GPS Attitude Determination Using a Genetic Algorithm

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***Abstract*-In this paper, a new technique that uses an especially tailored genetic algorithm is proposed for attitude determination via the GPS carrier phase observables. The technique overcomes restrictions due to computational overheads incurred by existing techniques such as the Ambiguity Function Method. We present experimental results which show that the algorithm is able to efficiently search the complex search space imposed by the problem in addition to being immune to cycle slips compared to other conventional methods.**

I. INTRODUCTION

Global Positioning System (GPS) is well-known for determination of a vehicle position and velocity with high accuracy. Less well-known is the use of GPS to provide the attitude of vehicle. Attitude determination using GPS receivers is increasingly becoming important in fields such as aircraft and ship navigation. There is a continuous demand for more information regarding the object in question, in addition to its position, in order to assess issues such as safety in fly-by-wire systems for example. In the past, attitude determination problem was solved using techniques based on inertial elements, sun sensors etc. Such techniques were associated with complex algorithms and control mechanisms. Recently, using GPS technology, it is possible to determine the attitude of a vehicle using a system based on one or more GPS receivers. Attitude determination using GPS receivers is characterized by being simple, more economic, more compact and less complex than other techniques. In addition, GPS based systems are not prone to accumulation errors as is the case with Inertial Navigation systems (INS).

The key to GPS attitude determination is to find the correct carrier phase integer ambiguity values [1]. Double difference observables between the satellites and receivers are used as the observation equations in the research in order to resolve the ambiguities. Recently, a number of techniques were developed for carrying out the search for integer ambiguity values. Examples are: Ambiguity Function Method (AFM) [2,14], which is a full search method and is not sensitive to cycle slips, but requires extensive computation time (1 to 2 minutes), even for a 1-metre search cube; Least Squares Search (LSS) [3]; Fast Ambiguity Search Filter (FASF) [4]; Modified Cholesky Search (CS) [5]; Fast Ambiguity Resolution Approach (FARA) [6]; and Lambda Decomposition [7]. From the techniques mentioned above, AFM is immune to cycle slips [8]. However, the computational burden of the AFM restricts its use since this makes it unsuitable for dynamic applications.

A new technique which uses an especially tailored genetic algorithm is presented in this paper in order to overcome the restrictions of the AFM. Genetic Algorithm based Ambiguity Function search (AFGA) is introduced, to resolve both GPS initial attitude determination and on-the-fly attitude determination problems using direct GPS carrier phase signals.

II. GPS CARRIER PHASE MODEL

The attitude parameters of a vehicle can be determined by more than two GPS antennas attached on the vehicle body [9, 10]. One antenna is assumed to be a reference. By finding the attitude of the baseline vectors defined between two antennas, the vehicle attitude can be resolved. Figure 1 shows an attitude determination problem using two GPS antennas A and B (including two GPS receivers). ***b*** is the baseline vector defined by A and B. λ is GPS carrier signal wavelength (where λ=0.19m for *L1 frequency*, 1575.42 MHz GPS carrier frequency. Commercial GPS navigation receivers can track only the *L1 frequency*). The signal wave front is planar on the scale of the baseline such that the direction of a satellite is the same as that viewed by both antennas. The carrier phase measurement equation [11] of the receiver antenna A from the j-th GPS satellite (S_j) is given by:

$$\Phi_A^j=\rho_A^j+C(dT^j-dT_A)+\lambda N_A^j-d_{ion}^j+d_{tro}^j+\varepsilon_A^j \qquad (1)$$

Where

Φ_A^j	is the carrier phase measurement (m);
ρ_A^j	is the true distance between the receiver A and the j-th satellite (m);
C	is the speed of light (m/s);
dT^j	is the satellite clock error (m);
dT_A	is the receiver clock error (m);
d_{ion}^j	is the ionospheric delay (m);
d_{tro}^j	is the troposheric delay (m);
N_A^j	is the integer cycle ambiguity (cycle);
λ	is the GPS carrier signal wavelength (m);

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ε^{j}_{A} is the unmodelled errors (m).

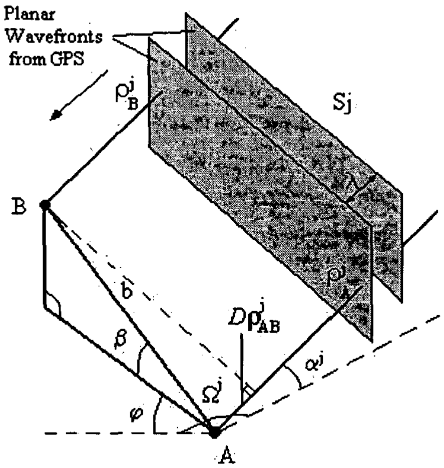

Figure 1 Carrier phase measurement between GPS antennas with a GPS satellite

The observation equation for the single difference GPS carrier phase between receivers A and B with respect to satellite S_j is given by:

$$D\Phi^{j}_{AB}=\Phi^{j}_{A}-\Phi^{j}_{B} \qquad (2)$$

Where *D* is the single difference operator. Equation (2) can be rewritten as:

$$D\Phi^{j}_{AB}=D\rho^{j}_{AB}+DdT_{AB}+D\,d^{j}_{ion}+D\,d^{j}_{tro}+\lambda DN^{j}_{AB}+D\varepsilon^{j}_{AB} \qquad (3)$$

As shown in equation (3), the satellite clock error is cancelled, but the receiver clock error still exists and is coupled with the ambiguity term, thus the single difference model is seldom adopted. The receiver clock error must be eliminated in the attitude applications because of having obvious difference between two receivers. We assume that the atmosphere (both ionosphere and troposphere) errors recorded by both receivers are no contribution to the equation as such a short baseline (Generally, the length of the baseline between A and B is less than 50 meters). Thus, the double difference observation equation between the antennas A and B with respect to satellites S_j and S_k can be described as:

$$\begin{aligned}DD\Phi^{jk}_{AB}&=D\Phi^{j}_{AB}-D\Phi^{k}_{AB}\\&=DD\rho^{jk}_{AB}+\lambda DDN^{jk}_{AB}+DD\varepsilon^{jk}_{AB}\end{aligned} \qquad (4)$$

Where *DD* is the double operator, and

$$DD\rho^{jk}_{AB}=D\rho^{j}_{AB}-D\rho^{k}_{AB}$$

$$=b[\sin\beta(\sin\alpha^{j}-\sin\alpha^{k})+\cos\beta(\cos\alpha^{j}\cos(\Omega^{j}-\varphi)-\cos\alpha^{k}\cos(\Omega^{k}-\varphi))]$$

$$=DD\Phi^{jk}_{AB}(\varphi,\beta,b) \qquad (5)$$

Where

α^{j}	is the elevation angle of the satellite S_j;
α^{k}	is the elevation angle of the satellite S_k;
β	is the elevation angle of the baseline ***b***;
φ	is the azimuth angle of the baseline ***b***;
Ω^{j}	is the azimuth angle of the satellite S_j;
Ω^{k}	is the azimuth angle of the satellite S_k;
b	is the length of the baseline ***b***;
$DD\Phi^{1j}_{AB}(\varphi,\beta,b)$	is the computed double difference value for the carrier phase (unknown).

III. AFGA SEARCH METHOD

A critical unit within the genetic algorithm is the fitness function which guides the search and contributes to its effectiveness. This is equivalent to the function guiding the search in traditional AFM. In this paper, we introduce a new ambiguity function for the GPS attitude determination. The function is defined in terms of baseline length and angles with both horizontal and vertical planes. According to equations (4) and (5), our new fitness function is defined as:

$$AFGA(\varphi,\beta,b)=\sum_{i=1}^{m}\sum_{j=2}^{n}\cos[2\pi(DDN^{1j}_{AB}+DD\varepsilon^{1j}_{AB}/\lambda)/(m(n-1))]$$

$$=\sum_{i=1}^{m}\sum_{j=2}^{n}\cos[2\pi(DD\Phi^{1j}_{AB}/\lambda-DD\Phi^{1j}_{AB}(\varphi,\beta,b)/\lambda)/(m(n-1))] \qquad (6)$$

Where

$DD\Phi^{1j}_{AB}/\lambda$	is the double difference value observed for the carrier phase (known);
m	is the number of epochs;
n	is the number of satellites.

The maximum value of the fitness function AFGA (φ,β,b) is very close to 1 but less than 1 because of the affect of the noise term $DD\varepsilon^{1j}_{AB}/\lambda$. The genetic algorithm performs a search for the values of φ, β and b which maximize the value of the AFGA(φ,β, b) function. This will in turn provide us with the correct body-fixed attitude angles (φ and β) and the baseline length b. Figure 2 shows the characteristic of the fitness function when a search range for φ varies from 85 degrees to 95 degrees, and that for β varies from -5 degrees to +5 degrees. b is a constant (equal to 16.27m here). As illustrated in the example using data from 6 satellites, the AFGA has a peak (point Pa) in the azimuth-elevation-angle space at the correct baseline azimuth and elevation angle (89.48 degrees and 2.14 degrees). It is obvious that AFGA is a multi-peaks function. Point Pb is a suspicious peak (the value of the fitness at this peak is close but not equal to the fitness at the true peak), which should be separated from the correct search result.

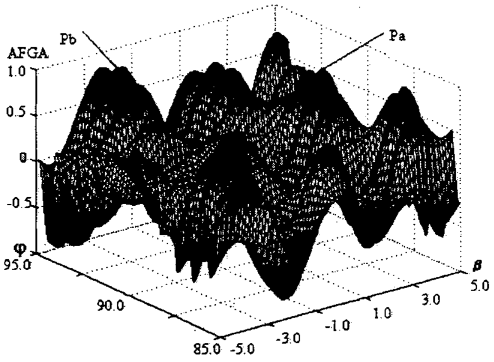

Figure 2 the characteristic of the fitness function

TABLE 1 THE DEFINITION OF CHROMOSOME

Parameters	φ	β	b
Bits	1 2 ... 14	15 16 ... 24	25 26 ... 32
Chromosome	1 1 ... 0	0 1 ... 0	0 0 ... 1

For reasons of compactness and speed, the AFGA is based upon populations of binary strings (chromosome) created by random generation of individual bits (genes). The search range for φ is a full 360 degrees, hence allowing for a search step of about 0.022 ($=360/2^{14}$) degrees. On the other hand, the search range for β is constrained to ±15 degrees, hence allowing for a search step of about 0.030 ($=30/2^{10}$) degrees. Furthermore, the search range for b is constrained to 16.27±0.10m, hence allowing for a search step of about 0.78 ($=20/2^{8}$) mm. In order to accommodate all of the above each chromosome requires 32 bits (As shown in Table 1).

To cope with the complex search space, which is characterized by multiple peaks, we developed a hierarchical genetic algorithm, which performs a two-stage search. The first a *Coarse* GA which targets searching the global surface, occupying the solution space, for regions of rich solutions (high fitness) and the second a *Fine* GA which searches local regions within the global search. Regions of rich individuals are identified by improvements in the average fitness value. For this our experimental results indicated a threshold value of 0.96 beyond which the *Fine* GA takes over. The overall flow of our algorithm is illustrated in Figure 3. For each GA elitism is employed together with a one-point crossover (as shown in Figure 4) for exchanging genetic material. Parents are selected using the Roulette Wheel method, with a probability of selection relating to their respective fitness values. Point mutation [12, 13] is used to inject genetic diversity into the population at various intervals.

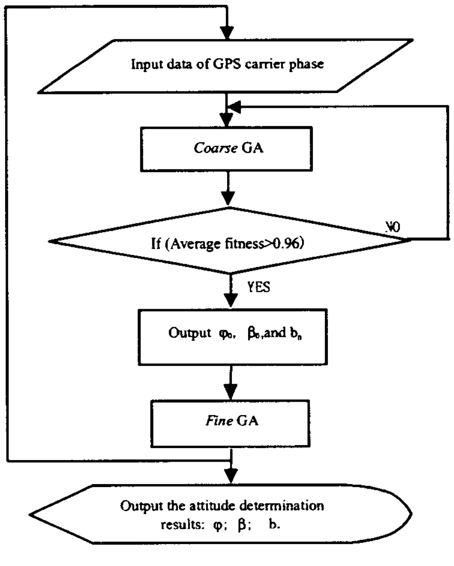

Figure 3 Basic AFGA flow

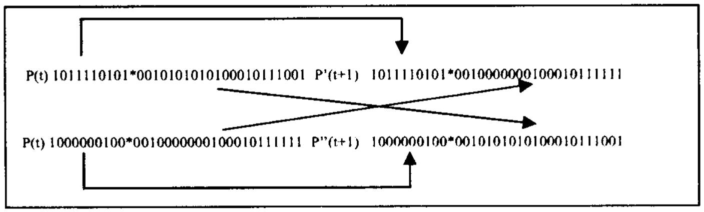

Figure 4 One-point crossover

IV. RESULTS AND DISCUSSION

In order to evaluate our technique we have used two Allstar-OEM GPS receivers and two antennae, which were fixed on special testing equipment (as shown in Figure 5). Carrier phase data, from the six satellites, is received by our GPS system at 0.1 second intervals, we term those *epochs*. This is then processed by AFGA. Our results are illustrated in Table 2 and Figure 6. Table 2 shows that there are no obvious differences between using one *epoch* to determine the attitude and using three *epochs*, and the accuracy of the azimuth angle is better than that of the elevation angle. The search time shown in Table 2 indicates that the AFGA search strategy is efficient and fast. Search time is basically less than 1.0 seconds in the initial attitude determination problem. If used for dynamic attitude determination, only Fine GA section is necessary, so the search time would be much shorter. On the other hand, if the technique is used in real-time attitude determination, with attitude output rate of up to 20 Hz, an ASIC solution will be needed.

Table 2 and Figure 6 shows one process of using one *epoch* data to resolve the attitude. The figure illustrates that *Coarse* GA is activated at 50 generation intervals in order to identify regions of 'rich' fitness individuals. Such a region is found after four *Coarse* GA search attempts, after which the *Fine* GA is able to identify an optimum solution. The process of *Fine* GA is a fixed (100) generation search strategy.

Figure 5 GPS attitude determination testing equipment

TABLE 2 ATTITUDE DETERMINATIONS EXPERIMENTAL RESULTS

Epochs	φ (degrees)		β (degrees)		Generations	Search times (sec)
	φ_{mean}	σ_φ	β_{mean}	σ_β		
1	89.487	.044	2.140	.140	391	0.39
3	89.485	.036	2.133	.094	430	0.43

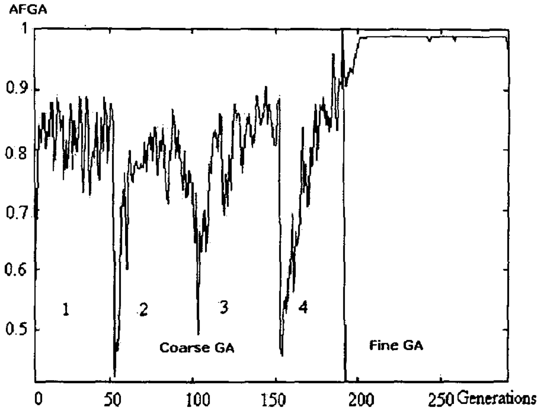

Figure 6 A search process using one epoch data

V. CONCLUSION

We have presented a novel approach based on using a genetic algorithm for determining the attitude of a GPS receiver system. We have shown that AFGA is very efficient in finding the correct attitude angles and the baseline in addition to being robust since it does not require 'good' initial conditions for resolving the initial attitude determination problem. For this reason it can be used for both initial attitude determination and on-the-fly attitude determination. Furthermore, AFGA can be used for dual frequency GPS receivers with slight modification of the fitness function.

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