Comparison of Opportunistic Signals for Localisation

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Abstract:
This paper presents a brief overview of how opportunistic signals can be utilised for localisation. Two different techniques for using opportunistic signals have been implemented and are validated through a number of experiments. These experiments show the performance of the navigation system when configured to use different signal types including Medium Wave radio, Digital Audio Broadcast, GSM and 3G. The same dataset is used for each experiment and uses data simulated from real transmitters operational in the Sydney region which enables a comparison of the performance benefits of using different signal types in this environment. Results show that there are three dominant factors that contribute to the quality of the solution: accuracy of the timing information contained in the signal, and the quantity and location of the transmitters used for the estimation.

Keywords: Navigation, Opportunistic Signals, Filtering

1. INTRODUCTION
Accurate localisation is a critical component for unmanned platforms and miscalculations in a navigation solution can significantly affect other areas of the system, for example path-planning, mapping and obstacle avoidance. Most commonly in outdoor robotics, a GPS/INS navigation system is used, which is an excellent solution for a range of operations, Cox (1978). However in some environments the GPS solution suffers from multipath or worse, is unobtainable, and so additional sensors are required to maintain a stable solution.

Navigation Via Signals of Opportunity (NAVSOP) is the concept of using signals from an established transmitter infrastructure intended for other purposes, to be used for the localisation of a platform. Individual examples of NAVSOP have been published (Drane et al. (2003), Duffett-Smith and Woan (1992)) yet there has few studies showing the implementation of NAVSOP using multiple signal types. This paper describes the integration of different signals into a navigation filter and shows preliminary results from a number of experiments which compare the performance of the navigation system with different input sources used to constrain an INS. Each experiment uses the same dataset, enabling a clear comparison of the performance of each signal type. Further experiments are presented to show the advantages of combining different opportunistic signals to improve accuracy.

2. NAVSOP
A number of signals can be used for NAVSOP including GSM, 3G, Digital Audio Broadcast (DAB), Digital Video Broadcast (DVB), Medium Wave (MW) radio and analogue television, Fisher (2005). Localisation can be performed using a number of techniques: time on arrival, time difference on arrival, cell ID, signal strength, signal fingerprinting, velocity, and carrier phase measurements. Details of these different techniques can be found in Fisher (2005). Two techniques that will be discussed in this paper are the time of arrival, and carrier phase measurements.

2.1 Time of Arrival Technique
The time of arrival technique is based on the following equation;

\[ \Delta t_{ij} = ||r_i - b_j|| + \epsilon_i - \alpha_j \] (1)

Where \( c \) is the wave speed, \( t_{ij} \) is the arrival time of the signal from the \( j \)th transmitter at the \( i \)th receiver location, \( r_i \) is the position of the \( i \)th receiver and \( b_j \) is the position of the \( j \)th transmitter. The timing offset errors are denoted by \( \epsilon_i \) and \( \alpha_j \) which represent the receiver clock and the transmitter clock respectively.

With multiple transmitters and/or receivers, a set of simultaneous equations can be constructed and the position estimate of the receivers can be resolved, and with enough observations so too can the position of the transmitters.

This technique is only suitable for signals with predictable behaviour, such as the regular broadcast of a known timing marker. Such signals include GSM, DAB, DVB and 3G. The precision is determined by the ability to measure accurately the position of the timing marker within the transmission, which can be corrupted by multipath interference. Higher bandwidth signals therefore yield higher precision. It should be noted that this technique does not require a synchronised transmitter network.
The time of arrival technique can be easily integrated into a navigation filter using an observation measurement and its corresponding matrix, $H(x)$, which describes how the measurement relates to the state vector. The observation measurement is the range between the transmitter and receiver, which is obtained by multiplying the timing information from the signal, Faragher (2009), by the speed of light. For an error state filter, this measurement is subtracted from the estimated range measurement calculated by substituting the latest navigation solution in (1).

The range error observation can then be used by the filter with the following observation model $H(x)$;

$$H(x) = \begin{bmatrix} -r_x \\ \frac{-r_y}{(r_x^2 + r_y^2 + r_z^2)^{\frac{1}{2}}} \\ \frac{-r_z}{(r_x^2 + r_y^2 + r_z^2)^{\frac{1}{2}}} \end{bmatrix}, \begin{bmatrix} 0, 0, 0, 0, 0 \end{bmatrix}.$$  

Where the state vector $x$ estimates the three-dimensional errors in position, velocity and attitude;

$$x = [\delta p, \delta v, \delta \phi]^T$$

### 2.2 Carrier Phase Technique

Opportunistic signals that do not contain timing information can still be used for localisation by adopting the differential carrier phase technique, Remondi (1985). A suitable example is MW radio. Carrier phase measurements monitor the change in phase of the signal as received by the receiver, and thus allow the user to infer the trajectory of the platform based on the expected phase behaviour measured by a stationary receiver. Phase can be measured to within a fraction of a radian, allowing the precision of carrier phase positioning to be the order of a hundredth of a wavelength in ideal conditions. The error is then determined by the measurement noise, integration period and interference effects.

The phase measurement of a continuous sine wave, $\phi_i(t)$, can be estimated by the following equation;

$$\phi_i'(t) = \omega^j t - \frac{\omega^j t}{c} r^j + \delta^j_{init} + \delta^j_{atmos}$$

Where $\omega^j$ represents frequency of the signal from the $j$th transmitter, $t$ is the time and $r^j$ is the geometric range between the $j$th transmitter and the $j$th receiver, and $\delta^j_{init}$ is the initial phase of the signal at the moment of broadcast. The additional errors are denoted by $\delta^j_{atmos}$, the atmospheric delays (in m).

This phase measurement is modulo $2\pi$ and therefore is not a unique solution, as a result care should be taken to prevent or at least detect cycle slips. As the signal wavelength reduces, the position resolution improves, however, so too do the chances of cycle slips.

To estimate the initial phase offset and the atmospheric delays it is necessary to perform a calibration step whereby the receiver position is known. If this is not possible, the differential carrier phase technique can be used which estimates the change in carrier phase between two consecutive time steps, and so provides a measure of the user’s velocity rather than position. This cancels out the atmospheric delays and the initial phase offset terms as these are assumed to be constant over the time step. The differential carrier phase equation is given by;

$$\Delta \phi^j_i(t) = \omega^j (t_2 - t_1) - \frac{\omega^j t}{c} (r^j_{t_2} - r^j_{t_1}) + \epsilon^j_{t_2} - \epsilon^j_{t_1} \quad (4)$$

Where $\Delta \phi^j_i(t)$ represents the change in carrier phase, and $t_1$ and $t_2$ denote two consecutive timestamps.

To integrate the carrier phase technique into a navigation filter, the change in carrier phase observation measurement is calculated by subtracting the previous carrier phase measurement from the current. For an error state filter, the observation measurement is the difference between the change in carrier phase generated from the input signal and the change in carrier phase estimated by substituting the latest navigation solution into (4).

The observation matrix $H(x)$ is;

$$H(x) = \begin{bmatrix} \frac{\omega^j}{c} r_x \\ \frac{\omega^j}{c} r_y \\ \frac{\omega^j}{c} r_z \end{bmatrix}, \begin{bmatrix} 0, 0, 0, 0, 0 \end{bmatrix}.$$  

### 3. EXPERIMENTAL RESULTS

The integration of NAVSOP into a navigation system was experimentally tested with simulated and real data, details of the simulated experiments are described below.

The simulated experiments used data generated from the NAVSOPGenerator developed by Faragher at BAE Systems which takes ground truth data and estimates the range or carrier phase measurements from a number of transmitters. The user can configure the number of the transmitters, in addition to their frequency, location and noise parameters.

The transmitters used in these experiments replicate real transmitters currently in operation in the Sydney region to provide an indication of the NAVSOP quality that may be possible in this region. The noise added to the measurements has been calculated through empirical tests and represent the errors expected in a light urban environment. Details of the GSM error sources can be found in Faragher (2007) which illustrates that the noise found on these measurements (and other range and carrier phase measurements) is well represented by a Cauchy distribution, Papoulis (1984). For each of these experiments it is assumed that a successful calibration stage has been performed and thus there is no peak offset, $x_0$, however signal availability will vary due to obstacles in the environment and the signals will suffer from multipath.

The NAVSOP was integrated into the All Source Navigation Filter (ASNF), a flexible navigation system that can be quickly and easily configured to use information from a range of different sensors, Connolly (2009). This system enables rapid results from which to analyse the performance of the system. Subsequently one or more different configurations can be interchanged to perform useful comparisons between different configurations.

A number of experiments were performed using the same datasets with varying signal types. A navigation grade
Fig. 1. Position of the MW Transmitters in Sydney. The start and end of the trajectory is also highlighted.

IMU running at 100 Hz was used in the ASNF which was corrected by the opportunistic signals at 1 Hz.

The ASNF was configured with an error-state EKF estimating the position, velocity and attitude of the platform, in addition to the accelerometer and gyro errors of the IMU. The validity of the results were checked by verifying the consistency of the solution errors with the solution covariance. A subset of these experiments are discussed below.

3.1 MW Signals

This experiment estimates the position of a platform generated using IMU and MW carrier phase measurements in the ASNF. In Sydney there are 10 transmitters mostly located in the west of the region, see Fig. 1, with two additional transmitters located south of the trajectory.

The position estimate generated using the simulated MW data created from the NAVSOPGenerator is presented in Fig. 2. Also visible is the ground truth measurement which was generated from an off-the-shelf DGPS/IMU positioning system. As expected from a relative correction, the position is very smooth, however it drifts from the ground truth over time due to the accumulation of integration errors and biases. The total displacement from ground truth at the end of the experiment is 10 m North and 17 m East.

Depending on the application, the drift in the MW carrier phase configuration is only suitable for short term operations. However due to its relatively smooth solution, it can be used in a longer term mission when combined with additional constraining sensors as discussed in Section 3.4.

3.2 GSM Signals

In populated areas, there is a large number of GSM transmitters and therefore a good signal geometry can be obtained, however there are real time processing constraints. Consequently, two experiments are presented in this paper that show the impact of different quality geometries, represented by the different shaped icons in the map in Fig. 3. The poor configuration, Configuration 1, is represented by the transmitters represented by triangles, and an improved geometry, Configuration 2, is denoted with cross icons. Signal availability in each configuration is variable and therefore each message comprises of information from usually 4 – 7 signals.

The position estimate generated by the ASNF with noisy GSM data from transmitters in Configuration 1 is shown in Fig. 4. It can be seen that the position estimate suffers significant jumps (up to 21 m) and drift from the ground truth. The maximum error from ground truth in this experiment is 22 m, which exhibits an improved performance to simulations performed by BAE Systems, Faragher (2009). This is likely to be due to a number of reasons, firstly we have assumed that a comprehensive calibration phase has been performed and so the time drifts have been well estimated and remain constant throughout the run. Secondly, unlike the BAE Systems filter, the ASNF uses an IMU which constrains the solution by providing information between updates. In addition, the validity of each range measurement is verified against the expected measurement using a validation gate, and so measurements generated from corrupt signals can be detected and removed prior to entering the filter. Removing this validation gate, and increasing the variance of the IMU results in a navigation solution which has jumps of up to 100 m as expected from analysis, Faragher (2008).

Improving the signal geometry by selecting transmitters that are closer to the trajectory and are better distributed surrounding the platform improves the position estimate generated from the ASNF as shown in Fig. 5. In this
Fig. 4. Position estimate generated from GSM (Configuration 1) and IMU data

Fig. 5. Position estimate generated from GSM (Configuration 2) and IMU data

experiment the maximum jump in position estimate is 9m, while the largest diversion from ground truth is 17m.

3.3 DAB Signals

DAB signals provide more accurate timing information than GSM signals and thus yield a more accurate range estimate to the transmitters. Further the DAB standard allows the location of the radio mast to be contained within the transmitter identification messages thus eliminating the need for predetermining the transmitter positions prior to operation. However, the significant disadvantage of using DAB for localisation is the limited availability of transmitters as clear from Fig. 6. Each transmitter broadcasts three different signals however the poor geometry will impact on the navigation solution estimated by the ASNF.

Fig. 7 shows the position estimate generated by the ASNF using DAB and IMU measurements. Although the accuracy of DAB timing information is greater than GSM signals, the solution is actually less accurate, mainly due to the limited number of transmitters in the region of interest.

Unfortunately, with the current configuration in Sydney, DAB signals are not a suitable navigation source when used alone. However if combined with DVB for example, which broadcast from an additional two transmitters in the Sydney region (East and South of the experimental trajectory), additional experiments have shown that this will significantly improve the accuracy of the solution (within 20m from ground truth) subject to the location of the platform.

Fig. 6. Position of the DAB Transmitters in Sydney.

3.4 3G Signals

Due to the higher bandwidth, 3G signals yield range measurements with a higher accuracy than all other NAVSOP signals considered in this paper as the timing errors associated with coherent multipath interference are greatly reduced, Faragher (2007). A further advantage of these signals is the high number of transmitters in urban environments thus yielding good signal geometry, and hence a solution will be more robust to biases. There are however a number of disadvantages, firstly, 3G transmitters use a Code Division Multiple Access (CDMA) coding technique, whereby the data streams use orthogonal spreading codes, such that the data codes can be superimposed using the total available bandwidth. This means that within each network, each transmitter broadcasts on the same frequency and thus when the receiver is located close to one transmitter, the signals from the other transmitters may not be identified. Further disadvantages include the complexity in extracting the data and also the broadcast does not contain information of the transmitter position, fortunately in Australia this information is made publicly available, Australia Communications and Media Authority (2009).

3G signals can be received up to 10 – 12km from the transmitter. In Sydney there are a large number of transmitters available to use, however due to the CDMA encoding technique, only four signals from the four different networks available in the region of interest were used for each experiment at one time.
The transmitters used in these experiments are shown in Fig. 8. The spatial distribution of the transmitters is reasonable, with signals constraining both the North-South plane and the East-West plane. The position estimate yielded from the ASNF using the data from this configuration can be seen in Fig. 9. As expected, the accuracy of the navigation solution is greater for the 3G range measurements than the other NAVSOP signals with a maximum error from ground truth of 12m.

Further experiments performed with an improved transmitter distribution (i.e. closer and equally surrounding the trajectory) result in an improved solution accuracy with maximum error from ground truth is approximately 6m. Therefore it is important to carefully select the position of the transmitters with respect to the receiver.

3G signals do provide excellent accuracy for estimating position, however they also require prior knowledge of the environment and information of the signals available. If an area is to be traversed, then it is necessary to know which signals may be received and thus the locations of the transmitters. It may be such that knowledge of a selection of transmitters on only one network may not be sufficient in providing a solution at all times of operation; if the platform is in close proximity to an unidentified transmitter, then the signals from the known transmitters may be ‘drowned out’ by the unknown signal. However if a stable navigation solution can be maintained it may be possible to reverse calculate the position of the new transmitter. Performing SLAM with NAVSOP has been demonstrated by Faragher (2009).

Further experiments were performed to analyse the performance of the ASNF when more than one signal type was used to estimate position. Results have shown that using measurements from more than one sensor can improve the accuracy of the solution and also improve redundancy of the system. Two examples of combining signal types are presented below.

**MW & DAB**

As discussed earlier, MW signals provide good relative corrections, however, the solution accumulates errors over time and thus the position estimate drifts from the ground truth. Pairing this signal type with a time of arrival message type, can help to constrain the solution. In this example, the ASNF is configured to use information from both MW measurements and DAB measurements. DAB was selected as DAB transmissions contain information on the location of the transmitter and thus little understanding of the region of interest is required prior to operation.

The position estimate generated from MW, DAB and IMU data can be seen in Fig. 10 which shows the fused solution is less smooth than the stand-alone MW solution. This is because the MW corrections are relative corrections, and so the covariance continues to increase (although at a slower rate than the INS alone). As the covariance increases, the Kalman filter increases the weighting on the DAB measurements, which attempts to globally correct the solution. Although the position estimation appears worse than the MW configuration, the covariance is continually constrained by the DAB measurements and so the position estimate maintains stability in a global frame. This is a good example to demonstrate that the NAVSOP data source should be selected depending on the application; if the solution has to be globally consistent then at least one absolute observation source must be used (i.e. range measurement), however, if the application requires the solution to be smooth for tasks like map building, then a relative observation (i.e. carrier phase measurement) may be more suitable.

This experiment runs for approximately 10 minutes and therefore the results show a limited advantage of using MW carrier phase information combined with another sensor, as the solution yielded from MW alone performs better that other range input sources. However, over a long time period, the drift becomes significant and so would require a global observation to constrain the solution. If, however, the number of MW transmitters decreases,
and as such, the transmitter distribution becomes poor, combining MW corrections with DAB (or GSM or 3G) corrections will prove more advantageous.

MW, GSM, DAB & 3G  Fig. 11 shows the position estimate generated from the ASNF using all the signal types discussed in this paper; MW, GSM, DAB, 3G and IMU. As expected, this is the most accurate solution from all experiments performed on this dataset as the solution is generated using the greatest number of signals from a large range of transmitters which provide an excellent signal geometry, thus reducing biases. With such a large number of observations of the system the user can configure the system to be more selective with the data that is used and consequently improve the quality of information entering the filter.

4. CONCLUSION

This paper has discussed the integration of NAVSOP functionality in the ASNF. The flexible design of the ASNF has enabled quick and easy comparisons between a number of simulated experiments in the Sydney region. The configurations reviewed include MW, GSM, DAB and 3G signals to aid the IMU driven filter, along with a brief overview of combining different signal types.

It was shown that each signal has advantages and disadvantages for use in position determination. MW signals can be received up to a few hundred kilometers from the transmitter and thus the area of operation is large. These signals can be used to extract carrier phase information which, as a relative position measurement can cause slow drifts in the solution.

GSM signals contain timing information and thus can provide range estimates to the transmitters. Within populated areas GSM transmitters are plentiful, and so this network can yield good signal geometry.

DAB signals can also be used to estimate the transmitter range, and with a higher bandwidth they exhibit a more accurate measurement. Little knowledge is required about the area prior to operation as the broadcast contains information on the transmitter locations. The disadvantage however, is the limited number of transmitters; Sydney only features two transmitters, which are located only 1.5km apart and therefore this network does not provide good signal geometry.

3G signals have a high bandwidth and thus multipath interference resulting in timing errors is greatly reduced, therefore a more accurate range measurement can be yielded. In populated areas there are a large number of 3G transmitters, this however is disadvantaged by the CDMA technique adopted by each network which superimposes 3G signals on the same frequency, thus reducing the number of signals that can be detected by the receiver at one time.

This paper has shown that there are a number of contributing factors to the accuracy of a solution. The main factors include the number of transmitters, the distribution of transmitters and the bandwidth of the signal. Each signal type has both advantages and disadvantages and therefore there is no single network that yields the best overall navigation solution. As a result, it was noted that a navigation system that can use a number of input sources is advantageous when working with opportunistic signals. A subset of results obtained by combining sensors was also presented in this paper. As expected, when combining a number of different signal types the accuracy of the navigation solution improves compared to using each signal type individually as this increases the number of signals used for the error corrections and also improved the distribution of transmitters.

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REFERENCES


