Aircraft Navigation Sensors/Systems and the significance of Multisensor data fusion

M. N. Narsaiah
Associate Professor
Department of Electronics and Communication Engineering
K G Reddy College of Engineering and Technology, Moinabad, RR District, Telangana, India

Dr. S. Vathsal
Ex Director DRDO, Professor
Department of Electrical and Electronics Engineering
IARE, HYDERABAD 500043

Abstract: The purpose of aircraft navigation is to determine significant position, velocity, attitude and time (PVAT) information of an aircraft with respect to reference frames. This paper propose comprehensive review of aircraft navigation sensors/system state of art and exploring the navigation systems used by aircraft are listed (self contained navigation and external aiding navigation system) and compared. The focus of this paper is on multisensor data fusion and the throughout this paper the terms data fusion and multisensory data fusion are used interchangeably this paper is endeavor to investigate the data fusion task including its potential advantages, challenging aspects, existing methodologies and the recent advances in particular, discussion of the existing data fusion methods relies on data centric taxonomy, and explores each method based on the specific data related challenging aspect(s) addressed. The rest of the paper is organized as follow popular definitions, conceptualization and purposes along with the major benefits of data fusion are discussed, the challenging problems pertaining to performing data fusion and before concluding this paper also provides a discussion of data fusion methodologies based on their data treatment approach.

Key words: Navigation functions, Trajectory, Data fusion, Multisensor systems, Taxonomy, Fusion methodologies

I. INTRODUCTION TO AIRCRAFT NAVIGATION SENSOR SYSTEM

The purpose of aircraft navigation is to determine significant position, velicity, attitude, and time (PVAT) information of an aircraft with respect to reference frames. These PVAT parameters are referred as to the navigation states in this thesis. Aircraft navigation systems, which measures the dynamic motion of an aircraft with reference to specific frames, provide continuous inertial data and other measurement information that is required by onboard avionics systems for the implementation of various functions, including aircraft flight control and guidance, navigation computation and attitude determination, flight management and display, local motion compensation and attitude determination, flight management and display, local motion compensation and inertial system correction and alignment, as well as air traffic management . a navigational sensor measures quantities related to one or more elements of the navigation states. A set of navigational sensors, which is able to determine all the navigation states by using appropriate navigation algorithms, makes up a navigation system. An air craft navigation system combines all the measurement information from the navigational sensor of an aircraft to determine the following parameters and information:

- Kinematic parameters (accelerations and angular rates)
- Navigation states
- Trajectory and track parameters
- System health status information

The main navigation sensors/systems used by aircrafts are summarized in table 1-1 from the literature survey. These air craft navigation sensors/systems can be categorized as two types: self- contained navigation systems and external aiding navigation systems. The self contained navigation systems perform the navigation functions independent of external signals. in contrast the external aiding navigation systems implement the navigation functions through reception of signals from and/or trans mission of signals to external systems these two types of navigation systems are examined in the following subsections.

Table 1-1 Aircraft Navigation Sensors/Systems

Navigation Systems	System	Sensors	Coordinates		
	Subsystems	Derived States	Sensors	Raw Data	Raw Measurements
Self-Contained Navigation Systems	INS, AHRS	Position Velocity Acceleration	Inertial sensors	Accelerations and angular rates	Inertial instrument frame
	Air Data System	Mach Airspeed Pressure	Air data sensor, Baro-altimeter, Air speed	Static and dynamic pressures, air	Air mass/wind reference frame
	Heading Indicator	Heading	Magnetic heading sensor	Earth magnetic field	
	Radar Altimeter	Height above ground	Radar altimeter	Range	Radar antenna frame
	Doppler Radar	Ground velocity	Doppler radar	Relative LOS range rate	Radar antenna frame
External Aiding Navigation Systems	Space-Based Navigation	Position Velocity	GNSS receiver	LOS range and range	WGS84 reference
	Ground-Based Navigation	Location Height	VOR, LORAN, VOR/DME,	Relative range and	Relative reference
	Relative Navigation	Position Velocity	MIDS (JTIDS) PLRS	Relative range and	WGS-84 and Relative grid

II. SELF-CONTAINED NAVIGATION SYSTEMS

A self contained navigation system is system that computes aircraft position, velocity and attitude relative to reference frame my means of dead-reckoning (DR) techniques without reception of externally generated signals using DR techniques, aircraft velocities are determined by integrating the measured aircraft accelerations from known initial velocities. Aircraft position is obtained by integrating the aircraft velocities from known initial positions. Typical DR procedure for a single axis case is illustrated in figure 1 where all initial values are zero. Position and velocity errors caused by white noise sensor errors are shown in fig 1c. This DR procedure continuously accumulates sensors errors so that the navigation state errors grow over time and are unbounded unless they are constrained by aiding navigation systems the characteristics is a vital limitation of all self contained navigation systems.

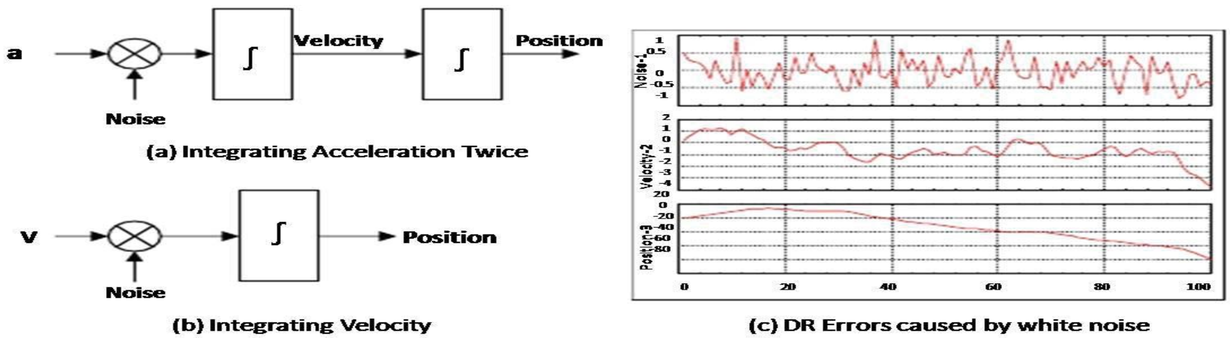

Figure -1 Dead Reckoning Procedure

The sensors systems applied for self-contained navigation systems are typicall inertial systems, air data sensor system and doppler RADAR.an air dat system provides altitude with respect to mean sea level and true air speed doppler radar can measure aircraft velocity relative the ground by transmitting a radar beam to and receive the echo beam from the ground but doppler rarar signals susceptible to interference fro external signals or the environment. Doppler radar and air data system connot provide all the navigation states, where as an inertial system alone can determine all the navigation states.

Two basic inertial mechanisations are used to implement an inertial navigation system(INS) the first method is known as a stable plotform system where a set of mutually orthogonal accelerometers is mounted on agimballed gyro plot form the gyros sense the anguler rate of plotform and control the gimbal servos so that the plotform maintains a stable plotforms orientation with respect to a known reference frame irrespective of the rotation.gimbal angles provide a direct read out of aircraft attitude angles. The accelerometer triad on the plot form provides accelerations releted to the known reference frame . integration of the accelerations can derive the velocity and position of the aircraft. The second method refererd to as strapdown inertial systems where gyros and accelerometers are mounted on a rigid frame that is strapped down to an air craft. The inertial sensors measure acceleration and anguler rates of the aircrafts relative to imertial space the aircraft attitude angles are then derived by perfoming a so-called analytical plotform algorthm, commonly known as strapdown attitude determination algortham. The accelerometer out are transformed to this analytical plotform frame and are then integrated to obtain the vellocity and position in the navigation reference frame .

Although inertial systems exhibit some disadvantages of dead reckoning method, their high dynamic characteristics and short-term meaaaaasurement accuracy are ideal for aircraft attitu determination and flight control systems in addition, other airborne avionics systems require inertial information to stabilise and compensate for local motion.

III. EXTERNAL AIDING NAVIGATION SYSTEMS

An external aiding navigation is radio navigation system and consist of two parts:airborne subsystems and externa signal sourse system. An airborne subsystem is signal-processing unit, which receives and processes the coded signals transmitted by external signal source to facilitate position fixing. An external position system is typically a network of transmitters that transmit coded signals and can be further classified as ground-based radio navaid systems (e.g;VOR/DME,ILS and LORAN) and space-based navigation systems, also known as Global Navigation Satellite System (GNSS). Two communication modes are used in external aiding navigation systems: one-ways and two-way modes. In the one-way communication mode, an airborne subsystem passivly receives signals and data from an external signal source system whereas in the two-way mode, an airborne subsystem actively transmits signals and receives replies from external signal sources. External aiding navigation systems are usually based on an algebraic geometry principle to determine the aircraft navigation states. The geometry is shaped by lines of sight (LOS) or lines of position (LOP) from external signal sources to an airborne receiver, as depicted in figure 2(a) and (b). the coordinates of the points, which are the positions of the aircraft and external transmitters, are represented by a set of nonlinear or linear algebric equations. The forms of and the constraints on the algebraic equations depend on the navigation mechanisms of external aiding navigation systems.

Navigation mechanisms applied to external aiding navigation systems are primarily based on the timing/ranging techniques, angle measurement and doppler techniques. The angle measuring technique measures the azimuth angle of an aircraft with respect to an external reference transmitter and is usually used in ground-based radio navaid systems. In other words, this method computes the direction of a radial line from the transmitter to the aircraft, that is the coefficient of a linear algebraic equation, as illustrated in figure 2(b). therefore, the position of an aircraft is the solution of a set of linear algebraic equations. Two transmitters provide a unique fix in angle measuring systems. As a result, the uncertainty of aircraft location caused by the measurement errors increase with distance from the aircrafts to the transmitters, as shown in figure 2(d). VOR/DME is a typical angle/range measurement navigation system.

The Doppler positioning technique, which measures the rates of changes of the relative ranges along the signal LOS between an aircraft and external signal sources, was used in the first generation of GNSS, known as the Transit system. The Doppler technique can provide an accurate velocity measurement. However, the uncertainties of position solutions, caused by integrating the Doppler measurements errors, increase over time. For example, the positioning accuracy of the Transit system degraded with time.

The timing /ranging techniques use the principle of elapsed time measurement as the basis for the LOS range measurements. The elapsed time is the time difference between the time at which the ranging signal is transmitter and the time at which it is detected by an airborne receiver. Several timing/ranging tecniques have been applied to the ground-based radio navigation system and space-based navigation system, including LORAL and GPS. The LOP geometry of GPS is the surface of sphere whereas LORAL is a location hyperbola. Hence the position of aircraft is computed in terms of the solution of non-linear algebraic equations.

In comparision with dead -reckoning techniques , a significant advantage of the timimg/ranging techniques does not degrade over time or distance, because the navigation states are derived from a set of non linear algebraic equations rather than a set of intergral equations. More over the uncertanity of a position solution is restricted to acircle or a hyperbola of location or the surface of a position sphere instead of the radial line in the angle measuring system. The Doppler positioning techniques can be also combined with the timing/ranging techniques used in GNSS navigation systems. Consequently GNSS affords long term stability of accuracy for the position and velocity solutions. A GNSS receiver is inexpensive, small size and low power. It is these advantages that make GNSS and ideal external navigation system to aid all self-contained navigation system, particuarly inertial systems.

The accuracy of external aiding navigation systems is effected by the geometryof the positions of aircraft and external transmitters. In space-based navigation systems the radio ranging signals transmitted by satellites propogate through the atmosphere to airbourne receviers, the signal dispersion and refraction caused by the ionosphere and troposphere introduce signal propagation path delay in the range measurements as shown in figure 2(c). in addition the uncertanity of satellite orbits and satellite and recevier clock errors also introduce range measurement errors as a result the measured time difference is not perfect and the resultant range is known as the pseudo range.

External aiding navigation system and other self contained navigation systems (such as Doppler radar) are generally used to aid inertial navigation systems such systems are referred to as navaid systems.

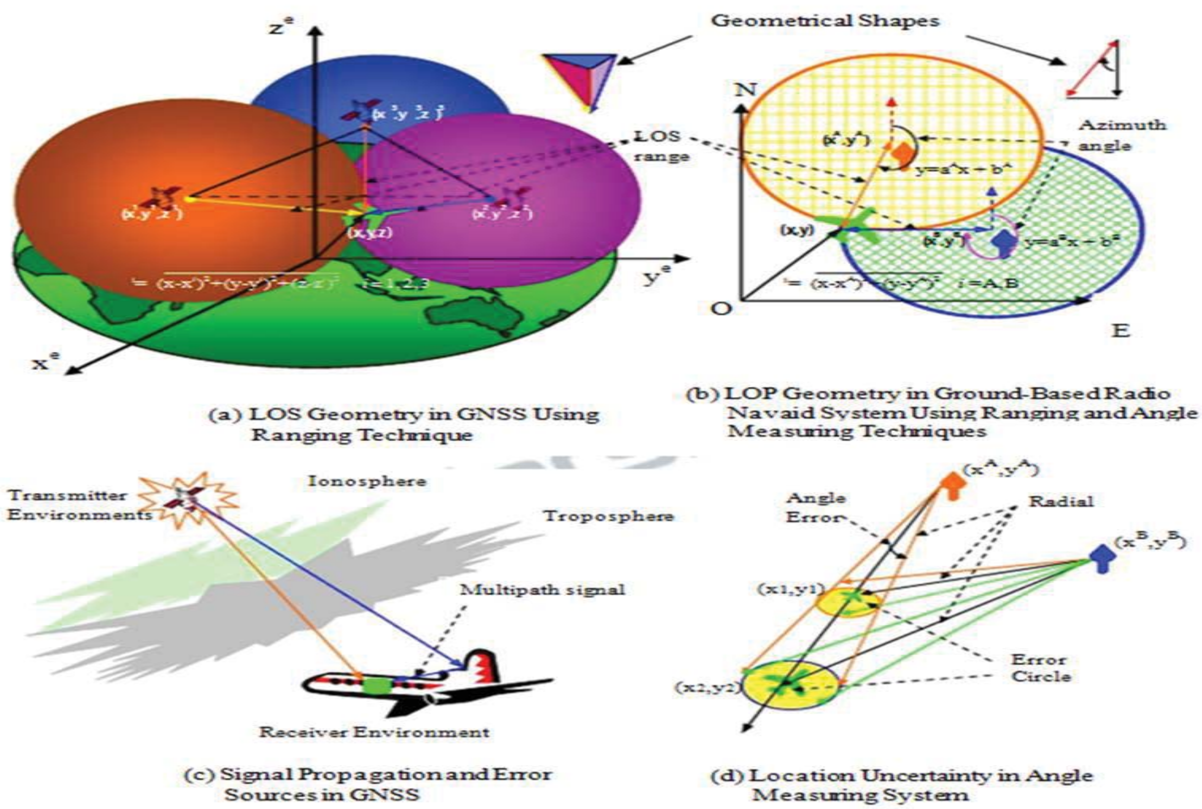

Figure - 2 Principles of External Aiding Navigation Systems

IV. MULTISENSOR DATA FOSION

Multisensor data fusion is technology to enable combining information from several sources in order to form a unified picture data fusion systems are are now widely used in various ares such as sensors networks, robotics, Video and image processing, and intellegent system design,to name a few. Data fusion is a wide ranging subject and many terminologies have been used interchangeably. These terminologies and ad hoc methods in a variety of scientific,engineering,management,and many other publications,shows the fact that the same concept has been studied repeatedly. The focus of this paperis on multisensor data fusion.thus, throughout this paper the terms data fusion and multisensor data fusion are used interchangeably.

The data fusion research community have achieved substantial advances,especially in recent years.neverthless realising a perfect emulation of the data fusion capacity of the human brain is still far accomplished.the data fusion task including its potential advantages,challenging aspects, existing methodologies and recent advances in particular descussion of existing data fusion methods relies on a data centric taxonomy and explors each method based on specific data related challenging aspects. We aslo present less studied issues pernent to data fusion and discuse future avenues of research in this area .

Many definations for data fusion exsist in the literature Joint Directors of Labolatories(JDL) defines data fusion as a multilevel ,multifaceted process handling the automatic detection,association ,correlation,estimation,and combination of data and information from several sources.klein generalises this defination stating that data can be provided either by single source or multiple sources. Both definations are general and can be applied in several fields including remote sensing.from the review and discussion of many data fusion definations based on the identified strength and weaknesses of previous work. A principled defination of information fusion is proposed as”information fusion is the study of efficient methods for automatically or semi automatically transforming information from different sources and different points in time into a representation that provides effective support for human or automated decision making" . Generally performing data fusion has several advantages. These advantages mainly involve enhancements in data authenticity or availability ,examples are improved detection, confidence , and reliability as well as reduction data ambiguity while extending the spacial and temperal coverage belong to the lateral catogiry of benefits. Data fusion can also provied specific benefits for some application contexts for example wireless sensor networks are often composed of a large number of sensor nodes. Hence possing a new scalability challenge caused by potential collisions and transmissions of redundant data. Regaring energy restrctions communication should be reduced to increase the life time of sensor nodes when datd fusion is performed during the routing process that is sensor data as fussed and only result is forwarded, the number of messages is reduced collisions are avoided and energy is saved.

Challenging problems of multi sensor data fusion

There are number of issues that make data fusion a challenging task the majority of these issues arise from the data to be fused, imperfection and diversity of sensor technologies and the nature of the application environment as following:

Data imperfection **:**data provided by sensors is always affected by some level of impreciseness as well as uncertanity in the mesurements. Data fusion algorithms should be able to express such imprefections effectively and to exploit the data redundancy to reduce their effects.

*Outliers and spurious data***:** the uncertainties in sensors arise not only from the impeciseness and noise in the measurements, but are aslo caused by the ambiguities and inconsistencies prasent in the environment, and form the inability to distinguish them, data fusion algorithms should be able to exploit the redundant data to alleviate such effects.

*Conflicting data***:** fusion of such data can be problematic especially when the fusion system is based on the evidential belief reasoning and Dempster's rule of combination.to aviod producing counter-intuitive results, any data fusion algorithm must treat highly conflicting data with special care.

*Data modality***:**sensors networks may collect the qualitatively similar (homogeneous) or different(heterogeneous) data such as auditory, visual and tactile measurement of a phenomenon. Both cases must be handled by a data fusion scheme

*Data correlation***:**this issue is particularly imporatant and common in distributed fusion settings, example wireless sensors networks, as for example some sensors nodes are likely to be exposed to the same external noise biasing their measurents. If such data dependencies are not accounted for the fusion algorithm may suffer from over/under confidence in results.

*Data alignment/registration***:**sensor dat must be transformed from each sensor's local frame in to a common frame before fusion occure . such an alignment problem is often referred to as sensors registration and deals with the calibiration error induced by individual sensors nodes.data registration of critical imporatance to the successful deployment of fusion systems in practice.

*Data association***:**multi target trcking problems introduce a major complexity to the fussion system compared to the single target tracking case. One of this new difficulties is the data association problem which may come in two forms: measurement-to-track and track-to-track association, the farmer refers to the problem of identifing from which target , if any , each measurement is originated while the latter deals with distingushing and combing tracks which are esstimating the state of the same real world target.

Processing framwork: data fusion processing can be performed in a centralized or decentralized manner. The latter is usually preferable in wireless sensor networks as it allows each sensor node to process locally collected data. This is much more efficient compared to the communinational burdern required by centralized approach. When all measuremts are to be sent to a central processing node for fusion.

*Operational timing***:** the area covered by sensors may span a vast environment composed of different aspects varying in different rates also in the case of homogeneous sensors the operation freqency of the sensors may be different, a well designed data fusion method should be incoperate multiple time scales in order to deal with such timing variations in data, in distributed fusion settings different parts of the data may traverse different routes before reaching the fusion centre which may cause out of sequence arriavial of data thia issue need to be handled properly esspecialy in real time applications,to avoid potential performance degradation.

*Static vs dynamic phonomena***:** the phenomena under observation may be time invarient or varying with time in the latter case it will be necessary for data fusion algorythm to incoperate recent history of measurement into the fussion process, particularly data freshness, i.e; how quickly data sources capture changes and update accordingly plays a vital role in the validity of fussion results.

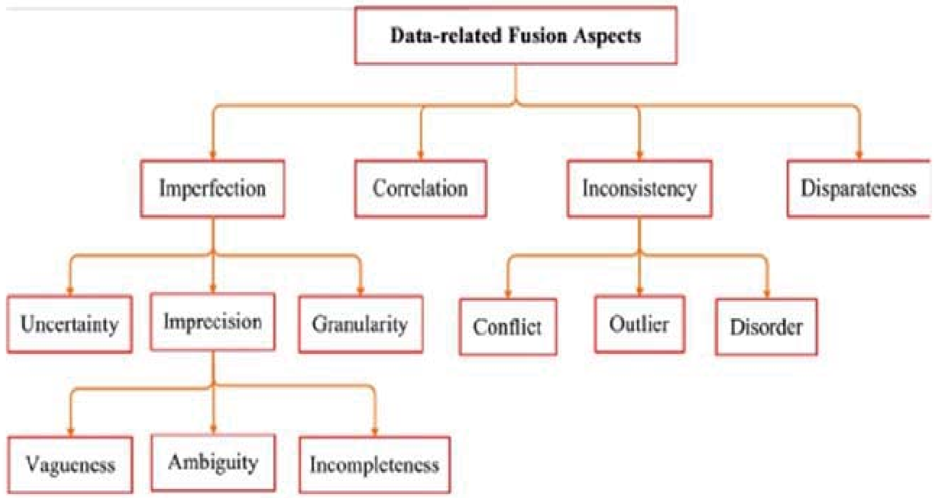

Fig. 3. Taxonomy of data fusion methodologies: different data fusion algorithms can be roughly categorized based on one of the four challenging problems of input data thatare mainly tackled: namely, data imperfection, data correlation, data inconsistency, an d disprateness of data form.

*Data dimensionality***:**the measurement data could be pre processed, either locally at each of the sensor nodes or globaly at the fusion center to be compressed into lower dimentional data, assuming a certain level of compression loss is allowed. This processing stge is benficial as it anables saving on the communication band width and power required for transmitting data.

V. CONCLUSION

While many of these problems have been identified and heavily investgated, no single data fusion algoritham is capable of addressing the all the aforementioned challenges. The verity methods in the literature focus on a subset of these issues to solve, which would be determined based on the application in hand . the existing fusion algorithms are explored based on how variouos data- related challenges are treated.

REFERENCES

[1] Aguirre,LA,Alves,GB and correa,MV.2007. Steady-state Performance constraints for Dynamical Models Based on RBF Networks.Engineering Applications of Artificial Intelligence, 20:924-935.[crossRef],[Web of Science]

[2] Aguirre,LA, Barroso,MFS, Saldanha,RR and Mendes, EMAM.2004. Imposing steady-state performance on Identified Nonlinear Polynomial Models by Means of Constrained Parameter Estimation.IEE Proceedings in control theory and Applications, 151: 174-179.[crossRef], [Web of science]

[3] Aguirre, LA,Teixeira,BOS and Torres,LAB.2005. Using Data-driven Discrete-time Models and the Unscented Kalman Filter to Estimate Unobserved Variables of Nonlinear systems.Physical review E,72(2): 026226[CrossRef], [Web of science]

[4] Alouani,AT and Blair,WD.1993.Use of a Kinetic Constraint in Target Tracking Constant Speed, Maneuvering targets. IEEE Transactions on Automatic Control,38:1107-1111. [CrossRef] ,[Web of Science]

[5] Bernstein,DS.2005. Matrix Mathematics, Princeton, USA: Princeton University Press.

[6] Bernstein,DS and Hyland,DC.1993. Compartmental Modelling and second-moment Analysis of State space Systems. SIAM journal on Matrix Analysis and Applications,14(3): 880-901. [CrossRef], [Web of Science]

[7] Chandrasekar,J, Barrero, O, Ridley, AJ, Bernstein, DS and De Moor, D. 2004. State Estimation for Linearised MHD Flow. Proceedings of the 43th IEEE Conference on Decision and control. 2004.pp.2584-2589. Paradise Island: The Bahamas

[8] Chandrasekar, J,Ridley, AJ and Bernstein, DS. 2007. A Comparison of the Extended and Unscented Kalman Filters for Discrete-time systems with Nondifferentiable Dynamics Proceedings of the 2007 American Control Conference.2007.pp.4431-4436. New York City,USA.

[9] Chaves,M and Sontag,ED.2002. State-estimators for Chemical Reaction Networks of Feinberg-Horn-Jackson Zero Deficiency Type. European Journal of Control, 8: 343-359. [CrossRef], [Web of Science]

[10] Chen, YH and Chiang, CT.1993. Adaptive Beamforming using the Constrained Kalman filter. IEEE Transactions on antennas and propagation, 41(11) : 1576-1580. [CrossRef], [Web of Science]