Cooperative PNT Overview: Cooperative / Collaborative PNT Technology Trends

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ABSTRACT

This paper takes a general look at navigation systems before GNSS navigation systems and after. Observing changes and user requirements, it looks at the future of the navigation systems and offers a better architecture for designing integrated navigation systems. The design, integration, and real life demonstration of offered new architecture is taking place in a separate study which is expected to finish and publish its results next year.

1.0 NAVIGATION SYSTEMS BEFORE GNSS

Navigation became a problem to be solved by invention of long distance ships. Early sailors had to keep land in sight not to get lost till they learned to use the stars, sun, and moon for navigational purposes. It was a dangerous and risky business to sail open seas. Even though it was relatively easy to be able to measure one's latitude at sea (using north star), measuring one's latitude needed accurate time and was only became possible by invent of chronometer by John Harrison in 1761, which stayed a military secret and a luxury for a long time.

By invent of airplanes navigation became a much greater concern. After invention of radios, inertial sensors and radar, and immense need from second world war many different navigation systems were invented. Intercontinental missiles and era of space exploration, race to the moon created more complicated and more reliable navigation systems.

Each navigation system was designed to solve a basic problem and they worked in their own world without really thinking about other possibilities or even existence of other navigation systems. If there were more than one navigation system, such as on a ship, it was the navigation officer's or the captain's duty to decide which system or systems to use, even keep a separate log and make measurements regularly to check the systems. Navigation systems generally did not know if there was a second system and never shared information with each other.

When inertial navigation systems started becoming dominant navigation system in military equipment this view had to be changed. Inertial navigation systems were the only possible choice for most military applications but their unboundedly increasing errors had to be controlled or limited by other means, and we started seeing inertial navigation system aided by other navigation systems, from celestial navigation to Doppler radar many different techniques are used to aid the inertial navigation systems. These integrated systems were designed by the designer of the inertial navigation system and were under full control of that designer including the algorithms used to do integration.

2.0 NAVIGATION SYSTEMS AFTER GNSS

In October 1957, the Soviet Union launched the world's first artificial satellite, Sputnik. Scientists monitor Sputnik's radio beacon to determine its orbit. The idea of working backwards, using known satellite orbits to determine an unknown position on the Earth's surface started the age of satellite navigation. Currently there are four global coverage satellite navigation systems (GNSS), they are

- Global Positioning System – GPS from USA
- GLObalnaya NAvigatsionnaya Sputnikovaya Sistema – GLONASS from Russia
- GALILEO from European Union
- BeiDou Navigation Satellite System from China

Use of these systems by civilians, rapid decrease in size, weight, and power consumption together with rapid increase of unmanned and robotic system use, brought an unprecedented explosion of navigation systems. GNSS systems find themselves uses in thousands of new areas and changed the understanding and use of navigation totally. There are now local and wide area augmentation systems available in most of the world to bring GNSS error down to a minimum. These together changed the expectation of users from navigation systems.

While a navigation officer was happy with 200 meters of error a few decades ago today's user expects to work within a few meters every day in all conditions. If GNSS systems did not had their issues and if they were available in all conditions all the time, we may even be not talking about any other navigation system at all.

2.1 GNSS Vulnerabilities

While there are four different global navigation system currently operational a closer examination shows that they are actually very similar to each other, in concept, in architecture and in vulnerabilities. One of the main problems is the power level of GNSS signals due to distance of the transmitters from earth (around 20,000 km.), coverage area per satellite (about 1/3 of earth's surface per satellite) and transmission power available at the satellite. This results in a very low power systems with received signal strengths of around -120 to -130 dBm. This is a very low power system making it open to spoofing (false signal transmission), jamming (intentional interference) and even to unintentional interference from other unrelated systems. The signal also will not penetrate dense foliage, buildings, caves etc. making use in indoors and underground impossible while use in urban areas could be problematic. Detailed information on GNSS vulnerabilities and possible remedies together with several military scenarios are given in an earlier work of this group, "Navigation Sensors and Systems in Global Navigation Satellite System Degraded and Denied Environments" published by STO.

2.2 What if GNSS is Unavailable

If GNSS systems are unavailable one assumes we can use the earlier systems as before. But user expectations and use areas of navigation are already changed and, in many cases, old systems performances are not acceptable any more. User demands a backup system that he can use in case GNSS is not available that delivers the same performance as a GNSS system. User also wants it to be as cheap as GNSS (for civil applications could be a few dollars), as small and light as GNSS (less than .1g GNSS chips exist) and this problem does not seem to have a solution at this time.

2.3 INS/GNSS or GNSS/INS Integrated Systems

Internal Navigation Systems are self-contained, continuous but they require initialization, and their errors increase with time (some errors with t^2 and t^3). On the other hand, GNSS systems need no initialization, errors are bounded and do not increase with time, but they are discontinuous and can be denied or degraded. Combining these two creates an almost ideal navigation system and they are probably the most widely used military navigation today. While these systems are called INS/GNSS 20 years ago thinking INS is the main system and GNSS is aiding that today they are more commonly called GNSS/INS systems (INS aided GNSS systems – another indication of popularity of GNSS systems).

In these systems INS measurements and GPS measurements are used together, most commonly, using a Kalman filter which not only can give blended position and attitude results that can also calculate INS error states (calibrates the INS system). If GNSS is available the final accuracy of the result will be very close to that – it will be a smoothed version of GNSS results. If GNSS is lost after some time accuracy will degrade according to the quality of the INS system. For a typical aircraft system this value is about 1 nm/hr, for a ship system 1 nm/day. Best systems, where money, volume, weight, and power consumption are not factors, can provide 1 nm/6months while very cheap and small MEMS sensor system can be as bad as 100m/sec. When GNSS is available all these systems perform very close to each other.

3.0 PROTECTING AND IMPROVING GNSS

We have seen above GNSS systems offer us the best performance to minimum cost, weight, size, power but they have vulnerabilities. So, the first thing to do is to see if we can eliminate or decrease these vulnerabilities either improving the GNSS system or by deploying other means to protect it. In this section we will mention some of the major ones that are open to public.

3.1 Signal Improvements

GNSS systems generally have two separate signals (like L1 and L2 for GPS, E1 and E2 for Galileo) to enable user to compute ionosphere delays and hence get better performance. Secondary signals that were once only open to military users are now open to civilian users as well. In addition, a signal in civil aviation band added (L5 or E5) to elevate civil aviation's GNSS use.

GPS system is adding a new signal, M code, both to L1 and L2 frequencies to make jamming and spoofing of GPS harder. This new signal will also enable GPS system to boost its signal around 10 fold in specific areas of interest making jamming and spoofing that much harder.

Galileo system has services to warn users if signals are out of specs for any reason.

GNSS producers are always looking for new way to improve their service but since this is a service provided from satellites and adding new capabilities will require new satellites this process is generally slow and it takes number of years for a new signal, service to be available.

3.2 Augmentation Systems

Another way to improve GNSS service is to have an independent system that measures observed errors in performance, computes possible corrections and disseminate this correction information over another signal. This can be done locally as in an airport (Local Area Augmentation System -LAAS) or on country scale (Wide Area Augmentation System – WAAS) or in continent scale (European Geostationary Navigation Overlay Service – EGNOS). The system can also provide an integrity message to inform users in the event of signal problems.

3.3 Use of Multi Constellation Systems

To use more than one GNSS system is another way of checking the performance and especially improving integrity. Today's GNSS based aircraft aiding systems are required to use at least two different frequencies and two independent GNSS systems. Even if this does not eliminate the intentional attacks on GNSS systems it is a precaution against unintended interference or operational problems in one of the GNSS systems.

3.4 Receiver Autonomous Integrity Monitoring (RAIM)

At the receiver software level, an improvement worth mentioning is a fault detection function called Receiver Autonomous Integrity Monitoring (RAIM). RAIM requires redundant satellite range measurements (at least 5 satellites with good geometry) to detect a faulty satellite signal and alert the user. Alert occurs when the receiver detects a satellite fault, assuming that enough satellites are available (minimum 6), RAIM has the ability to detect the faulty satellite and then exclude that satellite and continue to provide reliable navigation data.

3.5 Antijam, CRPA, Antennas

Adaptive antenna array technology, such as Controlled Reception Pattern Antenna (CRPA) is an established solution to counter jamming threats. An adaptive antenna consists of an array of antenna elements and a signal processor that can automatically sense the presence of high levels of jamming coming from particular directions. It then changes the gain pattern of the antenna array so that areas of low gain are steered towards the directions of the jammers, while retaining areas of high gain in all other directions, particularly toward the GNSS satellites. There are currently many products of different sizes and shapes exist in the market that boast over 40 dB protection against jamming.

3.6 Chip Scale Atomic Clocks

Improving a GNSS user equipment's clock can decrease its vulnerability to jamming and spoofing. As the price of chip scale atomic clocks are decreasing this may be another way to protect the GNSS system.

4.0 BEST SOLUTION

While GNSS systems appear to be most useful navigation systems for most applications their vulnerabilities prevent them from being the only solution. There has been intensive research on new navigation systems but the solution seems to be the one everyone can see, integrate all possible navigation systems and use the ones available on the platform on the day of the task to best of their performance.

While this sentence is easy enough to say how to do it becomes much more complicated. Creating a Kalman filter integration of all known navigation systems to the best of their individual performance as well as to get the best overall performance can be an immense task, it will not only take huge amount of work it will also create a large amount of where most of it gets never used in this or that application. Plus, it will be property of the company who undertake this immense challenge, as a result it will not be flexible or easy to update when changes happen.

Even though, Kalman filter integration of several navigation systems provides optimal combined result for those navigation provided that designer knows error statistics of the integrated navigation systems this is still a big challenge, especially if you want to integrate more than a few systems. Companies are designing more and more integrated navigation systems each day, but this does not seem to converge to a final system and creates more questions each day.

- Which navigation Systems should we integrate
  - INS / GNSS
  - INS / GNSS + Doppler Radar
  - INS / GNSS + TACAN
  - INS / GNSS + LORAN
  - INS / GNSS + Speed Sensor (Tachometer, Log speed etc.)
  - IMU / UWB
  - IMU / Vision Based
  - IMU / Radar
- For which user we need to do the integration
  - Air – fast aircraft, sudden manoeuvres
  - Sea – slow steady systems
  - Land – slow systems that can stop
  - Space –
  - Undersea –
  - etc.

5.0 BETTER SOLUTIONS

Even though it stands to reason integrating every available navigation data according to its performance idea is the way to go, seeing this integrated navigation system is not an easy task to complete a new way of looking at the problem is needed. Let us go back and ask the main question:

How can you integrate two independent navigation system with each other? Let us deepen the question a bit more, if you have two independent navigation systems one with 30m of error and another with 300m of error how do you combine these two navigation systems and get a blended result? What if the system errors were 3m to 3000m? What if you do not know their error characteristics?

It should be obvious to even a novice reader that unless you know the error characteristics of each navigation system integrating (averaging them) results are quite likely to give worst results then trying to select the better one. This is one of the reasons why different navigation systems such as LoRAN, TACAN even GNSS were not integrated in early systems and sits next to each other on an airplane or ship leaving all the responsibility to the user, navigation officer or captain.

The way to change this dilemma is to change what we ask of the navigation systems, ask them to acknowledge that most probably that navigation system is not the only one on the platform, its results will be integrated with other systems, and they have to provide information necessary to integrate their results with the results of different navigation systems. This means all navigation systems have to provide error covariances for each position, attitude or speed data they provide as well as the exact time this information was valid. If each navigation system provides such a rich data then an integration engine can integrate such navigation data from several navigation systems and produce integrated best result.

In such an architecture, navigation systems and integration systems can be designed separately making the system flexible. If precautions are taken it might even be possible to make this system anonymous and plug and play, that is integration system can integrate navigation systems without knowing which is which (since everyone also providing its own relating data) and only integrate available systems.

Please note that, precautions need to be taken for determining exact time when the provided data was valid, if standalone sensors (such as a barometer) are allowed to be integrated or not, and also if the error characteristics of integrated navigation system are somehow correlated.

NATO STO SET 309 / RTG – "PNT Open System Architecture for Navigation in GNSS Denied Environments" is working to demonstrate such an architecture and try to get it as a NATO standard. The architecture currently being demonstrated in this study by Turkey completed its first set of trials on real hardware in real time and successfully integrated several navigation systems with each other. Plug and play capability also demonstrated.

6.0 CONCLUSIONS

This paper tries to explain the train of thought behind the NATO STO SET-309 / RTG – "PNT Open System Architecture for Navigation in GNSS Denied Environments" study. This study hopes to prove this new way of integrating navigation systems is the way to the future and hopes to see this new structure as a NATO standard for future navigation systems.