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Optimising the Transfer Alignment of Weapon INS

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Transfer alignment is the process of initialising and calibrating a weapon INS using data from the host aircraft's navigation system. To determine which transfer alignment technique performs best, different design options have been assessed, supported by simulation work. The dependence of transfer alignment performance on environmental factors, such as manoeuvres, alignment duration, lever arm and inertial sensor quality has also been studied. 'Rapid' alignment, using attitude as well as velocity measurements was found to perform better than 'conventional' techniques using only velocity. Innovative developments include the estimation of additional acceleration and gyro states and estimation of force dependent relative orientation, which has enabled robust alignment using wing rock manoeuvres, which do not require the pilot to change trajectory. Transfer alignment has been verified in real-time by flight trials on a Tornado aircraft. In addition, techniques have been developed to prevent transients in the aircraft integrated navigation solution following GPS re-acquisition after an outage of several minutes from disrupting the transfer alignment process.

KEY WORDS

1. Weapon Guidance. 2. INS. 3. Alignment.

1. INTRODUCTION. An essential requirement for the control and guidance of an aircraft-launched guided weapon is knowledge of position, velocity, attitude, acceleration and angular rate. This is usually provided by a navigation system including a strapdown inertial navigation system (INS), comprising a set of accelerometers and gyroscopes (gyros), known as an inertial measurement unit (IMU), and a navigation equations processor (e.g. Titterton and Weston, 1996). It is common for the IMU to be supplied as a unit, with the navigation equations hosted aboard the weapon's main processor. As the INS obtains a navigation solution by integrating the specific force and angular rate measured by the IMU, it is necessary to initialise the position, velocity and attitude. This process should be as accurate as possible even where the weapon is equipped with a Global Positioning System (GPS) receiver. This is because jamming may prevent or limit the use of GPS to continuously calibrate the INS (Groves *et al.*, 2002a).

A weapon undergoes power-up and launch whilst it is in captive carriage underneath the host aircraft. Thus, the simplest way of initialising the INS is with a 'one-shot' transfer of data from the aircraft's navigation system. However, this requires accurate knowledge of the relative position and attitude of the two navigation

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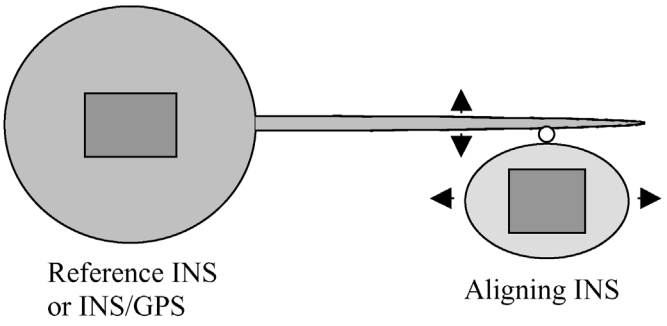


Figure 1. Relative motion of a weapon INS on an aircraft wing pylon.

systems. A weapon is typically carried underneath the aircraft on pylons that have a certain amount of give, responding to aircraft manoeuvres and turbulence. Many weapons are mounted underneath the wing, which is flexible and changes shape as fuel is consumed and other weapons are launched. Figure 1 illustrates this. Even where a weapon is stored on a trapeze inside a bomb bay, it still moves around. The airframe is also subject to vibration at a number of resonant frequencies. These effects severely limit the accuracy of a 'one-shot' attitude and velocity initialisation. For a wing pylon mounted weapon, the attitude may only be initialised to within about 2°, which can lead to position error growths in excess of 500 m in the first minute. Data synchronisation errors can also degrade the accuracy of initialisation. A further difficulty is that the IMUs fitted to guided weapons are usually of relatively poor quality, so if the weapon is kept in stand-by mode for a significant time, it will need to be re-initialised.

Transfer alignment provides a more sophisticated method of initialising the weapon INS by comparing a succession of its outputs against the host aircraft navigation system. This averages out the effects of airframe flexure and vibration. Provided there is some host aircraft manoeuvring, the weapon attitude and velocity errors are calibrated recursively, noting that a 'one-shot' initialisation at launch is sufficient to calibrate the position. Transfer alignment can also calibrate accelerometer and gyro errors, such as the biases, which can significantly improve weapon navigation performance.

There are three phases of transfer alignment, as shown in Figure 2. Firstly, the weapon INS is initialised with a 'one-shot' transfer of position, velocity and attitude from the aircraft navigation system, as described above. Although this only provides a rough initialisation, it does allow the main transfer alignment algorithm to be simplified as it only needs to estimate errors as opposed to a complete navigation solution.

The second phase is the main alignment phase, which continues until the weapon is launched. The differences between 'like' quantities such as position or velocity and attitude or angular rate, output by both navigation systems, are measured. These measurements are corrected for the relative position of the two INS, known as the lever arm, and for the relative orientation if known. The measurements may be time synchronised, compensating data transmission lags, by delaying the weapon INS outputs to match the aircraft navigation outputs' time of validity. If the errors of the aircraft navigation solution are assumed to be negligible, the differences that form the

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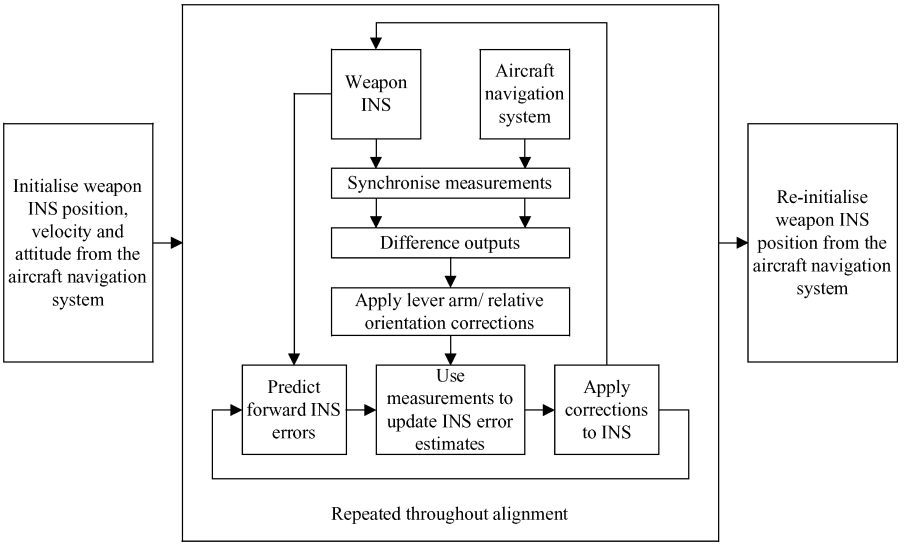


Figure 2. Schematic of the transfer alignment process.

measurements may be attributed to the weapon INS attitude, velocity and instrument errors. The weapon INS errors are estimated using a Kalman filter based estimation technique (e.g. Gelb, 1974; Farrell and Barth, 1999; Jazwinski, 1970). This maintains a working estimate of the errors, together with their associated uncertainties and covariances, which are predicted forward according to the system's motion. With each measurement, a new working estimate is obtained from the new measurement. The two estimates are combined according to their relative covariance.

The final phase of the transfer alignment process is a re-initialisation of the weapon INS position from the aircraft navigation solution as the weapon is launched. This must be as accurate as possible, so it is important to account for data lags and the lever arm between the two INS. This can be omitted where position measurements are used in the main alignment phase.

The principal distinguishing features between different transfer alignment techniques are the iteration rates, choice of INS measurements to be compared and choice of errors to be estimated by the Kalman filter. QinetiQ has conducted a research programme to determine and test the optimum configuration in pursuit of three main goals:

- To improve the accuracy of INS alignment and calibration to enable a weapon INS to navigate to a given accuracy for longer;
- To enable current performance levels to be obtained for short periods with lower grade inertial sensors;
- To reduce the time and manoeuvre level required to obtain a given alignment accuracy.

To these ends, following a literature survey, a re-configurable set of transfer alignment algorithms has been developed in-house and assessed by simulation (Groves and Haddock, 2001; Groves *et al.*, 2002b). Performance was then verified in real-time flight trials on a Tornado aircraft.

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This paper surveys the different options available in designing a transfer alignment technique, the motivations behind them and which perform best. Measurements are discussed first, followed by state selection, noise modelling and then other design issues. The dependence of transfer alignment performance on environmental factors, such as manoeuvres, alignment duration, lever arm and inertial sensor quality is then discussed. Next, flight trials results are presented. Lastly, the relationship between transfer alignment and INS/GPS integration is discussed.

2. MEASUREMENTS. Two main issues must be addressed when designing the measurement model for a transfer alignment technique: which measurements to use and at what rate? Faster measurement update rates are better at capturing the dynamics needed to observe the INS errors and to average out the effects of airframe vibration. For example, taking measurements at 20 Hz enables the INS errors to be estimated twice as fast as with measurements at 1 Hz. Faster update rates require more processing power, but averaging measurements at a faster rate with the Kalman filter updated at a slower rate produces performance closer to that obtained with a faster update rate (Spalding, 1992).

There are two types of measurement that can be input to the Kalman filter: linear and angular. Transfer alignment performance using solely angular measurements is very poor, so the choice reduces to between both types or linear only. However, provided there is sufficient host aircraft manoeuvring, attitude errors can be estimated using only linear measurements as they are observable through their effect on the velocity errors. Linear measurements comprise velocity and position, or their variants such as integrated velocity. These essentially comprise the same information, so there is no advantage in using more than one. When slower measurement updates ($\sim$1 Hz) are used, position measurements can be better as the noise due to lever arm flexure and vibration is smoothed out, a similar effect to measurement averaging. At faster update rates ($>$10 Hz), the use of velocity measurements tends to give a faster calibration of the INS errors.

Traditionally, only the horizontal components of velocity or position measurements have been used for transfer alignment. This is because, prior to the advent of GPS, INS were aided in the vertical channel by a barometric altimeter. This sometimes led to transients in the vertical channel which were difficult to account for in the transfer alignment Kalman filter. Use of an INS/GPS aboard the aircraft as the alignment reference, enables all three components of position or velocity to be used safely. Simulations have shown that use of three-component velocity measurements over two-component measurements can improve vertical navigation accuracy by a factor of two (Groves and Haddock, 2001).

Angular measurements, comprising attitude or angular rate, traditionally have not been used due to the difficulty in obtaining data of sufficient quality from the platform INS of some host aircraft. The advent of strapdown INS aboard aircraft resolves this problem. Again, attitude and angular rate essentially comprise the same information. However, angular rate measurements can be severely disrupted by wing flexure and vibration, especially during roll manoeuvres, whilst use of attitude measurements provides smoothing.

Techniques that use attitude as well as velocity measurements are known as 'rapid' alignment. This is because they allow a medium quality alignment to be obtained

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much more quickly than with a 'conventional' technique. In particular the addition of attitude measurements speed up estimation of the heading error (Kain and Cloutier, 1989). Some authors only apply the heading component of the attitude measurement (Hallingstad, 1989; Reiner, 1996). Use of three-component attitude as well as velocity measurements over a longer alignment can improve post-alignment navigation accuracy by a factor of 3:2 (Groves and Haddock, 2001). Thus, three-component attitude and three-component velocity measurements, updated at 10 Hz or more, have been selected for the optimised transfer alignment algorithm.

3. STATE SELECTION. The quantities estimated by the Kalman filter are known as states. The minimum INS errors that must be estimated for transfer alignment are attitude and velocity. Most transfer alignment algorithms also estimate the accelerometer and gyro biases, i.e. the fixed acceleration and angular rate errors. Estimating either of these triads can affect transfer alignment performance by a factor of two. In theory, many higher order accelerometer and gyro errors may be estimated. However, some error sources may not be observable, either because they vary with dynamics in the same way as existing states or their effects are difficult to resolve above the system and measurement noise. Processing power is also an issue as the computational load varies approximately as the cube of the number of components which are estimated as states and considered in the covariance propagation (Hallingstad, 1989).

QinetiQ investigated, by simulation, the benefits of estimating further inertial instrument errors (Groves and Haddock, 2001). Accelerometer and gyro biases comprise two components. The static or 'turn-on' component is constant each time the instrument is used, whereas the dynamic component or 'in-run variation' varies over times of order a minute. Typically the dynamic component is about 10 times smaller than its static counterpart. It was found that, for alignment times in excess of the dynamic bias correlation times, estimating the biases as separate static and dynamic states improved estimation of the static components. The estimation of scale factor and cross-coupling errors was found to improve overall alignment performance, particularly for longer alignments. Although estimation of the states themselves was poor, their inclusion improved the estimation of accelerometer bias. Overall, the inclusion of dynamic biases, scale factor and cross-coupling errors in the state vector improved navigation performance following a two-minute alignment of a 10°/hr INS by a factor of about 4:3.

For attitude measurement matching to work, the relative orientation of the weapon and aircraft IMUs must be estimated as states. However, because the aircraft wings and pylons flex, the relative orientation cannot be treated as a constant (Rogers, 2000). A number of authors have proposed modelling it as a Markov process comprising static and higher order states (Spalding, 1992; Graham and Shortelle, 1995; Schneider, 1990). However, using this approach, Kalman filter stability problems were observed in simulations incorporating roll manoeuvres such as a wing rock. This severely biased some of the attitude and instrument error estimates. The problem arises because the relative orientation varies with the non-gravitational forces on the wing and pylon. In the interval between the initial roll and the roll back during a wing rock manoeuvre, the forces in the aircraft body frame are significantly different to those in level flight. However, in a co-ordinated turn, where no problem

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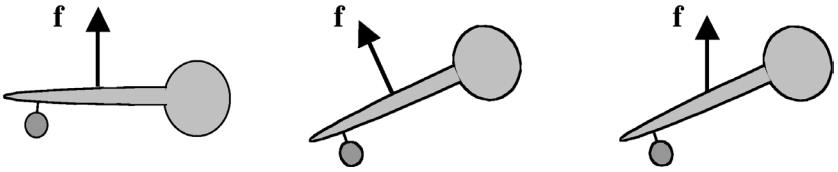


Figure 3. Specific forces on the wing.

has been observed, the body frame forces are closer to those experienced in level flight, remaining roughly perpendicular to the wing as there is a force turning the aircraft in addition to the aerodynamic lift. This is illustrated in figure 3. The problem was solved by introducing 6 Kalman filter states to model the coupling of specific force in body axes into the relative orientation in addition to the static relative orientation (Groves *et al.*, 2002b).

Estimation of the errors in the measured lever arm between the aircraft and weapon INS was found to have negligible impact on transfer alignment performance, with the forward component unobservable. The transfer alignment process was also found to be tolerant of lever arm errors, requiring errors to be in excess of 0·5 m before the alignment accuracy was affected (Groves and Haddock, 2001). Using a measurement sampling rate of 1 Hz, albeit with GPS measurements using the aircraft antenna, improved performance has been demonstrated by estimating the time varying accelerometer and gyro biases that arise from airframe vibration at frequencies near to or at multiples of the sampling rate (Wendel and Trommer, 2001; 2002). With measurements updated or averaged at 10 Hz or more, the vibration induced biases are much smaller.

The optimised transfer alignment algorithm thus estimates:

- Attitude and velocity;
- Accelerometer and gyro static and dynamic biases;
- Accelerometer and gyro scale factor and cross-coupling errors;
- Static relative orientation and force-dependent relative orientation coupling.

4. NOISE MODELLING. There are two types of noise considered in transfer alignment, system and measurement. System noise comprises those errors on the weapon INS outputs that are not functions of the states estimated by the Kalman filter. Measurement noise comprises errors on the measurements that are independent of the states. Noise cannot be estimated by a Kalman filter but its effects must be accounted for in order to correctly determine the weighting of the new measurements against existing estimates.

System noise arises in the accelerometer and gyro outputs as a function of random walk, quantisation errors, bandwidth limitations and small high order deterministic errors. Further system noise can arise in the inertial navigation equations due to the truncation of mathematical functions, limitations in the accuracy of numerical integration schemes and computer word length limitations. There is no benefit from treating each source separately, so these errors are modelled as white noise, causing the attitude and velocity state uncertainties to grow with time in the absence of new measurements. Systematic errors that are not estimated as states, such as the gyro g-dependent errors, can be modelled as time correlated system noise using a model based on the Schmidt-Kalman filter (e.g. Jazwinski, 1970).

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The measurement noise in transfer alignment arises from a number of sources:

- Random and quantisation errors on the aircraft navigation solution (systematic errors are neglected as alignment is relative to the aircraft navigation system);
- Uncompensated time synchronisation errors between the weapon and aircraft navigation systems;
- Errors in the estimated relative position and orientation of the two INS, compounded by flexure and vibration.

The latter two noise sources increase with the manoeuvre level of the aircraft. Due to the complexity of its variation with dynamics, an analytical derivation of the measurement noise covariance is not practical. Therefore, two alternative approaches have been considered: empirical and statistical. In the empirical approach, the measurement noise covariance is treated as a function of the aircraft dynamics, such as specific force, angular rate and their differentials. The coefficients are determined empirically. This method was found to improve the stability of 'rapid' alignment during roll manoeuvres (Groves *et al*., 2002b). The alternative, statistical, approach uses the standard deviation of the last few measurement innovations to determine the measurement noise covariance. This is useful for applications where the measurement noise is poorly characterised.

The tuning of the system and measurement noise parameters used by the transfer alignment algorithm is important for optimising performance. If the measurement to system noise ratio is too high, the gains in the Kalman filter will be too low, slowing down the rate at which the weapon INS is calibrated. Conversely, if the measurement to system noise ratio is too low, the Kalman filter gains will be too high resulting in instability and potentially biased estimates. In an ideal Kalman filter, tuning the noise models to give consistent estimation errors and uncertainties will also produce stability. However in practice, as approximations are made in the Kalman filter design and smaller real-world effects are neglected, extra noise must be modelled to maintain stability. In transfer alignment, the initial state uncertainties and system noise are reasonably well defined, with the weapon INS manufacturers' specifications and laboratory test data available. However, the measurement noise covariance tends to be more nebulous, so a good tuning philosophy is to vary the coefficients to find the smallest values that meet a stability criterion.

5. OTHER DESIGN ISSUES.

The INS errors estimated by the transfer alignment algorithm may be used either to correct the inertial navigation equations processor continuously, known as closed-loop correction, or left until the weapon is launched, known as open-loop correction. Closed-loop correction has the major benefit that it keeps the Kalman filter estimates small, enabling more approximations to be used. In particular, the transfer alignment algorithm is much simpler where the small angle approximation may be used. Open-loop correction is useful in simulations and where the corrections are impeded by interfacing issues. However, many weapon systems implement the transfer alignment and navigation equations on the same processor, making closed-loop correction straightforward. Thus, closed-loop correction is generally the optimum approach.

Transfer alignment algorithm design is a trade-off between performance, processor efficiency and complexity. There is major scope for improved efficiency by implementing sparse matrix multiplication routines. These take advantage of the fact that many

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of the matrices to be multiplied in transfer alignment have large numbers of zero elements. So by bypassing these processing speed is increased. In addition, different phases of the Kalman filter can be processed at different rates. For example, propagating the error covariance is much more processor hungry than propagating the state estimates but, as it does not have to be as accurate, it can be run at a lower rate.

Spurious spikes can occur in the measurement stream as a result of electrical interference, data communication errors, timing problems and flexure under extreme dynamic manoeuvres. Incorporation of such spikes in the Kalman filter measurement updates will degrade transfer alignment accuracy, so there is clear benefit in filtering them out. This can be done simply by comparing each measurement residual (the difference between the actual and predicted measurements) with a multiple of its predicted standard deviation and rejecting those measurements that exceed the threshold. Lastly, where the Kalman filter estimate of an instrument error significantly exceeds its specification, this can be used to signal an instrument fault, triggering abandonment of the weapon launch (Hallingstad, 1989).

6. ALIGNMENT ENVIRONMENT. The transfer alignment technique is not the only factor determining post-launch navigation performance of a guided weapon. Other important factors include the mounting of the weapon aboard the host aircraft, manoeuvres during the alignment and the autonomous phases, alignment duration and the grade of weapon inertial sensors.

The larger the lever arm between the weapon and aircraft INS, the greater the observability of attitude and gyro errors through velocity measurements. However, larger lever arms also result in greater measurement noise due to increased flexure and vibration, which reduces the observability of INS errors. To determine which effect is dominant, extensive flight trials are required to assess different flexure and vibration environments.

The level of host aircraft manoeuvre during transfer alignment affects performance because changes in the attitude and/or trajectory are needed to observe separately the states estimated by the Kalman filter. Most importantly, when the velocity and attitude are constant, the effects of attitude errors and accelerometer biases on the navigation solution cannot be separated if the relative orientation is unknown. When attitude and velocity measurements are used, the error sources can be observed separately by changing attitude. However, if only velocity measurements are used, a trajectory change is necessary. Once the attitude errors are calibrated, the gyro bias can then be estimated from the rate of change of the attitude error over time. Estimation of scale factor and cross-coupling errors requires further manoeuvres. The measurement noise can mask the effects of dynamics on state estimation and system noise can degrade state estimates. Consequently, to improve the quality of state estimates, there must be sufficient dynamics to overcome the noise effects. This is known as stochastic observability.

The alignment time also affects transfer alignment accuracy. In the first few seconds, the uncertainty of the states that have a large effect on the measurements, such as velocity and attitude, will drop rapidly from their initialisation values. Following this, other states will start to be estimated. As the uncertainty of each state improves, the weighting of new measurements will reduce. Thus as the alignment time is increased a law of diminishing returns applies concerning the benefits gained. Eventually, the Kalman filter will approach an equilibrium point where the increase

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in the standard deviation of residual errors due to system noise matches the decrease due to each new measurement.

A simulation study was conducted to determine how performance of an optimised 'rapid' transfer alignment algorithm varied with the alignment duration and manoeuvres performed over 90 different trajectories (Groves *et al.*, 2002b). It was found that performance varies largely independently with duration and manoeuvre. Aligning for 30 s resulted in post-alignment navigation performance about 25% better than aligning for 10 s, with a further 25% improvement obtained by extending to 2 minutes. Longer alignment times had little effect on performance. The best manoeuvre to perform during alignment was found to be an s-weave (pair of co-ordinated turns) with larger heading changes and higher lateral acceleration improving performance up to a point. Wing rock manoeuvres led to navigation performance around a factor of 3:2 poorer than the best obtained with an s-weave. However, they have the tactical advantage that no trajectory changes are required.

Weapon navigation performance also depends on the post-launch trajectory. The greater the degree of manoeuvre, the more the attitude errors and accelerometer scale factor errors couple into the velocity and position, resulting in the navigation accuracy decaying more quickly. Alternatively, the greater the post-launch dynamics, the greater the demands on transfer alignment in order to obtain a given navigation accuracy. The least demanding trajectories are near-ballistic; the most demanding involve a manoeuvre just after launch, such as the boost phase undergone by some weapons.

The last factor affecting transfer alignment performance is the grade of the weapon inertial sensors. Lower grade IMU exhibit larger correlated errors, such as biases and scale factor errors; consequently the relative impact of transfer alignment is larger, though it will take longer to achieve a given accuracy. However, lower grade IMU also exhibit higher noise, so the residual errors when the Kalman filter reaches equilibrium are larger. Thus overall post-launch navigation performance is poorer with lower grade IMU. Simulations have been conducted with a number of different grades of weapon IMU, varying from 1°/hr to 100°/hr gyro drift (Groves and Haddock, 2001). These showed that the performance of the aligned and calibrated INS varies roughly as the square root of the raw IMU errors.

7. FLIGHT TRIALS RESULTS. To assess the real-time performance of the QinetiQ 'rapid' transfer alignment algorithms, flight trials were conducted on a Tornado GR1 aircraft at QinetiQ Boscombe Down in December 2001. A Honeywell H764G Embedded GPS in INS (EGI), with inertial sensors meeting the SNU84 specification, was used as the 'aircraft' navigation system. The 'weapon' IMU was a Litton LN200 with accelerometer and gyro bias standard deviations of 100 μg and 2·3°/hr, respectively. This was located in a 454 kg bomb case, mounted on the starboard wing pylon, and remained attached to the aircraft throughout. The GPS antenna for the EGI was mounted on the aircraft behind the cockpit. The rest of the trials equipment was contained in a 1000 litre fuel pod, mounted on the aircraft's centre pylon. This configuration provided a flexing lever arm of order 3 m between the two sets of inertial sensors, a realistic transfer alignment configuration.

The transfer alignment algorithms and weapon inertial navigation equations were coded into the Tightly-coupled closed-loop IMU/GPS Navigation System (TIGNS).

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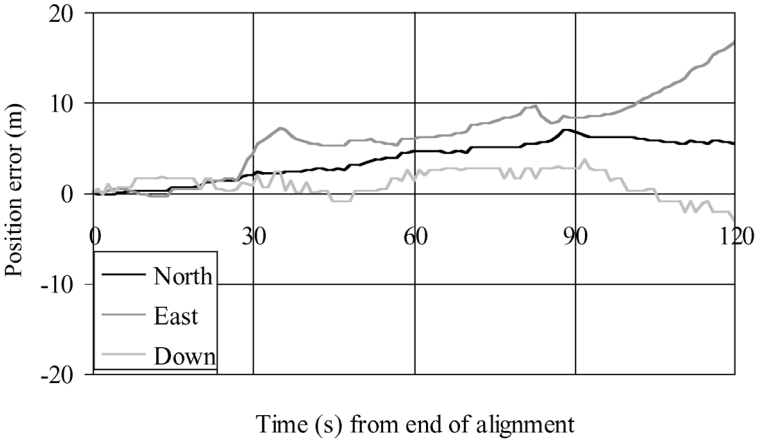


Figure 4. INS position error growth following transfer alignment for ~120 s with an s-weave manoeuvre.

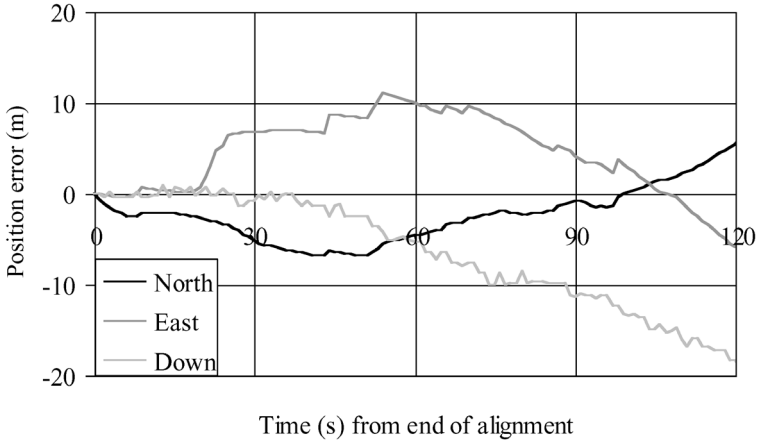


Figure 5. INS position error growth following transfer alignment for ~120 s with a wing rock manoeuvre.

This was developed as a navigation systems test-bed in collaboration with Raytheon Systems (UK) Ltd. The transfer alignment algorithm configuration was based on the results of the simulation studies with the system noise tuning based on the IMU manufacturer's specifications. Results are presented from two transfer alignment runs. In the first run, an s-weave, comprising a pair of co-ordinated turns through about 30° at about 10 ms^{-2} lateral acceleration was performed. In the second run a wing rock manoeuvre comprising 3 pairs of rolls through about $\pm 60°$ was performed but there was no trajectory change. Both alignments lasted about 2 minutes and were followed by a period of unaided inertial navigation to test the performance of the aligned INS. During this period, the aircraft flew straight and level for about 10 s, then climbed about 200 m over 20 s, performed a 10° co-ordinated turn at 10 ms^{-2} lateral acceleration and then flew straight and level. Figures 4 and 5 show the position error growth during the unaided inertial navigation phase after the s-weave and wing

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rock alignments respectively. This is the change, from the end of transfer alignment, of the 'weapon' INS indicated position relative to the EGI reference indicated position, corrected for the lever arm between the two sets of inertial sensors. This gives only the errors from the main transfer alignment process and excludes errors from the EGI's own navigation solution and the at-launch position reset. In each case, the position error growth stayed largely within 10 m per axis for the first 90 s after alignment and 20 m per axis for the first 120 s. Performance was generally better following the s-weave than the wing rock. The performance is consistent with previously published 'rapid' transfer alignment fast jet trials results (Shortelle and Graham, 1998; Graham *et al*., 1998).

8. TRANSFER ALIGNMENT AND INS/GPS INTEGRATION.

The relationship between transfer alignment and INS/GPS integration spans two topics: INS/GPS aboard the host aircraft and INS/GPS aboard the weapon. Where the aircraft is equipped with GPS as well as INS, up to 3 navigation solutions may be available for use as the reference for transfer alignment: the inertial navigation solution (with baro aiding), the GPS navigation solution and the integrated INS/GPS navigation solution. An INS provides a continuous high bandwidth navigation solution with low short-term noise and provides attitude as well as position and velocity. However, the accuracy of the position and velocity solution slowly degrades with time. By contrast, the GPS navigation solution does not degrade with time, but is noisy, has a comparatively low bandwidths ($\sim$1 Hz) and is subject to outages, particularly in a jamming environment.

From a transfer alignment perspective, use of an INS reference enables a faster alignment as attitude data is available and measurements can be generated at a faster rate. However, use of a GPS reference reduces the size of the aircraft navigation system errors passed onto the weapon. An integrated INS/GPS navigation solution provides the benefits of both of the other options. It also provides a more accurate position and velocity reference than the GPS as the INS integration smoothes out the effects of tracking errors and enables a GPS signal to be tracked at higher jamming levels. However, when a GPS signal is re-acquired after several minutes of jamming, a transient can appear in the INS/GPS velocity solution as the error growth during the outage is corrected. This can severely disrupt the transfer alignment process because the transient in the measurement stream due to the aircraft navigation system is falsely attributed to weapon INS errors. It was found by simulation and using trials data that transients of greater than 0·1 ms^{-1} can disrupt alignment, causing severely biased heading and instrument error estimates (Groves, 1999; Groves *et al*., 2002b). This disruption occurs to both conventional and rapid transfer alignment and regardless of how long it takes the INS/GPS integration algorithm to respond to the re-acquisition of GPS.

A number of different transient detection and handling techniques have been developed. The most direct method is to compare the integrated INS/GPS and pure inertial velocity from the aircraft and if the rate of change of the velocity difference exceeds a certain threshold, this is attributed to a transient. By applying the same change in velocity difference as a correction to the weapon INS velocity the transient is prevented from disrupting transfer alignment. This technique has been verified as effective by simulation (Groves *et al*., 2002b). Where a pure inertial

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velocity is not available from the aircraft navigation system, the INS velocity corrections applied internally may be used instead. If neither of these is available, or the aircraft-weapon database does not support them, Kalman filter based techniques must be used. The most successful of the Kalman filter based transient detection techniques is residual bias monitoring, which is based on the principle that a transient in the aircraft velocity will produce a series of large velocity measurement residuals. Thus, by comparing the statistics of the last few residuals with the values expected during normal operation, a transient is detected. The most successful Kalman filter based technique for responding to transients is the Q boost, which increases the uncertainty of the weapon velocity error estimates to make these states respond to the correction in the aircraft velocity without disrupting the other state estimates. Both residual bias monitoring and the Q boost have been verified by simulation (Groves *et al.*, 2002b).

Where the weapon is equipped with GPS it can be used to align and calibrate the INS. However, as discussed above, the aircraft navigation solution provides a better reference. The aircraft GPS equipment may have more sophisticated anti-jam technology but, if the weapon GPS antenna is obstructed by the airframe, a high capacity ($\sim$2 Mbit/s) data link is needed to use the aircraft antenna.

It is important that the handover from transfer alignment to weapon INS/GPS integration is handled correctly. Any INS error estimates that have not been fed back to correct the weapon INS should be passed on to the INS/GPS integration process. The state uncertainties should also be passed across, but as transfer alignment is relative, they must be combined with the predicted standard deviations of the host aircraft position, velocity and attitude errors.

9. CONCLUSIONS

A 'rapid' transfer alignment algorithm set has been developed and its optimum configuration determined by simulation. Innovations include the estimation of additional acceleration and gyro states and estimation of force dependent relative orientation. This has enabled robust alignment using wing rock manoeuvres, which do not require the pilot to change trajectory. Transfer alignment has been verified in real-time by flight trials on a Tornado aircraft. In addition, techniques have been developed to prevent transients in the aircraft integrated navigation solution following GPS re-acquisition after an outage of several minutes from disrupting the transfer alignment process.

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