An Integrated Low Cost GPS/INS Attitude Determination and Position Location System

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BIOGRAPHY

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Robert Wolf received a diploma in aerospace engineering in 1995 from the Munich University of Technology. In 1995 he joined the Institute of Geodesy and Navigation as a Research Associate, working in the field of GPS/INS integration.

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ABSTRACT

Advances in the technology of low cost solid-state inertial sensors have brought the price for a inertial measurement unit (IMU) down to the $ 10,000 level. Such an IMU, Systron Donners' MotionPak^{TM}, has been purchased by the Institute of Geodesy and Navigation (IfEN) in order to develop an integrated GPS/INS attitude determination system. As GPS component for the integrated system, IfEN has selected the Trimble Advanced Navigation Sensor (TANS) Vector receiver system, which is a multi antenna attitude determination and position location system.

IfEN has developed a realtime navigation software to calculate position, velocity and attitude from the outputs of the MotionPak gyroscopes and accelerometers. These computed values are integrated with position, velocity and attitude information from the TANS Vector in a Kalman filter. Test results show that this system can achieve up to 0.1 degrees attitude accuracy (RMS).

This Paper describes the low cost integrated GPS/INS System, including GPS and INS hardware, data acquisition and software.

INTRODUCTION

Many applications require position and velocity information, as well as attitude determination. A multi antenna GPS system like the Trimble TANS Vector provides accurate position, velocity and (but not so accurate) attitude. Also the data rate is restricted to a maximum of 10 Hz for attitude solutions.

Since many applications require attitude information at a much higher data rate, an integrated INS/GPS system will meet the requirements. The idea of integrating inertial sensors with GPS is not new. Even the integration with a low cost sensor like Systron Donner's MotionPak has been done previously. The relativly low acquisition cost of such an integrated system makes it attractive for many applications. In most cases, the GPS receiver had been a normal one antenna receiver, thus position and velocity information had been taken to update the INS Kalman filter. By using DGPS the obeservations where accurate enough to estimate roll and pitch errors and therefore correct gyro drifts, which are the main problem with low cost inertial sensors. Only the azimuth could not be determined by such a system.

The integration of a low cost sensor with a GPS attitude determination system has the great advantage that the integrated system can also determine the azimuth. The accuracy of the horizontal angles, roll and pitch should increase also, by direct measurements of angle differences.

This study investigates the achivable accuracy of such a system.

HARDWARE DESIGN

The low cost integrated system uses the following hardware components:

– Systron Donner MotionPak, inertial sensor assembly

– Trimble TANS Vector, multi antenna GPS receiver

– Keithley DAS 1802 HR, 16 bit data acquisition plug in board

– Packard Bell 486/ DX 66, personal computer

The data acquisition board is used to convert the output of the MotionPak to 16 bit digital values computer. The TANS Vector is connected to the computer via serial link.

Multi Antenna GPS Receiver

The Trimble TANS Vector is multi antenna position and attitude determination system. It is equipped with four antennas, one master and three slave antennas and a six channel GPS receiver.

The three attitude angles roll, pitch and azimuth are determined by differential carrier phase measurements between the master antenna and each of the three slave antennas.

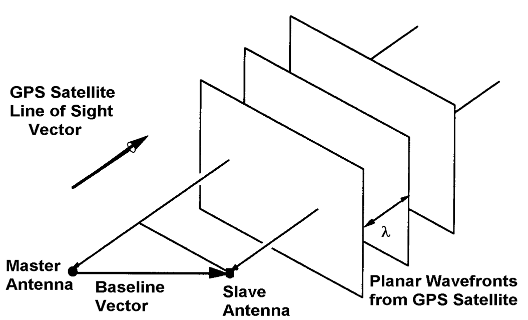

Figure 1: Differential Carrier Phase Measurement

The TANS Vector provides two serial data channels:

> Channel B is used to transmit attitude data at a rate up to 10 Hz, while position and velocity information has low priority and is therefore only transmitted about every 1 - 3 seconds.
>
> Channel A is mainly used for position and velocity information at a higher rate, and for data input in differential mode.

So far, the TANS Vector is not used in differential mode, but this has no impact on the accuracy of GPS attitude determination. Table 1 indicates the specifications of the Trimble TANS Vector.

Azimuth accuracy	0.3 ° (RMS), 1 m Baseline
Position accuracy	100 m horizontal, 156 m vertical, SA enabled Differential GPS, Base station within 500km: 5m horizontal, 8 m vertical
Velocity accuracy	0.2 m/s , without SA Differential GPS: 0.1 m/s
Power	28 VDC , 7 Watts
Weight	Receiver: 1.42 kg Antenna: 0.19 kg
Dimmensions	Receiver: 127 x 241 x 64 mm³ Antenna: 96 x 102 x 13 mm³

Table 1: Specifications of the TANS Vector

Trimble delivers the TANS Vector completely integrated with receiver and processor unit and antennas in a 0.52 x 0.52 x 0.08 m³ housing, thus getting 0.58 m baseline on the diagonal. Figure 2 indicates the reference axis for the four antenna system.

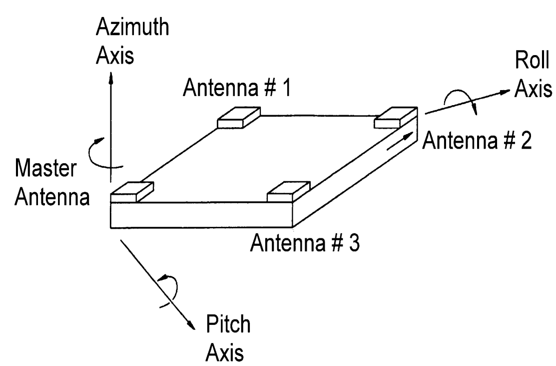

Figure 2: Attitude Reference Axis Definition

Low Cost Inertial Sensor

The Systron Donner MotionPak is a six degree of freedom inertial sensor, measuring three linear accelerations along orthogonal axes and three angular rates. The angular rates are sensed using oscillating quartz tuning forks and linear accelerations are sensed using a vibrating quartz beam. Additionally, it has a temperature sensor. This is necessary, because the MotionPak is not temperature compensated. The output of the MotionPak is a voltage proportional to acceleration or angular rate input. Table 2 gives an overview of the specifications of the MotionPak.

Size	7.6 x 7.6 x 9.0 cm³
Weight	0.81 kg
Power	
Input Voltage	+/- 15 VDC
Input Power	7 Watts
Measurement Range	
Gyro	± 200 °/s
Accelerometer	± 5 g
Inertial Sensor Performance	
Gyro	
Null	0.09 °/s
Bias Teperature Change	< 3 °/s
Scale Factor Temperature Change	± 0.03% /°C
Noise	0,01 °/s √Hz
Misalignment	< 0.33 °
Accelerometer	
Bias	± 3.6 mg
Bias Temperature Change	± 15 µg
Scale Factor Temperature Change	± 0.001 %/°C
Noise	< 2.5 mV RMS
Misalignment	< 0.2 °

Table 1: Specification of the MotionPak

Computer and Data Acquisition Board

The computer, used to perform data acquisition and processing is a commercial available personal coumputer Packard Bell with a 66 MHz Intel 486 processor.

The acquisition of the MotionPak data is performed by the Keithley DAS 1802 HR plug in data acquisition board. It is used to convert the voltage outputs of the MotionPak's gyros and accelerometers to 16 bit digital integer values with a sampling rate of 600 Hz.

These are written from the acquisition board into a ring buffer via direct memory access. The board also provides a status word which contains information about the currenly written data entry and the buffer number. These information are used as a time tag.

The DAS 1802 HR provides 8 differential inputs, enough for the three accelerometers, rate sensors and the temperature sensor.

SOFTWARE DESCRIPTION

The software developed at the Institute of Geodesy and Navigation (IfEN) provides the possibility of sampling data from the MotionPak and the TANS Vector for post mission processing, as well as real time processing capability.

Due to performance limitations by the currently used personal computer, the results obtained by post processing are better than those obtained by real time processing.

The software consists of three main parts:

- the inertial navigation software

- the GPS data sampling

- and the Kalman filter

These parts are described in the following sections.

Inertial Navigation Software

The output of the MotionPak contains three accelerations and three angular rates refenced in sensor coordinates. These values have to be integrated to get velocity, position and attitude.

There are several possibilities of mechanization of the strapdown algorithms. We found some computational advantages in computing the direction cosine matrix and integrating the specific forces in an earth centered inertial frame. From there, the desired values can easily be transformed into the desired reference frame, normally the local level navigation frame with north, east and down axes.

To avoid algorithmic errors like coning and sculling resulting form the direction cosine matrix being not constant during the sampling interval, the inertial data sampled at 600 Hz is corrected by pre-integration. These delta-velocity and delta-angle values are processed now at a rate of 200 Hz.

In real time mode, this part of the software has the highest priority, because the values are computed by iteration. If for example some angular rate information is lost while turning the sensor (or the host vehicle), the attitude angle will be too small. This can be compared with platform tilt of an mechanical INS.

High accuracy INS can determine the initial transformation matrix from the sensor output. Due to large and unstable gyro drifts, the MotionPak can only determine the "down" direction from the accelerometer output, i.e. pitch and roll angle. In the integrated system, the azimuth is taken from the TANS Vector.

GPS Data Recording

The GPS data received from the TANS Vector via serial interface is marked with a time tag and stored together with a code for the type of observation (velocity, position or attitude) in a file during sampling.
In realtime or post mission processing the values, type-code and time tag are read either from the file or the serial interface and stored in a buffer for further processing in the Kalman filter.

Kalman Filter

In post processing, one complete filtercycle is performed after a well defined interval. In real time mode the filter routines have the next priority after the navigation routines, and are executed when the system is not busy with the INS navigation. This leads usually to longer filter cycles than in post mission mode.

The Kalman filter uses GPS position, velocity and attitude information to estimate navigation and sensor errors of the inertial measurement unit as well as the offset angles between the GPS and INS axes.

The state vector of the filter consists of the following 27 elements:

$$X_{INS/GPS} = (\delta\varepsilon \;\; \delta v \;\; \delta r \;\; d \;\; b \;\; d_T \;\; \kappa_a \;\; \kappa_g \;\; \Psi)$$

with nine INS navigation error states

- $\delta\varepsilon$ Vector of attitude error with respect to north, east and down axes
- δv Vector of velocity error in latitude rate, longitude rate and altitude rate
- δr Vector of position error in latitude, longitude and altitude

15 INS sensor error states

- d Vector of uncompensated gyro drift
- b Vector of uncompensated accelerometer bias
- d_T Vector of gyro drift due to temperature changes
- κ_g Vector of gyro scale factor error
- κ_a Vector of accelerometer scale factor error

and three GPS error states

- Ψ 3 offset angles between GPS and INS axes

The state estimates are fed back to correct the navigation computation and the sensor output. The estimation of the offset angles is necessary because the TANS Vector shows a (nearly) constant offset in attitude that can't be neglected.

The following observations are used to update the Kalman filter:

- GPS Position
- GPS velocity
- GPS attitude

provided by the TANS Vector and

- Pitch
- Roll

provided by the accelerometers of the MotionPak during initial alignment.

TESTING OF THE LOW COST INTEGRATED SYSTEM

The system is still under development, but some static tests had been conducted to test hardware, data collection, navigation software and the Kalman filter model.

The TANS Vector had been placed on a plane ground, to determine the error in pitch and roll.

The next step will be to perform tests on a three dimensional angle simulator, which has 0.03° accuracy. After that dynamic tests on a van will be conducted.

FIRST TEST RESULTS AND ANALYSIS

TANS Vector

Trimble Navigation specifies the roll, pitch and azimuth accuracy of the TANS Vector for 1 m baseline as 0.3 degrees RMS. The azimuth accuracy for other baseline lenghts can be determined by the following relationship

$$\varepsilon = \arctan\left(\frac{0.5\text{ cm}}{\text{baseline in cm}}\right)$$

To obtain the accuracy for roll and pitch errors, this value has to be multiplied with factor 1.5 to 2, according to the TANS Vector manual.

This leads theoretically to

$$\varepsilon_{Azimuth} = 0.5\,° \text{ (RMS)}$$
$$\varepsilon_{Roll,\,Pitch} = 0.75\,° - 1\,° \text{ (RMS)}$$

for 0.58 m baseline.

Figure 3 shows the roll error of the TANS Vector. The mean value has still an offset of 1.82 degrees. This offset is estimated in the Kalman filter so it can be compensated.

There is another benefit from estimating the offset angles between INS and GPS. Normally, the GPS antennas will be mounted outside, i. e. on top of the host vehicle, while the inertial sensor will be installed inside. The estimated offset angles would also contain these physical misalignment angles between the two sensors. Thus, they would be also compensated.

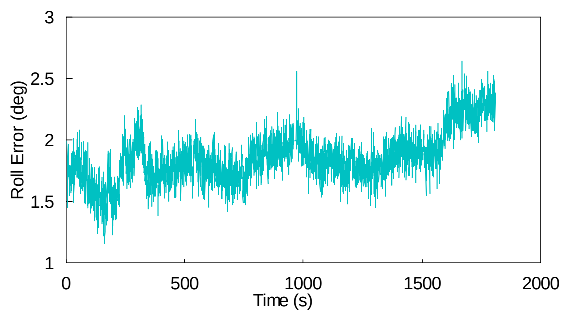

Figure 3: Roll Error of TANS Vector

The offset compensated roll angle has then an accuracy of 0.2 ° (RMS). An analysis of the graph shows that the noise is not pure white noise. The reason for this moving average could be multipath, although this data has be recorded in the absence of near-by standing buildings.

Figures 4 and 5 show the sampled values for pitch and azimuth.

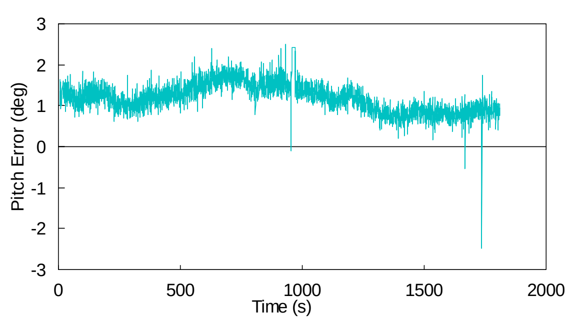

Figure 4: Pitch Error of TANS Vector

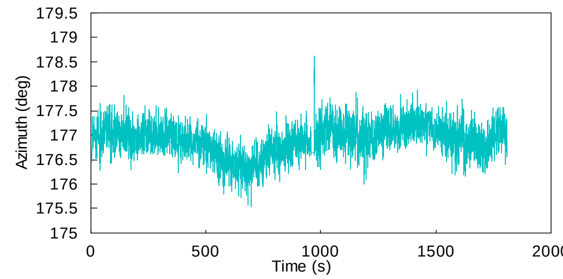

Figure 5: Azimuth of TANS Vector

The pitch angle has also a large offset of 1.22 °. The offset compensated accuracy is 0.35 °. For the azimuth angle there is no reference, but it can not be assumed that there is no offset. The RMS error relative to the mean value is 0.35 °.

In the dynamic case, there is the possibility to estimate the azimuth offset angle from the heading angle, i. e. the horizontal direction of the velocity angle.

MotionPak

Figures 6 and 7 show the typical output of an accelerometer and a gyro of the MotionPak over a temperature range. This time interval for this temperature change is half an hour.

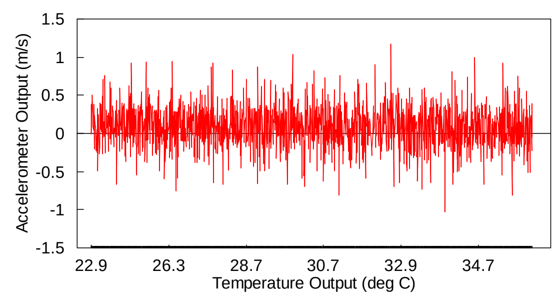

Figure 6: Temperature Effect on Accelerometer Output

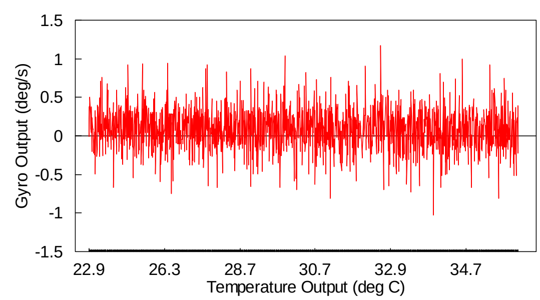

Figure 7: Temperature Effect on Gyro Output

Both graphs show a nearly constant value for the mean bias over the temperature range. Unfortunately, this can differ from turn-on to turn-on.

The temperature performance of the gyros can be up to 3 °/s, as can be seen from Table 2. For this reason, the temperature related gyro drift is also estimated in the Kalman filter.

Figures 8 and 9 show roll and pitch angles of the free drifting MotionPak. The first 90 seconds the software had been running in calibration mode to achieve a coarse calibration of the sensors.

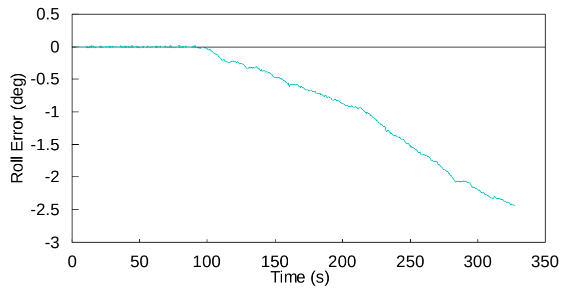

Figure 8: Roll Error of the MotionPak

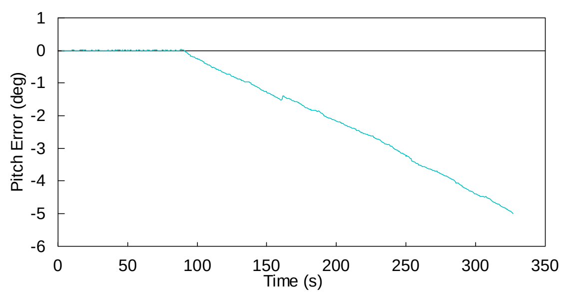

Figure 9: Pitch error of the MotionPak

Integrated System

The next three figures show the results from the integrated system. The reference for horizontal attitude angles roll and pitch had been taken from the accelerometer outputs of the MotionPak. The difference from these angles are shown in the figures. Although this is no exact reference, it is good enough to see the angle drifts of the integrated system.

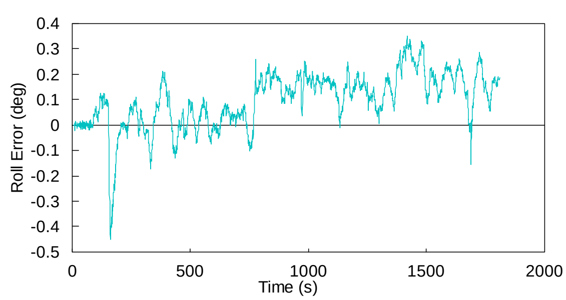

Figure 10: Roll Error of the Integrated System

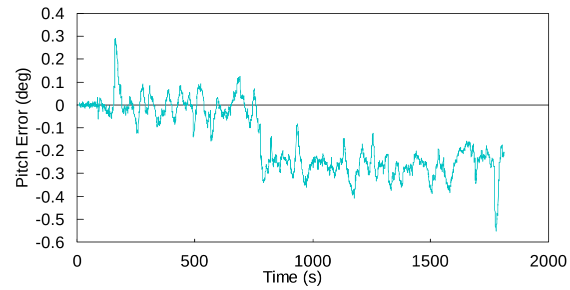

Figure 11: Pitch Error of the Integrated System

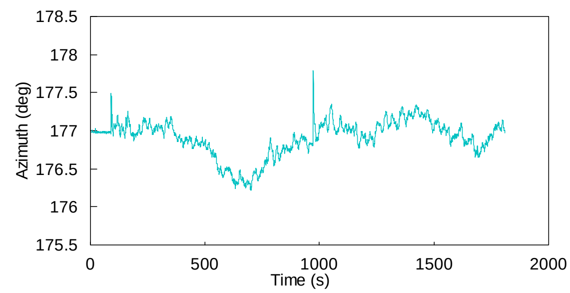

Figure 12: Azimuth of the Integrated System

A comparison with Figures 3 and 4 indicates that the roll and pitch angle from the integrated system follows in principal the tendency of the GPS attitude, but are smaller in magnitude because the horizontal angles can also be estimated by position and velocity updates.

The azimuth, of course follows the tendency of the GPS determined attitude, because there are no other observations from which azimuth could be estimated in the static case.

The achived accuracies, related to the mean values are indicated in table 3.

	Roll	Pitch	Azimuth
Mean	0.1	- 0.14	176.9
RMS Error	0.13	0.10	0.24

Table 3: Attitude Errors of the Integrated System

As mentioned above, also the azimuth offset angle of the GPS system could be estimated in the dynamic case.

There are many possibilities to enhance the performance of the system. The next step will be to use differential GPS for velocity and position update instead of absolute positioning. The presence of SA in the GPS position and velocity observations causes the Kalman filter to "correct" the gyro drifts to compensate position and velocity errors, because the gyro drifts are not constant.

An other possibility is to extend the Kalman filter and use the raw GPS measurements instead of the computed position, velocity and attitude values.

CONCLUSION

This first studies of an low cost integrated INS / GPS attitude determination system using a low cost inertial sensor and a multi antenna GPS have shown, that accuracies in attitude of better than 0.2 ° in roll and pitch and 0.3 ° in azimuth can be achieved. The use of DGPS will be the next step to improve performance.

The relatively modest acquisition costs, compared to a medium precision INS makes such a system very attractive.

The result of this study will be used as a baseline for further improvements.

ACKNOLEDGMENTS

The Kalman filter concept is based on the Kalman filter software STRAP from M. M. Ertel and the diploma thesis from J. C. Peri.

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