Differential GPS supported navigation for a mobile robot

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Abstract: The objective of this work is the development of a low cost differential GPS system suited for mobile robotics applications which enhances positioning accuracy compared to a single receiver system. In order to keep costs minimal we used single frequency (L1) receivers, namely U-Blox AEK-4T. We adapted the GPS Toolkit (GPSTk) to work with single frequency (L1) observations in real-time. This allowed us to apply an already existing algorithm, originally intended for Precise Point Positioning (PPP) applications using a double frequency receiver. The core of this algorithm is a Kalman filter that processes code and carrier phase single differences. Carrier phase ambiguities are treated as real (float) values, we do not try to fix them to their correct integer values. In a static test with a baseline length of 11m, observations were collected for five minutes. The developed system achieved a horizontal RMS of 6.9cm. Furthermore we carried out a dynamic test where the rover drove around in a circle. Seven circles were driven in about five minutes. The system determined the circle's radius with an RMS error of 13.2cm.

Keywords: Differential GPS, DGPS, carrier phases, single differences, single frequency, Kalman filter, mobile robots

1. INTRODUCTION

Many outdoor robotics applications require positions that are more accurate than those obtained by a single GPS receiver. Existing RTK-GPS systems already provide accuracies in the sub-centimeter level. However, the geodetic grade double frequency receivers that are usually required for these systems are expensive. Other important factors as size, weight or power consumption limit the possible forms of applications and the acceptance in the field of mobile robotics. Nowadays, inexpensive, small, light and power saving devices exist, but usually they do not provide raw observation data, which is absolutely needed for any differential GPS (DGPS) solution. Some new generation modules promise to bridge this gap by combining the above mentioned factors while remaining inexpensive (U-Blox AEK-4T: €295) and providing raw pseudorange, carrier phase and Doppler observations at an update rate of up to ten Hertz.

This allows the use of these receivers in the context of a scientific application. Especially the carrier phase observation promises to enhance positioning accuracy to a level which should be sufficient for most mobile robotics applications. Compared to existing RTK-GPS solutions that usually use double frequency receivers, the AEK-4T represents a single frequency receiver. This makes the solution of the carrier phase ambiguity problem, involved in carrier phase based DGPS applications, more complicated. Already accomplished research shows that fixing the ambiguities within reasonable time is a problem when inexpensive single frequency receivers and cheap antennas are used (Liu et al. (2003), Pinchin et al. (2008)). Inexpensive receivers and antennas feature high noise levels in the pseudorange observations, which is a problem even for very short baselines. Odijk et al. (2007) examined the popular *LAMBDA* ambiguity resolving algorithm with a single frequency receiver. They conclude that "instantaneous ambiguity resolution based on single-frequency data is only successful with many (> 10) satellites." Takasu and Yasuda (2008) obtained a mean time to first fix with ambiguity resolution of almost eleven minutes for the U-Blox AEK-4T receiver with ANN-MS antenna. Note that losses of lock, which are likely to occur with inexpensive single frequency receivers under dynamic conditions, require the reinitialization of the ambiguities.

Based on these results, we decided to implement a float approach based on Salazar et al. (2008). However, we work with pseudorange and carrier phase single differences at the L1 frequency instead of linear combinations of double frequency observations as presented by Salazar, who worked with double frequency receivers. The solution presented in this paper requires an initialization phase of about four to five minutes. During this period, the positioning accuracy increases. However, the system does not need to be reinitialized after losses of lock or when new satellites are introduced in contrast to single frequency approaches that fix the ambiguities to integer numbers. In our case, positioning accuracy decreases temporary, but quickly reaches an acceptable level when the receiving conditions improve again.

The tests presented in this paper result in a sub-decimeter horizontal RMS error in a static test and a horizontal RMS error of about 13cm in a dynamic test after an initialization phase of five minutes in each case.

2. DIFFERENTIAL GPS BASED ON CARRIER PHASE OBSERVATIONS

The goal of a DGPS system is to enhance positioning accuracy by using two GPS receivers. Usually, one is stationary and its position is exactly known. It is called *reference-* or *base station*. The second receiver whose position is to be determined is called *mobile receiver* or *rover*. A DGPS system enhances the accuracy because the common-mode errors (errors common to both receivers) can be determined and eliminated when the two receivers operate in a limited geographic region. This is usually done by calculating the *baseline vector* (vector between mobile receiver and reference station), where the common-mode errors are canceled out. In order to determine the baseline vector, a classical DGPS system uses the *coarse/acquisition (C/A)* code. By utilizing the carrier signal, on which the C/A code is modulated, the positioning accuracy can be enhanced again.

2.1 Carrier phase observation

Because the discussed method is based on phase observations of the L1 carrier signal (1575.42MHz), a short explanation of the basics of this measurement is provided here according to Odijk et al. (2007). A standard GPS receiver computes its position based on range measurements to the GPS satellites by applying the trilateration technique. These range measurements are usually obtained by tracking the coarse/acquisition (C/A) code. As the name suggests, this code is rather coarse because of its short code length compared to a long chip rate (~300km/~300m). The signal propagation delay is obtained by cross correlation between the received C/A code and a replica code generated by the receiver. The coarse nature of the C/A code leads to range measurements that are affected by high noise levels. Especially inexpensive receivers and antennas which are used in this work are affected by this problem. But, in order to track the C/A code, the receiver needs to track the carrier signal as well. This is usually done via phase-locked loop (PLL) filters, which enable the receiver to compute the so called phase ranges. Because of the short wavelength of the L1 signal (~19cm), these ranges are very precise and characterized by low noise levels. The problem is that the phase ranges are offset to the C/A code ranges by an ambiguous number of whole phase cycles. One can imagine this problem when trying to read from a measurement tape, but only a small area is visible around the measuring point. For example, you would read 47,3cm but you do not know if it is 47,3cm or 147,3cm or even 1047,3cm. The phase range Φ [m] can be described mathematically as follows:

$$\Phi(t) = \rho(t) + c\,(\tau_r(t) + \tau_s(t)) + \lambda_1 N^{'} \qquad (1)$$

where

$\rho\,[m]$	true geometric range between satellite and receiver
$c\,[m/s]$	speed of light
$\tau_r, [s]$	receiver clock error
$\tau_s, [s]$	satellite clock error
$\lambda_1, [m]$	L1 wavelength ($\sim$ 19cm)
$N^{'} \in \mathbb{R}, [cycles]$	Carrier phase float ambiguity

In fact, the carrier phase float ambiguity term $N^{'}$ consists of three components:

$$N^{'} = \Phi_s(t_0) - \Phi_r(t_0) + N \qquad (2)$$

Where $\Phi_s(t_0)$ is the satellite offset in cycles at initial time t_0 and $\Phi_r(t_0)$ the receiver offset, respectively. $N \in \mathbb{N}$ is the unknown initial number of whole carrier phase cycles between satellite and receiver. Because we do not try to fix N to an integer number, we stay with the term $N^{'}$ as presented in Gao (2006).

Once the ambiguity problem is completely solved, which means that the exact integer number of whole phase cycles between satellite and receiver is known, accuracies in the sub-centimeter level can be reached. Such a system is most commonly referred to as *Real Time Kinematic GPS (RTK-GPS)* or *Carrier Phase Enhancement GPS (CPGPS)*. Usually, these systems use geodetic grade double frequency receivers. This is needed in order to be able to fix the ambiguities to the correct integer values within short time. As stated in section 1, the ambiguity resolution is not possible within short time in our case. Therefore, we float the ambiguities in this approach. This means that the accuracy will not reach the sub-centimeter level but should stay in the decimeter or centimeter level.

As the double differences that are usually applied in RTK-GPS systems achieve their full potential only when fixing the ambiguities to integer values, which we are not doing here, we decided to work with single differences to simplify matters. Thus, we do not have to select a master satellite which would introduce the hand-over problem and additional measurement noise when obtaining the double differences.

2.2 Kalman filter design

Our approach is based on the well-known Kalman filter. A good introduction to the filter is given in Welch and Bishop (1995). The design of the filter that we use for our approach is presented in the following section.

System model The Kalman filter is trying to estimate the state vector x_t, which describes the system. The state vector of our system has the following form:

$$x_t = \begin{bmatrix} \Delta b \\ \tau_{m,r} \\ N^{'1}_{m,r} \\ \vdots \\ N^{'n}_{m,r} \end{bmatrix} \qquad (3)$$

The symbol Δb represents the baseline vector change compared to the last epoch. The baseline vector is given in a local north (N) east (E) up (U) system. Thus, it consists of the three components ΔN, ΔE and ΔU. Because we work with single differences, the combined receiver clock error $\tau_{m,r}$ of the mobile (roving) receiver m and the reference (base) station receiver r does not cancel out. Therefore, we have to estimate this error. $N^{'i}_{m,r}$ are the float phase ambiguity estimates of the i-th satellites, which are received by both the mobile receiver and the reference station.