

An EHW Architecture for Real-Time GPS Attitude Determination Based on Parallel Genetic Algorithm

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Abstract

The paper describes a parallel genetic algorithm for the VLSI implementation of real-time GPS attitude determination systems. The genetic algorithm is based on a fine-grained model and utilises AFM (Ambiguity Function Method) for GPS attitude determination. The paper describes various implementation choices with for the genetic algorithm in order to achieve both functionality and practical performance constraints such as speed, compactness and scalability. Simulation results using GPS carrier phase experimental data show that, in addition to low hardware complexity, our final genetic algorithm architecture achieves a linear speed-up with the number of processors utilised in the target VLSI chip.

1 Introduction

Attitude determination using Global Positioning Systems (GPS) is increasingly becoming important in fields such as the navigation system design of spacecrafts, aircrafts, ships and other vehicles. Increasingly there is a demand for such systems to be simple and economic [1].

GPS is well known for its use in the determination of vehicle position and velocity with high accuracy. Less well known is the use of GPS to provide the attitude of a vehicle. Using differential carrier phase measurements from three non-collinear GPS antennas, which are properly mounted

on a platform, the baseline vectors between the antennas can be precisely determined and thus the attitude parameters of the platform by the three corresponding antennas can be derived from these baseline vectors. The development of GPS multi-antenna systems, which integrate three or more GPS antennas into one system with a proper antenna configuration in a plane, in space or on ship, has resulted in another leap in GPS applications. In addition to providing position and velocity information, the multi-antenna GPS system can also determine the attitude parameters of the platform within an accuracy of several arc minutes [2-5]. This has the potential of replacing, to some extent, some sophisticated and expensive attitude sensors such as Inertial Navigation Systems (INS) for air and marine applications.

Recently, there have been a few GPS multi-antenna receivers commercially available, such as the Ashtech 3DF and ADU3 system (Magellan Corporation, USA), and the Trimble TANS VECTOR system (Trimble Navigation Limited, USA). These receivers integrate four antennas into one self-contained unit and operate all its tracking channels from a single receiver oscillator. Field tests have shown that the attitude accuracy of these receivers is at the level of 0.03 to 0.5 degrees per second depending on the antenna configuration, the separation between antennas as well as multipath influences on the measurements. However, the proliferation of these dedicated GPS multi-antenna receivers may be limited by their overall lack of flexibility and cost. Furthermore, in some receivers, residual receiver clock biases among the different antenna banks may exist, which limits the advantage of using a common oscillator to integrate all tracking channels. With the continuous advancement of GPS receivers and VLSI technology together with the emergence of new methods for attitude

determination in recent years, a wide range of high performance Original Equipment Manufacturer (OEM) GPS sensors are now available to users at a relatively low cost with high accuracy. Many researchers [6, 7] still pay more attention to study GPS attitude determination system using non-dedicated GPS receivers, which are characterized by being flexible and more compact, and new technique including software and hardware methods [8, 9].

In order to determine the attitude from GPS carrier phase measurements, the ambiguities should be resolved, in other words, the correct carrier phase integer ambiguity values should be found. This is the key to GPS attitude determination. Almost all researchers in this area have paid significant attention to this point. Recently, a number of methods to solve this problem have been proposed. An example is AFM [10, 27], 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. Other examples include: Least Squares Search (LSS) [11]; Fast Ambiguity Search Filter (FASF) [12]; Modified Cholesky Search (CS) [13]; Fast Ambiguity Resolution Approach (FARA) [14]; and Lambda Decomposition [15]. From the techniques mentioned above, AFM is immune to cycle slips [16]. However, the computational burden of the AFM restricts its use since this makes it unsuitable for dynamic applications.

In [26] the authors have developed a genetic algorithm for GPS attitude determination. The developed GA has superiority over the techniques above in identifying good quality solutions in a relatively faster time. However, the complexity of the GA makes it unsuitable for hardware implementation due to size, cost, and speed overheads.

Parallel GAs have frequently been cited as an important area of research as they provide a means of rapidly developing a solution to a wide range of problem [17,18]. In particular a parallel GA has the potential for solving problems far faster than a conventional GA. The parallel GA can be categorized into three types: global, coarse-grained and fine-grained. The parallelism in coarse-grained and fine-grained GAs lends itself to hardware implementation due to the inherent speed advantages. This parallelism is manifested by an architecture which consists of identical sub processors [19-21].

A parallel GA has the potential for solving problems far faster than a single GA provided its sub processors are specially tailored for a given application together with the utilization of an effective interconnection topology. However, the implementation of parallel genetic algorithms in the literature is mainly restricted to software [22]. The work proposed in this paper describes a parallel GA is

targeting custom hardware implementation, which reduces the execution time and increases the computational efficiency. A compact genetic algorithm realized using Verilog HDL and then fabricated in Silicon runs more than 1,000 times faster software executing on a workstation [23]. Thus, a hardware version of the parallel GA can cope with real-time GPS attitude determination problem much better. In this relative application area, only Hassan [16] introduced an evolutionary search algorithm to obtain the correct carrier phase integer ambiguity values for GPS positioning.

This paper describes a parallel genetic algorithm targeted for VLSI implementation of real-time GPS attitude determination systems. AFPGA (Ambiguity Function Parallel Genetic Algorithm) is based on a fine-grained model and utilises AFM, for GPS attitude determination. The paper describes various implementation approaches for the genetic algorithm in order to achieve both functionality and practical performance constraints such as speed, scalability, compactness. Simulation results using GPS carrier phase experimental data show that, in addition to low hardware complexity, our final AFPGA achieves a linear speed-up with the number of processors utilised in a VLSI chip.

2 GPS Carrier Phase Attitude Determination

The attitude parameters of a vehicle can be determined by more than two GPS antennas attached on the vehicle body [6,8]. 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

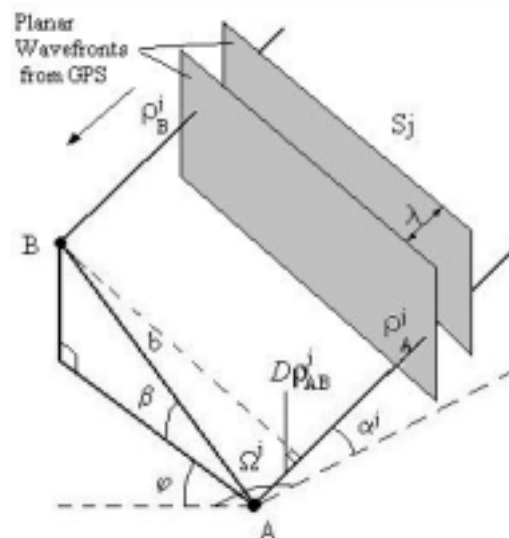


Figure 1: Carrier Phase Measurement Between GPS Antennas with a GPS Satellite

shows an attitude determination problem using two GPS antennas A and B (including two GPS receivers). \mathbf{b} is the baseline vector defined by A and B. λ is the GPS carrier signal wavelength (where $\lambda=0.19\text{m}$ 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 [26] of the receiver antenna A from the j -th GPS satellite (S_j) is given by:

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

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_A^j is the satellite clock error (m);
- dT_{AB}^j is the receiver clock error (m);
- d_{ion}^j is the ionospheric delay (m);
- d_{tro}^j is the tropospheric delay (m);
- N_A^j is the integer cycle ambiguity (cycle);
- λ is the GPS carrier signal wavelength (m);
- ε_A^j is the unmodelled errors (m).

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

$$D\Phi_{AB}^j = \Phi_B^j - \Phi_A^j \quad (2)$$

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

$$D\Phi_{AB}^j = D\rho_{AB}^j + DdT_{AB}^j + Dd_{ion}^j + Dd_{tro}^j + \lambda DN_{AB}^j + D\varepsilon_{AB}^j \quad (3)$$

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:

$$DD\Phi_{AB}^{jk} = D\Phi_{AB}^j - D\Phi_{AB}^k \\ = DD\rho_{AB}^{jk} + \lambda DDN_{AB}^{jk} + DD\varepsilon_{AB}^{jk} \quad (4)$$

Where DD is the double operator, and

$$DD\rho_{AB}^{jk} = D\rho_{AB}^j - D\rho_{AB}^k \\ = b[\sin\beta(\sin\alpha^j - \sin\alpha^k) + \cos\beta(\cos\alpha^j\cos(\Omega^j - \varphi) \\ - \cos\alpha^k\cos(\Omega^k - \varphi))] \\ = DD\Phi_{AB}^{jk}(\varphi, \beta, b) \quad (5)$$

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 \mathbf{b} ;
- φ is the azimuth angle of the baseline \mathbf{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 \mathbf{b} ;

$DD\Phi_{AB}^{lj}(\varphi, \beta, b)$ is the computed double difference value for the carrier phase (unknown).

3 AFPGA Search Algorithm

3.1 Fitness Function

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 use the fitness function introduced in [26] 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), the fitness function is:

$$AFGA(\varphi, \beta, b) = \sum_{i=1}^m \sum_{j=2}^n \cos[2\pi(DDN_{AB}^{ij} + DDE_{AB}^{ij}/\lambda)/(m(n-1))] \\ = \sum_{i=1}^m \sum_{j=2}^n \cos[2\pi(DD\Phi_{AB}^{ij}/\lambda - DD\Phi_{AB}^{ij}(\varphi, \beta, b)/\lambda)/(m(n-1))] \quad (6)$$

Where

$DD\Phi_{AB}^{ij}/\lambda$ is the double difference value observed for the carrier phase (known);

- m is the number of epochs (in real-time application, m=1);
- n is the number of satellites (generally, n=4 to 6 according to the number of observed satellites).

The maximum value of the fitness function AFGA (φ, β, b) is very close to 1 but less than 1 because of the effect of the noise term $DD\varepsilon_{AB}^{ij}/\lambda$. 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 .

The fitness function is combined by multi-value functions such as sine and cosec. There is also noise within the GPS carrier phase data. Therefore, the fitness function is a very complex multi-peak function when the search range of φ, β only varies 10 degrees (when b is a constant). If the initial azimuth and elevation angles are not known in advance, several suspicious peaks (the value of the fitness at those peaks are close but not equal to the fitness at the true peak during the whole testing process), which should be separated from the correct search result.

3.2 Fine-grained Architecture

Fine-grained parallel genetic algorithms act on each member of the population in parallel. Consequently each member of the population performs crossover with its immediate neighbors, where the neighborhood is defined by the topology and some distance parameter (Figure 2).

Coarse-grained genetic algorithms are more complex than fine-grained genetic algorithms because each processor must control a complete population, whereas for the fine-grained case only one chromosome is processed. Consequently for a single chip VLSI implementation, a large number of simple processors is far more attractive than a few complex processors.

In this paper, AFPGA is therefore based on a fine-grained parallel genetic algorithm for the implement of the GPS attitude determination system because it is easy to be realized by hardware on single chip.

The fitness function of AFPGA is defined by equation (6). The definition of distance parameter (D) is follows: If each number of the population just performs crossover with its neighbors (north, east, south and west of the population), we say the distance is 0 (D=0). If each number of the population

performs crossover with the next population's (next processor's) neighbors, we say the distance is 1. For example (as shown in Figure 2): when the population in processor No.22 performs crossover with the neighbors of the population in No. 23 processor, the distance is 1; when the population in processor No.22 performs crossover with the neighbors of the population in No. 34 processor, the distance is 7. The maximum distance (D=Max) in Figure 2 is 12.

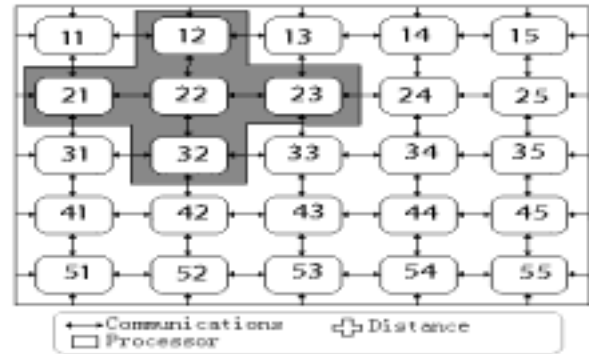


Figure 2: The Distance Definition of AFPGA

The basic algorithm functionality in each unit of AFPGA is given below [24,25]:

Begin

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t ← 0;
read GPS carrier phase data;
initialize population (Xi);
evaluate f(Xi);
While (not termination condition) do
  get XN, XE, XS, XW;
  get fN, fE, fS, fW;
  fm = max { fN, fE, fS, fW } ;
  (X', X'') = Xi ∞ Xm; (Xm ← fm)
  evaluate f(X'), f(X'');
  fm}' = max { f(Xi), f(X'), f(X'') } ;
  Xi = Xm}' ; (Xm}' ← fm}' )
  mutate Xi with probability pm;

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End;

End;

∞: crossover with probability p_c;
f_m: fitness of the maximum valued string;
X_i: chromosome in processor i;
f(): fitness;
X', X'': two children of chromosome X_i;
X^N, X^E, X^S, X^W: the four chromosomes adjacent to chromosome X_i assuming a grid topology;
f^N, f^E, f^S, f^W: the fitness of the four adjacent chromosomes.

4 Experiment Results and Compare Analysis

We have evaluated AFPGA through comparison using different evolution strategies. We have considered the performance of three algorithms and three versions of AFPGA. The efficiency and efficacy of these algorithms in solving the GPS attitude determination problem is compared using the same experimental data. The above algorithms versions are labeled as Table 1 and Table 2.

Table 1: Three Algorithms

Algorithms	Description
AFPGA	Probability (D=0) =1.0; Coarse and Fine searches
SGA	a standard GA
AFGA	SGA with Coarse and Fine searches; elitism

Table 2: Three Versions of AFPGA

Versions	Description
AFPGA1	Probability(D=0)=0.8; Probability (D=Max)=0.2
AFPGA2	Probability (D=0)=0.8; Probability(D=random)=0.2
AFPGA3	Probability(D=0)=0.6; Probability(D=random)=0.4

The efficiency of an algorithm can be measured as the number of generations required to find an optimal solution according to the termination condition. The efficacy of an algorithm can be measured as the success rate to obtain a correct result together with the accuracy of the result.

The same GPS carrier phase data as in [26] is used in this paper in order to compare the different algorithms and versions.

Figure 3-5 illustrate the elevation angle and azimuth angle search results with a population of 25 individuals after searching 100 times repeatedly by each algorithm. Figure 3 shows that the AFPGA can coverage to the correct result each time but there is a larger deviation, SGA and AFGA (as shown in Figures 4 and 5) show that they can obtain more accurate results at the expense of extended search duration. Figure 4 shows that SGA search strategy only provides 69% search success rate (in all algorithms of this paper, a search process is defined as a unsuccessful search when the algorithms have restarted 20 times and the coarse search termination condition could not be satisfied).

Next, we run SGA, AFGA and AFPGA with different population size, 9, 16, 25, 36 and 49. The results shown in Figure 4(a) indicate that the mean of average fitness is decline with the increase of the population size. The means of average elevation and azimuth angles are not different when the population size is 9 and 16. More interesting

results are shown in Figure 4(d) and Figure 4(e). With the increase of the population size, the number of generations required to find an optimal solution in AFPGA is decreased, but in SGA and AFGA are increased. Hence, the more processors to be used in AFPGA, the faster the solution should be given. Figure 4(d) shows that the AFPGA has the highest average success rate, and SGA is the lowest one. Thus, the AFPGA can solve the attitude determination problem faster and more effective compared with SGA and AFGA.

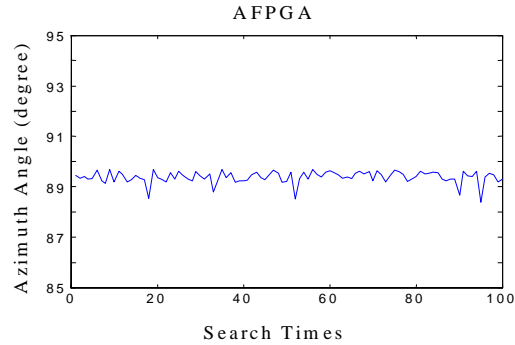


Figure 3(a): Azimuth Angle Search Results by AFPGA

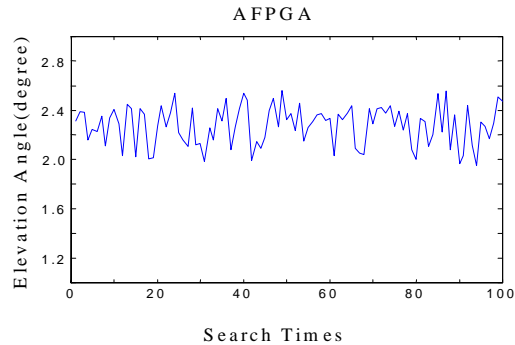


Figure 3(b): Elevation Angle Search Results by AFPGA

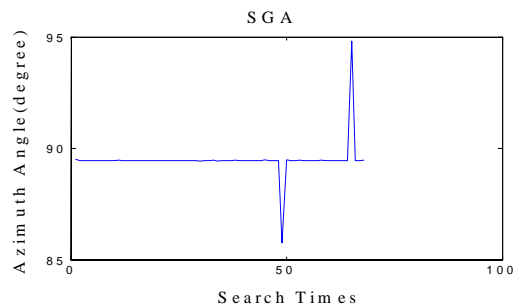


Figure 4(a): Azimuth Angle Search Results by SGA

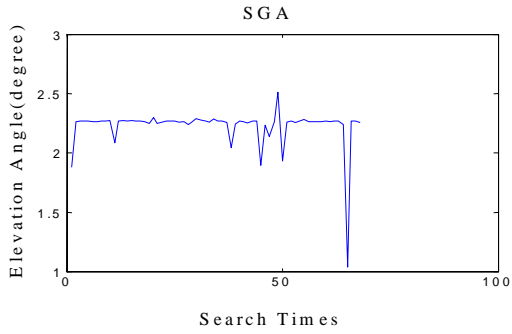


Figure 4(b): Elevation Angle Search Results by SGA

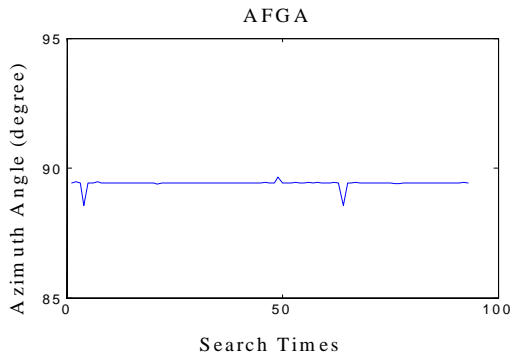


Figure 5(a): Azimuth Angle Search Results by AFGA

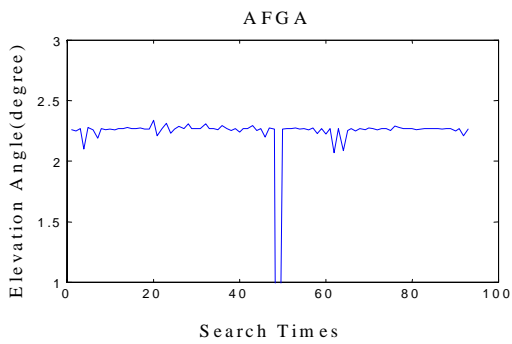


Figure 5(b): Elevation Angle Search Results by AFGA

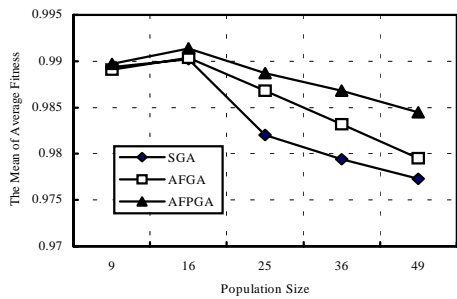


Figure 6(a): Fitness Function Value

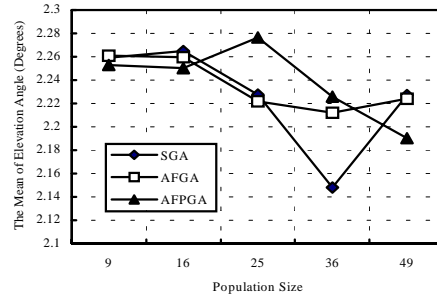


Figure 6(b): The Mean of Elevation Angle Output

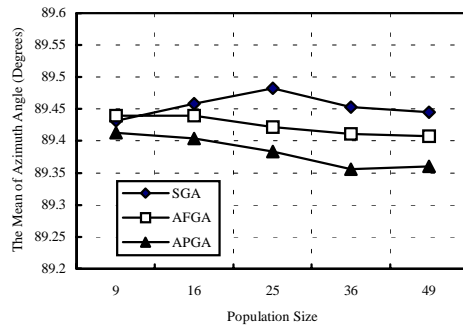


Figure 6(c): The Mean of Azimuth Angle Output

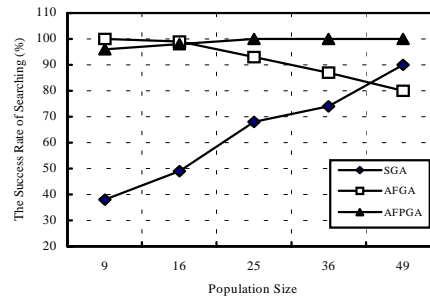


Figure 6(d): The Search Success Rate

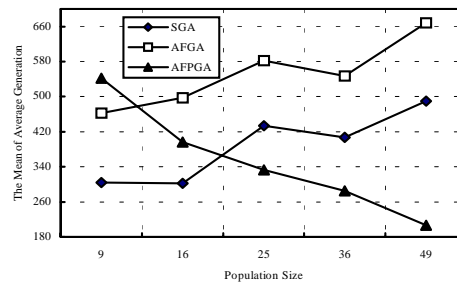


Figure 6(e): The Search Generations

Figure 7 illustrates the results using the different versions of AFPGA. There is no obvious difference between the versions, particularly when the population size is 9, 16 and 25. With the increase of the population size and the different migration policy in AFPGA, AFPGA1, AFPGA2 and AFPGA3, there is little variance in the results (Figure 7(b-d)). Figure 7(f) and 7(g) shows clearly that all the versions of the algorithm AFPGA can solve the problem more effective and faster with the increase of the population size.

Therefore, these results indicate that the AFPGA is a practical algorithm, which is easy to implement by hardware, and the reasonable population size for AFPGA is about 25.

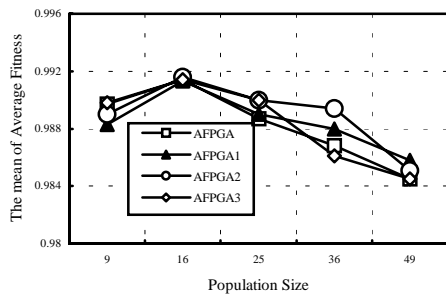


Figure 7(a): The Mean of Average Fitness

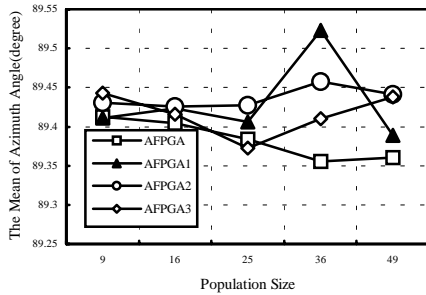


Figure 7(b): The Mean of Azimuth Angle

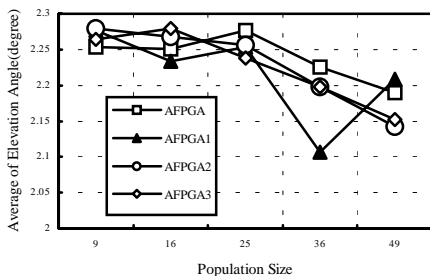


Figure 7(c): The Mean of Elevation Angle

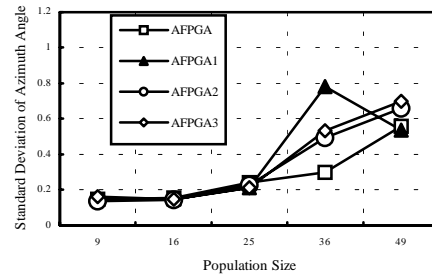


Figure 7(d): The Standard Deviation of Azimuth Angle

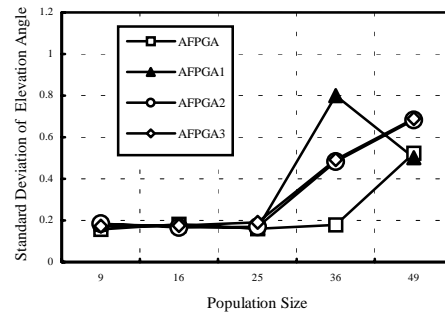


Figure 7(e): The Standard Deviation of Elevation Angle

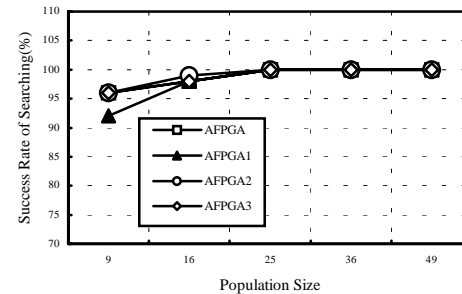


Figure 7(f): The Search Success Rate

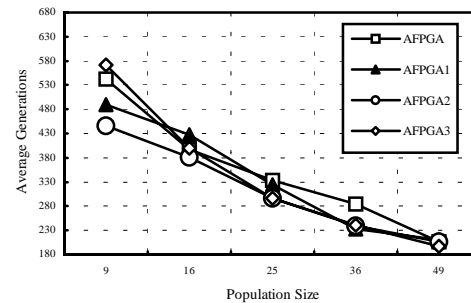


Figure 7(g): The Average Search Generations

5 Conclusions

In this paper, we have presented AFPGA, an architecture combining parallel genetic algorithms with the AFM method for the implementation of a EHW system for real-time GPS attitude determination. Simulation comparisons with the GPS experimental data shows that the system is capable of solving the attitude determination problem, faster than SGA and AFGA when the population size is larger than 25. Similar results are obtained with architectural variations AFPGA1, AFPGA2 and AFPGA3.

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