-in scenario where navigation data from alternative sources/sensors must be fused in the existing navigation solution.

Second, the integrated navigation solution generally includes an extensive set of algorithmic methods, which forms a black box to the end-user. Due to this obfuscation of the details in the signal processing, the behavior of the integrated navigation is not always trusted or well understood by its end-user, especially under GNSS-challenged conditions.

Integrated navigation solutions lack standardization on interfaces and algorithmic behavior. The lack of modular/open architectures for navigation systems result in a cost explosion when new sensors must be integrated into existing navigation solutions. Many defense organizations identified this problem and started developing their own 'white box' navigation toolkits focused on modular and open architectures for PNT solutions.

TNO[1], the Netherlands Organization for applied scientific research, is an independent and not-for-profit research organization with in depth knowledge of different (sensor) technologies. TNO is the center of excellence for research and development for the Netherlands Ministry of Defense (MoD). TNO developed a roadmap for navigation technology based on a shared vision with the MoD. Based on this roadmap, TNO took the challenge to start the development of the Timing, Orientation & Positioning Service (TOPS) software suite which addresses the specific requirement for a 'white-box' navigation toolkit for the Dutch armed forces.

[1] TNO is an acronym for "Toegepast Natuurwetenschappelijk Onderzoek" which means "Applied Scientific Research".

2.0 WHAT IS THE TOPS SOFTWARE SUITE?

The TOPS software suite consists of a collection of flexible software components that can be used for developing navigation solutions. These tools can be categorized into three distinct modules (visualized in figure 2-1):

- **Fusion engine –** includes the state estimator and configuration files as well as optional preprocessing and post processing components. The fusion engine is capable of fusing both real-time and offline sensor data.
- **Graphical User Interface** – for configuring, monitoring and analyzing the sensor fusion tool.
- **Sensor Suite Optimization toolset** – for offline simulation and optimization of the sensor suite.

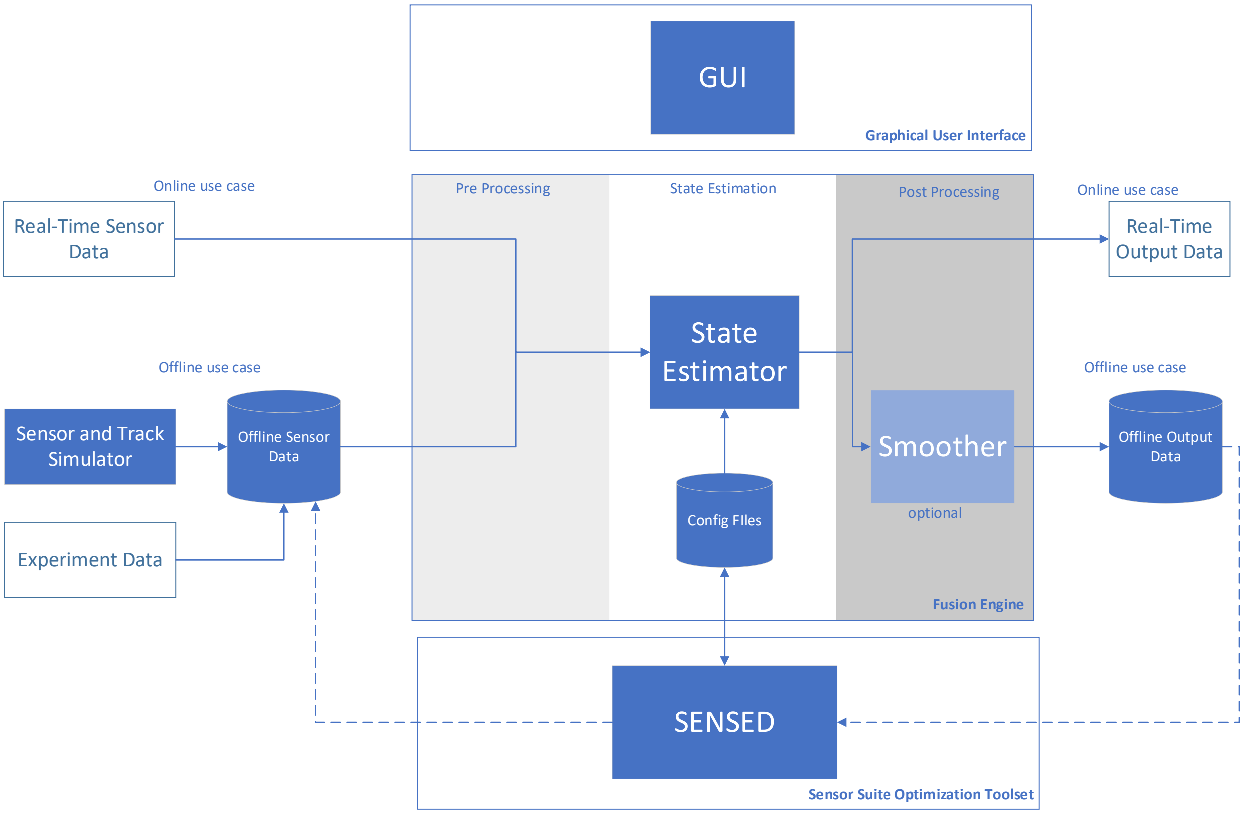

Figure 2-1: TOPS main components and two distinct use-cases (online/offline).

2.1 The Fusion Engine

The fusion engine is modular in its setup in order to maximize reusability. The software components are all written in high quality C++ and have a minimum dependency on external software libraries. The software components are operating system independent. The aim for the fusion engine is that navigation fusion software can be automatically generated for different hardware configurations (sensor suites) through configuration files only.

Although the initial development took some extra effort, the reusability now provides a return in efficiency during the development of the sensor fusion software for user-specific navigation solutions.

The fusion engine includes a long list of software components for integrating specific and generic navigation sensors as depicted in figure 2-2. As a result of the modular approach new sensors can easily be added to the fusion engine.

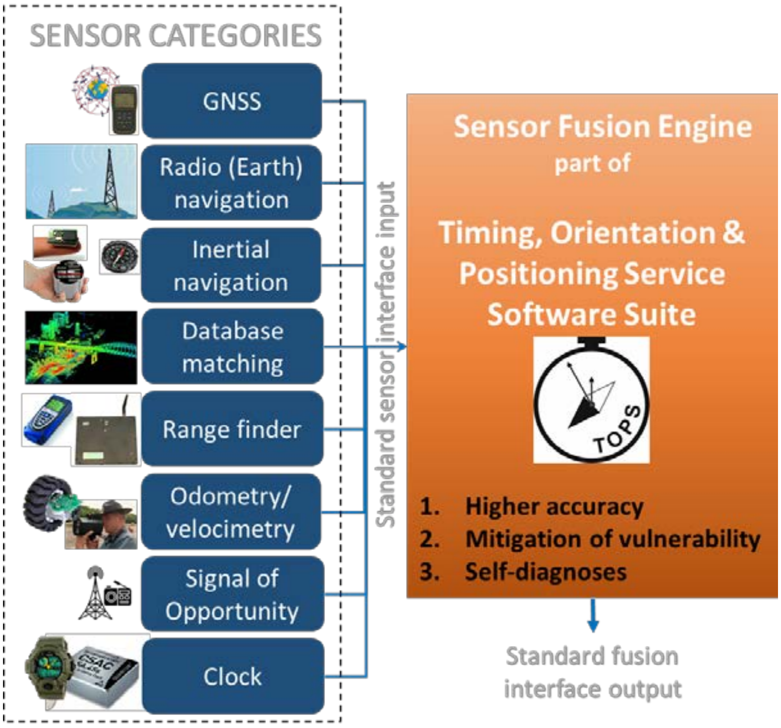

Figure 2-2: TOPS concept overview.

Currently the main method to interface with TOPS is via Comma Separated Files (CSV) for the offline use case and via Robot Operating System (ROS) [3] topics/messages for the online/real-time use case. ROS is an open-source robotics middleware suite. Similar to the sensors, new interfaces can be added without any impact on other modules in the fusion engine.

The fusion engine incorporates a version of the Unscented Kalman Filter (UKF) [4], which allows for non-linear transformations between sensors and states, making it usable by a more diverse set of sensors and is significantly more accurate than the linearization-based Extended Kalman Filter (EKF) [5]. On top of that, the UKF is highly extended with distinctive features such as outlier detection, covariance intersection and more. This significantly improves the consistency of the position estimates, as it accounts for unknown/unmodeled measurement correlations, which is essential for SLAM-based navigation solutions and map-matching techniques.

Besides that, the fusion engine provides an alternative for this high-end fusion algorithm, named Bare-UKF, which utilizes the same UKF algorithm but does not include all the above mentioned features. As a result, it provides less accurate results but reduces the computational burden significantly and therefore addresses (embedded) navigation solutions which require a small Size, Weight, Power and Cost (SWaP-C). This version of the UKF can also be used in civil projects, since it does not contain government classified technology.

Figure 2-3 illustrates the current predefined components which can be selected. However, the TOPS software suite keeps growing based on needs.

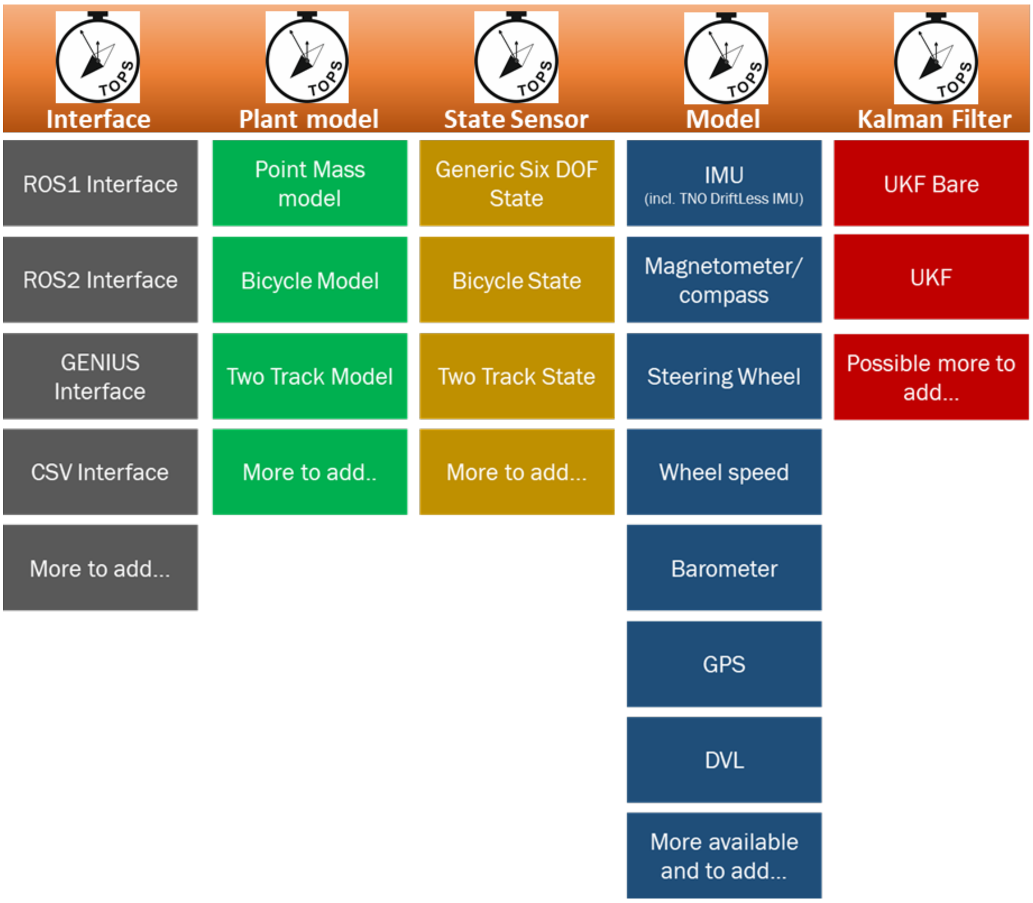

Figure 2-3: Overview of TOPS predefined components at September 2021.

2.2 The Graphical User Interface

The current Graphical User Interface (GUI) in the TOPS software suite is developed as a flexible analysis tool for the evaluation/comparison of existing navigation sensors and integrated navigation solutions. An example of the GUI can be found in Figure 2-4 and figure 2-5. In the near future maintenance and operational views with the end user in mind will be designed and added.

The main features of the GUI include:

- Displaying input sensor data from either an offline source or online sensors.
- Displaying fusion engine output data from offline data or from online fusion engine.
- Comparison of multiple datasets, including computed metrics.
- Manipulating the configuration of the fusion engine:
  - Component selection for the fusion engine. This defines which components of the toolset will be activated during runtime, tailored to the specific use case.
  - Parameter tuning. This contains all tuning parameters used in the algorithms.

- Enabling/disabling of sensors in the fusion engine. Sensors can easily be enabled/disabled to see the effect in the fused output.
- Interface specific settings. This defines where input data can be found and where to send output data.

Figure 2-4: TOPS GUI, showing the configuration tree and the plotting capabilities.

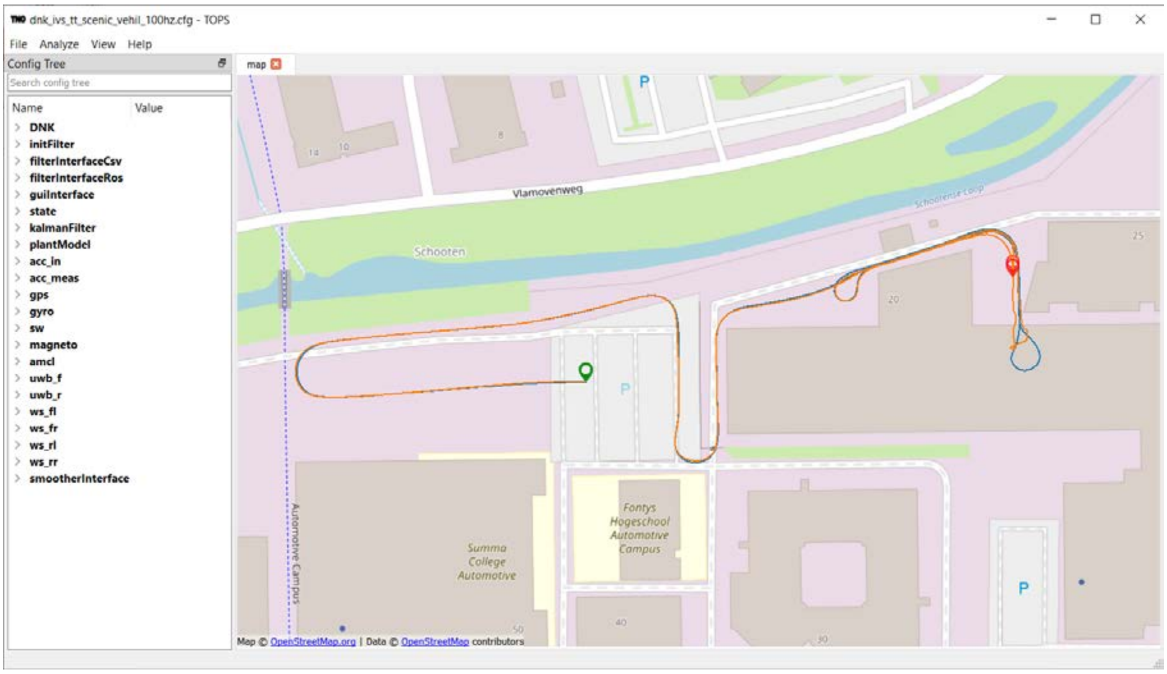

Figure 2-5: TOPS GUI, showing the map plot

2.3 The Sensor Suite Optimization Toolset

When designing a navigation solution, users often find it difficult to define the required individual sensor specifications to meet an accuracy requirement on the fused output. Due to the complex nature of the fusion algorithms, the influence of individual sensors on the estimation of position and intermediate states cannot be easily derived.

The TOPS software suite incorporates the optimization toolkit Simulation ENhanced SEnsor Designer (SENSED) to design a navigation solution. SENSED allows running the TOPS fusion engine in a continuous loop inside a simulated environment (offline mode). Different sensor set(s) and parameters can be evaluated and optimized to achieve the most affordable sensor set for a certain (position) accuracy requirement. Sensor parameters are for instance: noise characteristics, outliers, sampling rate, time delay and jitter. It also allows (end) users and engineers to perform a sensitivity analysis on their sensor set; the relation between improving sensor (suite) characteristics and cost can be made evident. Consequentially a well-educated selection of sensors can be made.

An advantage of this approach is that for evaluation, changes can be easily contained in a list and combined where necessary. This makes considering multiple adaptations (taking place at the same time or not) to the sensor set very accessible.

Figure 2-6 shows the SENSED program layout. The user needs to translate their requirements and constraints to compatible parameters for the program, supply ground truth data and sensor specifications. Then SENSED can optimize or evaluate parameter sets, returning the cost function of each solution to the user.

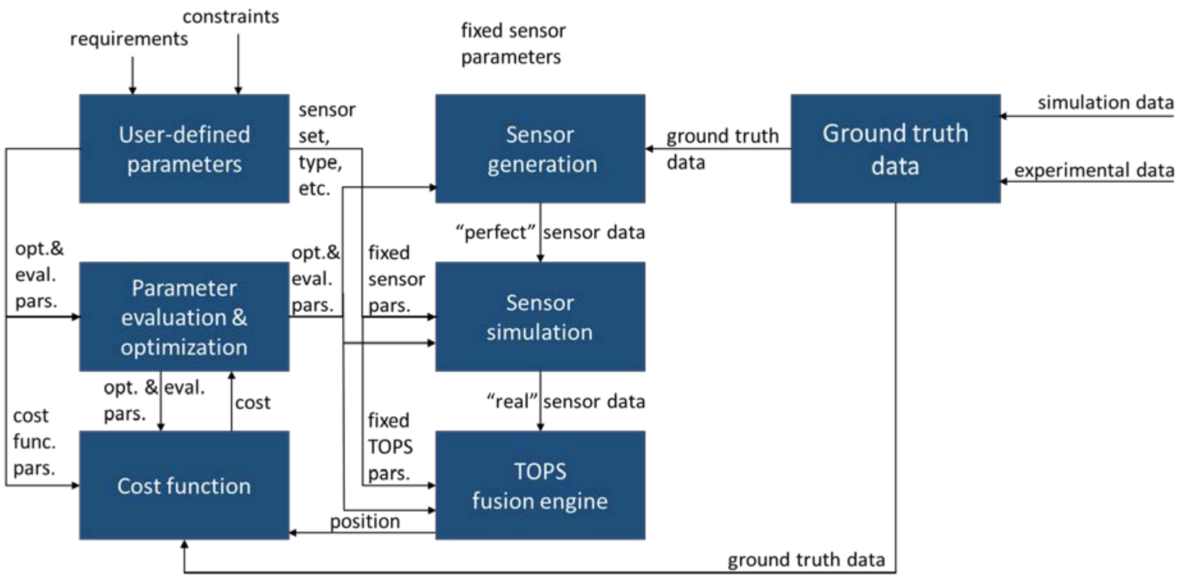

Figure 2-6: SENSED program layout.

Figure 2-7 shows an example of an application of SENSED. In this case it is used to find which sensor characteristics are needed to achieve a position accuracy requirement, for a novel sensor design. Optimization is used to find the highest measurement noise of the sensor at which the position accuracy requirement may be achieved. The left plot shows the trend between measurement noise and standard deviation in position error with requirement level indicated. The right plot shows the cost function that was used. This cost function consists of two parts, one part pertains to the requirement and the other to the measurement noise. Consequently, a sensor manufacturer can be provided with these specifications to produce the sensor.

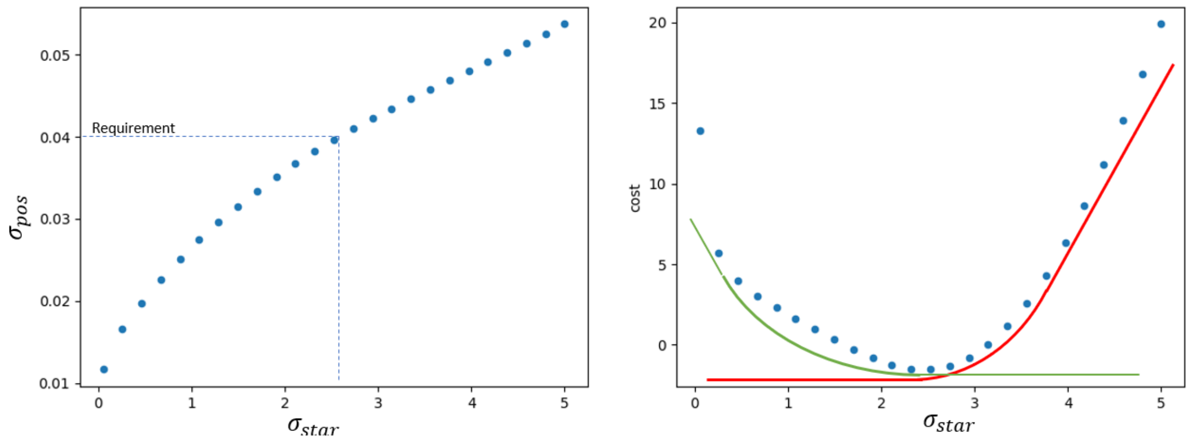

Figure 2-7: Example of SENSED application, design of a sensor; finding the noise parameters needed to achieve a certain position estimation accuracy.

3.0 TOPS RESULTS FOR DIFFERENT USE CASES

Within TNO there are multiple departments, including Intelligent Autonomous Systems, Radar, Acoustics & Sonar, Intelligent Imaging and Electronic Defense, which each have their expertise in certain (sensor) technologies used in different domains, e.g. air, land, water and underwater. These expertise/research groups enable the fusion of multiple disparate sensors on the lowest possible level (tight coupling) to get an optimal state with known certainty. In 2010 TNO, together with the Royal foundation Netherlands Aerospace Centre (NLR2) and Dutch Space, nowadays Airbus Defense and Space Netherlands part of EADS Astrium, won the Dutch Defense Innovation Game with the concept of sensor fusion. As a result a successful feasibility study was conducted to show the effects of different combination of fusing the data from INS, GPS, relative range measuring and barometer. A very early version of TOPS [1] was used to fuse data of the TNO DriftLess™ Inertial Measurement Unit (IMU) [2] together with Ultra Wideband (UWB) beacons for real-time underground navigation in mines. Two more recent use cases are discussed in section 3.2 (underwater use case) and 3.3 (land based use case).

3.2 Underwater Navigation, Aided By Feature Tracking Algorithms

One of the domains for which TOPS is highly applicable is the underwater domain. Due to the characteristics of water, the usage of GNSS sensors is impossible, and therefore one needs to navigate on internal sensors, such as IMU's, a Doppler Velocity Logger (DVL), a magnetometer or a barometer. Due to the modularity of TOPS, these sensors can be configured with relatively low effort, making it possible to apply sensor fusion to this specific set of sensors.

Figure 3-1 shows an example of how TOPS compares to an onboard position estimator provided by the manufacturer of the AUV used in this test case. The image illustrates the data captured during a one hour long underwater campaign, in which the AUV completed four laps of the designated course, while actively detecting features on the lakebed. Initially, the AUV was floating on the surface and had a strong GPS connection. During this period there is a close overlap between the performance of the AUV and TOPS filters, this is to be expected as the AUV's position is well known. After the AUV dives the TOPS-UKF starts to diverge from the AUV's onboard estimator. During this period both filters suffer from drift, but in different directions. The magnitude of this drift (the absolute performance) is similar as both had comparable offsets with the GPS upon

[2] NLR is an acronym for "Nederlands Lucht- en Ruimtevaartcentrum" which means "Netherlands Aerospace Centre".

completing the course and returning to the surface. The AUV has a Side Scan Sonar that allows it to detect bottom features, which enable it to judge the relative drift over time for each filter. By doing multiple laps the same features are detected multiple times, allowing for comparison of the spread and analyze the relative drift over time. The spread of these features is almost equal, which demonstrates that TOPS-UKF filter is able to perform as well as the onboard state-estimator that is specifically tuned for the system. It should also be noted that the onboard estimator has higher IMU data-rates available. This showcases an important strength of TOPS, that while being system-agnostic, it is capable to perform as well as tailor-made sensor fusion algorithms.

In a similar fashion, TOPS offers the possibility to fuse higher-level 'sensors', such as a SLAM-based feature tracking algorithm. Figure 3-1 shows how the addition of SLAM has significantly reduced the location uncertainty of the AUV by matching bottom features that are detected by the Side Scan Sonar when passing over them multiple times. The ability to add and configure any module that provides navigation-related data, makes TOPS a versatile tool. Founded on the same strong UKF algorithm, it is configurable for any vehicle, whether it is an underwater-, aerial- or land vehicle.

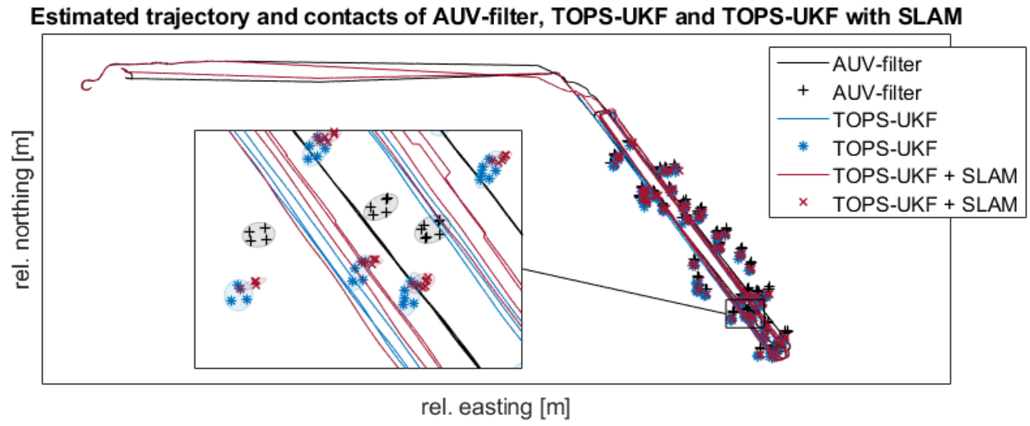

Figure 3-1: Performance of TOPS on AUV data (blue, red) compared to the onboard position estimator (black).

3.3 Land Based Navigation, Aided By Odometry And High Fidelity Vehicle Models

In 2020-2021 a subsidy project was undertaken to investigate the possibilities of automation of a bus depot. For this purpose the possibility of autonomously driven buses was investigated for which precise positioning is needed. Bus routes typically include stretches of outdoor and indoor driving which makes GNSS unsuitable as the continuous solution, other local position systems such as UWB can be applied but suffer from higher errors.

Therefore, the added value of a high fidelity vehicle model was investigated. The purpose of the model is to fill in the positioning gaps when a position signal of GNSS and/or UWB was lost and to smooth out noise from the UWB. A "two-track" model was developed where four individual wheels with forces and moments are modelled.

Figure 3-2 shows the planar position result of a 15 minute test drive with a Renault Grand Scenic. Both the GNSS position and the fusion positioning result are shown. The GNSS signal is labelled OxTS which is a RTK GPS system with cm accuracy. However there is one defect in the signal in the left part of the graph where the route went in between two buildings. The test drive was performed at the automotive campus in Helmond the Netherlands in February during snowy conditions. The fusion does not use any GNSS signal, instead it fully relies on the steering wheel, IMU, wheel-speeds and two-track vehicle model. The error over the test drive varies, with a maximum of around 20 meters. The general shape of the path is clearly captured by the fusion result, however the corners tend to cause small deviations. The expected cause for this is that the model parameters were estimated on a different day where weather conditions were significantly better.

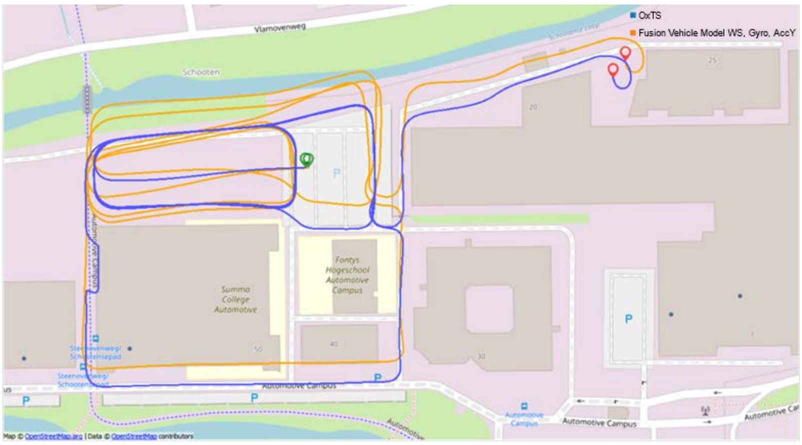

Figure 3-2: RTK GPS (OxTS) position signal and fusion result in 15 minute data set Renault Grand Scenic.

Although this development was originally targeted for civil use-cases the results show real potential for military purposes. The sensor combination used is much cheaper than state-of-the-art INS used in military vehicles while maintaining similar or even better position accuracy. The introduction of high fidelity vehicle models can give the armed forces a GNSS denied capability for their land vehicles while simultaneously reducing the hardware cost. There is a research opportunity to find the applicability of higher fidelity models to off-road conditions that better capture the military use-case.

4.0 FUTURE DEVELOPMENTS

4.1 TOPS Software Suite

TNO will continue to develop and improve the TOPS software suite with an emphasis on enhancing the functionality of the three main components. The starting point is and remains the development of good future-proof software that is easy to configure by the end user. The output of TOPS will be monitored, analyzed, explained and traced via intuitive GUIs. For research applications within TNO and when TOPS is deployed in Defense, the code base will be transparent making it possible to resolve unexpected behavior which can't be easily explained with the different tools from TOPS.

4.1.1 Sensor Fusion

Research will be conducted on developing robust fusion algorithms which can guarantee good PNT estimates, that are reliable over long time periods, with minimal or no required infrastructure. Additional focus will be placed on developing new sensor techniques and in improving models, for example considerable effort is being placed on enhancing the current land based vehicles models.

Keeping one eye on the future, the adoption of possible self-learning methods and other Artificial Intelligence (AI) techniques like neural networks to minimize the amount of tuning parameters for the end-user are being investigated. Such approaches will foster novel fusion algorithms and/or enhancements of current implementations. Regardless of the path forward, TOPS fusion engine will strive to boost the accuracy, robustness, integrity and reliability of PNT services.

4.1.2 Graphical User Interface

Although new features will be added to the GUI to enhance TOPS as a research software suite, focus will be shifted to GUI's for operational and maintenance usage. It is foreseen to have TOPS running in real life Defense application.

4.1.3 Sensor Suite Optimization

Quantum technology promises to bring new sensors to the market with potential new capabilities. TOPS and in particular SENSED will be expanded to model and simulate the capabilities of these new sensors to examine their possible effect on the total navigation solution. The positive side effect is that TOPS is already prepared to integrate such new sensors in an operational setting.

4.2 Research Into And Provision For New Disruptive Technology

One of the technologies which will significantly profit from quantum sensing technology, is gravity gradiometry. A Gravity Gradiometer Instrument (GGI) or gradiometer is an instrument that measures the earth gravity gradient.

A significant benefit of including a (moving base) gravity gradiometer in a navigation solution is that the Earth's gravity field cannot be jammed and is practically unspoofable by adversaries. A second benefit of gravity gradiometry is the (theoretical) independence of the gravity gradient measurement on the linear motion or acceleration of vehicle/platform where the gravity gradiometer is installed. Accelerometers can only measure the sum of the gravitational acceleration and the platform's acceleration, which makes it challenging to make an independent estimate of both components.

In the past decades, Gravity Gradient Referenced Navigation (GGRN) systems have been used in submarines, aircraft and satellites, but its applicability has been limited due to the following aspects:

- the challenging requirements that GGRN systems impose on the isolation of the sensor system.
- the bulky nature of the system, both in size and weight, makes it unfit for all but the largest platforms.
- the (still) limited precision these sensors can provide.
- the limited availability of high resolution gravity gradient maps of the world.

With the development of (new) quantum sensors, the limits imposed by the first three aspects are beginning to shift. The current limits in size, weight and measurement precision are engineering limits. No fundamental physics will block further miniaturization. In the long run, a chip scale alternative navigation system could be constructed that delivers GPS precision in GPS denied environments.

In order to support the anticipated trend in GGRN system solutions, the TOPS framework is being extended with specific features that support the evaluation and design of GGRN system solutions. These features include:

- A high fidelity gravity field simulator.
- A collection of quantum sensor models (accelerometers, gravity gradient sensors and atomic clocks) which make use of the high fidelity gravity field model.
- Algorithms for map-matching navigation extended to gravity gradient maps.

4.3 Cooperation And Standardization

In order to support the standardization of navigation systems, the Dutch Ministry of Defense has the intention to join the new NATO Research Task Group for PNT Open System Architecture & Standards to Ensure PNT in NAVWAR Environments (SET-309). Here TNO will be tasked to leverage our knowledge of the TOPS development to the standardization of navigation systems within NATO, and to contribute to the development for future navigation systems.

5.0 CONCLUSION

With its strong scientific background, engineering experience and a long history in navigation technology research, TNO supports the Dutch Ministry of Defense (MoD) and its allies in developing the navigation solutions of tomorrow. The TOPS software suit, resulting from the implementation of the TNO navigation roadmap, is focused on GNSS independent, autonomous navigation solutions, standardization and international collaboration. No single sensor system is (at this moment) capable of providing assured-PNT for all conditions and scenarios which varies from platform to platform, from operation to operation and from domain to domain. Moreover, there is also no single fusion algorithm capable of combining disparate sensor data in a meaning manner.

The TOPS software suite consists of a collection of flexible software components, that can be used for developing navigation solutions for a wide variety of use cases and input sensors. The fusion engine, the GUI and SENSED are highly configurable. TOPS enable the ability to research and analyze innovative sensor processing methods, to determine which sensors to use and or buy, to analyze sensor fusion output online and offline and to test and validate navigation solutions. TOPS is at this moment primarily a research tool, however at its core TOPS has been mindfully designed and developed with operational usage in mind. Good software development techniques have been employed to guarantee high quality software. The TOPS software suite has a single software base to maintain and deploy, is platform independent and highly modular.

Although not yet operationally deployed, the TOPS fusion engine is capable of running as a real time service to suit a wide variety of use cases. By avoiding single sensor dependency and complementing the strengths of different sensor techniques, redundancies are created and robustness and resilience are obtained as well as high accuracy. Due to self-diagnoses, the integrity of input signals is also obtained. Future development of the TOPS software suite focusses on further enhancement of the fusion engine, added sensor support for new disruptive technologies not yet on the market, as well as maintenance and operational GUIs for Defense and enhancement of SENSED.

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