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Original Article

A dynamic model for GPS based attitude determination and testing using a serial robotic manipulator

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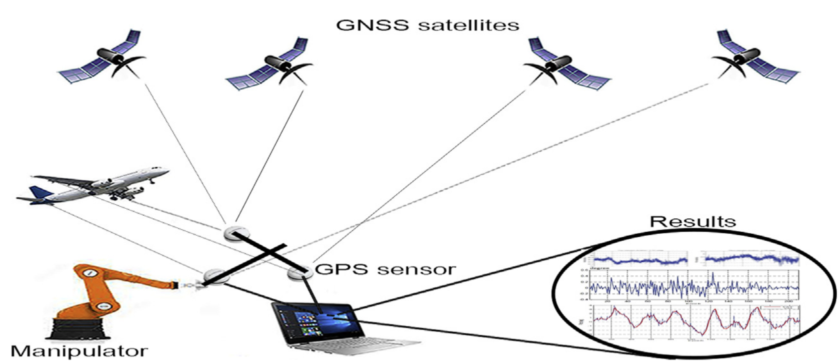
GRAPHICAL ABSTRACT



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ABSTRACT

A computational algorithm is developed for estimating accurately the attitude of a robotic arm which moves along a predetermined path. This algorithm requires preliminary input data obtained in the static mode to yield phase observables for the precise, 3-axis attitude determination of a swinging manipulator in the dynamic mode. Measurements are recorded simultaneously by three GPS L1 receivers and then processed in several steps to accomplish this task. First, artkconv batch executable converts GPS receiver readings into RINEX format to generate GPS observables and ephemeris for multiple satellites. Then baseline vectors determination is carried out by baseline constrained Least-Squares Ambiguity Decorrelation (LAMBDA) method that uses double difference carrier phase estimates as input to calculate integer solution for each baseline. Finally, attitude determination is made by employing alternatively Least-squares attitude determination (LSAD) in the static mode and extended Kalman filter in the dynamic mode. The algorithm presented in this paper is applied to recorded data on Mitsubishi RV-M1 robotic arm in order to produce attitude estimates. These results are confirmed by another set of Euler angles independently evaluated from robotic arm postures obtained along the predefined trajectory.

Introduction

Double-differenced carrier phase measurements might be utilized for GPS-based high precision attitude determination of the object, and many techniques can be introduced by making use of integer ambiguity resolution. A lot of methods are proposed in this area of research and more recent ones make use of the LAMBDA, which is an abbreviation of Least-squares AMBiguity Decorrelation Adjustment method. Standard LAMBDA method can only be used for unconstrained and/or linearly constrained GPS models; however, a baseline constraint is nonlinear. So, most of the given methods take advantage of this additional information

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by optimizing a search space and checking whether or not the candidate ambiguities correspond to the given baselines. Although that kind of procedures improves the effectiveness of integer ambiguity resolution, the methods considered are still not able to achieve very high robustness, because formerly available information is not entirely brought into the ambiguity resolution procedure. Moreover, the success rate of ambiguity resolution diminishes significantly when implemented in a single frequency, epoch by epoch attitude determination systems [1]. For single epoch attitude determination, Park and Teunissen [2] and Teunissen [3] in their works propose two nonlinear constrained integer least square methods and relevant searching strategies. Both methods bring nonlinear constraints into an ambiguity objective function, the first method is related to LAMBDA ellipsoidal search area, while the second method is related with a more precise but complicated non-ellipsoidal search area. There are other more recently introduced methods, employed for constrained attitude determination solution, which are Least-Squares Ambiguity Solution Technique (LSAST) method [4], and Multivariate Constrained Approach [5,6]. Furthermore, a comparative analysis between methods of baseline constrained Least-Squares Ambiguity Decorrelation (BC LAMBDA) and multivariate constrained Least-Squares Ambiguity Decorrelation (MC LAMBDA) is provided in Bing et al. [7]. Whilst they enhance the success rate to a higher level as compared to unconstrained models, it may be not sufficient for implementing in the competitive application. As the same with methods mentioned before, they mostly employ the baseline length as preliminary information. One of the approaches to fully integrate prior information is the addition of an appropriate dynamic model of the body that can be used to predict and correct ongoing angular estimates in the real time mode.

This study emphasizes the real-time requirement of attitude determination of the moving object and propose a reliable single frequency, epoch by epoch attitude determination algorithm constrained by baseline lengths and an auxiliary dynamic model of the platform. This algorithm utilizes prior information of baseline lengths and the predictive model of the rotating platform based on its potential trajectory and angular rates of rotation. This article is structured in the following way. Firstly, the paper discusses in detail the mathematical model and methods used to solve the given problem of attitude determination. Secondly, an experimental setup constructed for testing and verification of the developed algorithm is presented. Then, an overview of the corresponding software designed to implement the above mathematical model described. Finally, results of the static and dynamic tests that indicate good performance of the proposed mathematical algorithm are presented.

Methodology

This paper proposes an the algorithm for attitude determination by computing phase differences of the GPS L1 signal obtained at three antennas. It is known that carrier phase GPS readings are subject to the issue of undesirable cycle slips. Once there is a cycle slip in any receiver because of not sufficient signal to noise ratio or loss of track by the signal processing unit, the error will increase and diminish precision of the angular solution. So the double difference measurements are used to furnish this GPS-based attitude determination approach. In order to determine the attitude from GPS carrier phase measurements, ambiguities have to be resolved. This means that one should search for correct carrier phase integer ambiguity values. This procedure is the most important part of accurate GPS-based attitude determination.

In this article, an equation which outlines the relationship among integer ambiguity, the attitude, and double difference carrier phase observables is derived in the first step. Then integer ambiguity resolution by means of BC LAMBDA method is carried out to enhance the float solution obtained in the previous step. Finally, attitude determination is conducted by extended Kalman filter that uses integer solution for each baseline as input to calculate Euler angles of the body based on the dynamic model of its movements. The overall technique is configured to deal with integer ambiguities which can be computed incorrectly because of the scarcity of carrier phase data accumulated by single frequency GPS receivers.

Baseline constrained LAMBDA method

For the problem of GPS-based attitude determination, preliminary information such as the length of the baseline is known and does not change. Therefore the baseline constrained integer ambiguity resolution can take advantage of the typical GNSS model by incorporating the length constraint of the baseline $\|b\|_{I_3} = l$ where l is known. Then observation equations are transformed into [8]:

$$E(y) = Aa + Bb, D(y) = Q_y, \|b\|_{I_3} = l, a \in Z^m, b \in R^3$$

where y is the vector of observed minus estimated double differences of carrier phases of the order m, a is the unknown vector of ambiguities given in cycles rather than range to preserve their integer nature, b is the baseline vector, for which the length is considered to be known and constant in attitude determination problems, B is the geometry matrix consisting of normalized line-of-sight vectors, and A is a design matrix which bounds the measurement vector to the unknown vector a. The variance matrix of y is determined by the positive definite matrix Q_y which is supposed to be known, E is the mathematical average or the estimated value, and D is the variance of y.

Utilizing this transformation, the least squares principle states:

$$\min_{\|b\|_{I_3}=l, a\in Z^m, b\in R^3} \|y - Aa - Bb\|^2_{Q_y} = \|\hat{e}\|^2_{Q_y} + \min_{\|b\|_{I_3}=l, a\in Z^m, b\in R^3} \times \left(\|\hat{a} - a\|^2_{Q_{\hat{a}}} + \|\hat{b}(a) - b\|^2_{Q_{\hat{b}(a)}}\right) == \|\hat{e}\|^2_{Q_y} + \min_{a\in Z^m}\left(\|\hat{a} - a\|^2_{Q_{\hat{a}}} + \min_{\|b\|_{I_3}=l, b\in R^3}\left(\|\hat{b}(a) - b\|^2_{Q_{\hat{b}(a)}}\right)\right)$$

where $\hat{b}(a)$ is the least squares solution for b, taking into account that a is known.

Numerous methods are already developed to solve this quadratically constrained least-squares problem. In this article, uses a method based on the repeatable computation of orthogonal projections onto an ellipsoid depicted in Teunissen [5]. Then the search for the integer least-squares ambiguity vector $\breve{a}$ in the integer search area will be conducted:

$$\psi(\chi^2) = \left\{a \in Z^m \middle| \left(\|\hat{a} - a\|^2_{Q_{\hat{a}}} + \|\hat{b}(a) - \breve{b}(a)\|^2_{Q_{\hat{b}(a)}}\right) \leqslant \chi^2\right\}$$

It should be outlined here that this search area is not ellipsoidal anymore because of the inclusion of the residual baseline term.

To implement the baseline constrained technique, first the potential integer vectors within the search area is calculated using the typical LAMBDA method

$$\psi_0(\chi^2) = \left\{a \in Z^m \middle| \left(\|\hat{a} - a\|^2_{Q_{\hat{a}}}\right) \leqslant \chi^2\right\}.$$

This search area comprises of all integer vectors of $\psi(\chi^2)$ and thereby the vector $\breve{a}$ which is currently under consideration. In order to constrain the search area, it is necessary to employ only those integer ambiguities that meet the condition:

$$\|\hat{b}(a) - \breve{b}(a)\|^2_{Q_{\hat{b}(a)}} \leqslant \chi^2 - \|\hat{a} - a\|^2_{Q_{\hat{a}}}.$$

The search area should be as small as possible to be able to complete the process in an acceptable time which is essential for real-time applications. Nevertheless, in order to ensure that the search area can provide correct solutions, the search area should not be selected too small.