Increasing DGPS Navigation Accuracy using Kalman Filter Tuned by Genetic Algorithm

M. R. Mosavi[1], M. Sadeghian[2] and S. Saeidi[3]

[1] **Department of Electrical Engineering, Iran University of Science and Technology**
Tehran, 16846-13114, Iran

[2] **Electronic Education Center, Iran University of Science and Technology**
Tehran, 16846-13114, Iran

[3] **Department of Electrical Engineering, Iran University of Science and Technology**
Tehran, 16846-13114, Iran

Abstract

Global Positioning System (GPS) is being used in aviation, nautical navigation and the orientation ashore. Further, it is used in land surveying and other applications where the determination of the exact position is required. Although GPS is known as a precise positioning system, there are several error sources which are categorized into three main groups including errors related to satellites, propagation and GPS receivers. Regarding wide applications of GPS systems and the importance of its accuracy, these exiting errors could be averted by Differential GPS (DGPS) method. In this paper, a Kalman Filter (KF)-based algorithm which is adapted with Genetic Algorithm (GA) is proposed to reduce errors in GPS receivers. The model's validity is verified by experimental data from an actual data collection. Using the practical implementations the experimental results are provided to illustrate the effectiveness of the model. The experimental results suggest that it is possible to reduce position RMS errors in single-frequency GPS receivers to less than 1 meter. Accordingly, effective error value improves to 0.4873 meter utilizing KF adapted with GA as compared to traditional KF.

Keywords: *Improvement in Accuracy, Differential GPS, Kalman Filter, Genetic Algorithm*

1. Introduction

GPS (Global Positioning System) is a satellite-based positioning and navigating system which is able to determine the instant position, velocity and the time of user on the earth anytime and anywhere. A constellation of at least 24 well-spaced satellites that orbit the Earth makes it possible for people with ground receivers to pinpoint their geographic location. GPS was funded by and controlled by the U. S. Department of Defense (DOD). While there are many thousands of civil users of GPS world-wide, the system was designed and was operated by the U. S. military. Consumer receivers are the approximate size of a hand-held calculator, cost a few hundred dollars, and provide a position accurate to 25 [m] or so. Military versions decode the signal to provide position readings that are more accurate. The exact accuracy is obtained by the military which can be considered as a military secret. GPS satellites are gradually revolutionizing driving, flying, hiking, exploring, rescuing and map making [1].

GPS provides coded satellite signals that can be processed in a GPS receiver, enabling the receiver to compute position (longitude, latitude and altitude), velocity and time. Four GPS satellite signals are used to compute positions in three dimensions and the time offset in the receiver clock. However, GPS receiver as any measurement tool is affected by different kinds of error sources including hardware, environment or atmosphere which can reduce its measurement accuracy [2].

In order to remove positioning errors and achieve more accuracy, DGPS method can be functional. The underlying premise of Differential GPS (DGPS) is that any two receivers that are relatively close to each other will experience similar atmospheric errors. DGPS requires that a GPS receiver be set up on a precisely known location. This GPS receiver is the base or reference station. The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is applied to the GPS data recorded by the second GPS receiver, which is known as the roving receiver. The corrected information can be applied to data from the roving receiver in real time in the field using radio signals or through post processing after data capture by special processing software [3]. The problem with this method is slow updating process of differential corrections [4,5].

The purpose of this paper is to represent an algorithm based on Kalman Filter (KF) which is adapted with Genetic Algorithm (GA) in order to reduce errors in GPS receivers. The advantage of the proposed method to traditional KF is its high accuracy. This paper is organized as follows; the sources of errors in GPS systems, DGPS method, and the process of design and implementation of KF-based estimator are first explained. Then, the optimization method which is used to optimize the KF parameters based on GA is discussed. Next, adopted data collection method and experimental test results, carried out on collected actual data, are reported. Finally, the conclusion is given in the last section.

2. Sources of Errors in GPS

Generally, there can be various factors that affect the quality of the GPS signal and cause calculation errors. These are [6]:

2.1 Errors related to satellites

There are still some errors related to satellites including errors in satellite clock, satellite geometry and also satellite orbits.

Satellite clock: There are two rubidium and two cesium clocks in each satellite responsible for generating GPS satellite signals. These clocks are corrected and adjusted every day by GPS control segment. It should be mentioned that the errors caused by these clocks, working for 24 hours, is equal to 17 [nsec] or 5 [m] in length.

Satellite geometry: In fact, satellite geometry describes the position of the satellites to each other from the view of the ground receiver. For the signals to work properly the satellites have to be placed at wide angles from each other. Poor geometry resulting from tight grouping can result in signal interference [7].

Satellite orbits: Although the satellites are positioned in predetermined orbits precisely, there could be slight changes in their exact positions due to natural phenomena happening in the space. Information about satellites including the orbit data are controlled and updated regularly and are sent to the receivers along with the satellite signals in the package of ephemeris data. Therefore, there can be some differences between the actual position of the satellites and the predicted position.

2.2 Propagation errors

Satellite signals propagate through atmospheric layers during their travel between satellite and GPS receiver. Two significant layers including ionosphere and troposphere cause the satellite signals to slow down as they passes through the atmosphere. However, the GPS system has a built-in model that accounts for an average amount of these disturbances.

Ionosphere layer errors: In the ionosphere developing at a height of 50 to 1000 [km] above the earth, a large number of electrons and positive charged ions are formed by the ionizing force of the sun. There are four conductive layers in the ionosphere which refract the electromagnetic waves from the satellites, resulting in an elongated runtime of the signals. In other words, the delayed coded information of GPS causes pseudo-ranges to appear longer than the real distance from satellite. Ionosphere delays are in connection to frequency and they are mostly corrected by the receiver by calculations. Delays may vary from 5 [m] (at night) to 30 [m] (in day) for low-height satellites and 3-5 [m] for high-height satellites [8].

Troposphere layer errors: The troposphere is the lower part of the earth's atmosphere that encompasses our weather. Tropospheric effect is a further factor elongating the runtime of electromagnetic waves by refraction. The reasons for the refraction are different concentrations of water vapor in the troposphere, caused by different weather conditions. The error caused in this way is smaller than the ionospheric error, but can not be eliminated by calculation. It can only be approximated by a general calculation model.

Multi-path effect: Multi-path is a phenomenon in which a signal of a GPS hits and is reflected off by the surrounding objects like tall buildings, rocks, etc. before being detected by antennas. This causes the signal to be delayed before it reaches the receiver [9].

2.3 GPS receiver errors

There are some errors that originate from measurement processes used in GPS receivers. These errors are referred to as GPS receiver errors. They are mainly connected to the design of antenna, the method of changing analog to digital, band width and calculation algorithms.
Selective Availability (SA) is the intentional degradation of the SPS signals by a time varying bias. SA is controlled by the DOD to limit accuracy for non-U.S military and government users. The potential accuracy of the C/A code of around 30 [m] is reduced to 100 [m] (two standard deviations). For civil GPS receivers, the position determination is less accurate (fluctuation of about 50 [m] during a few minutes). Meanwhile, SA has been permanently deactivated since May 2000 due to the broad distribution and worldwide use of the GPS system [10].

3. Kalman Filter

KF is an optimal estimator which can result in an optimum estimation of a system state using state space principle and system error modeling. KF is a linear, unbiased and

recursive algorithm that optimally estimates the unknown state of a dynamic system from noisy data taken at discrete real time intervals by minimizing the mean-squared error. The most important feature of KF is that it is recursive, hence it does not require storage of all past observations; the KF algorithm is ideally suited to dealing with complex estimation problem [11].
To achieve recursive equations of KF, we start with state and measurement equations [12]:

$$X_{k+1} = \phi_k X_k + W_k \tag{1}$$

$$Z_k = H_k X_k + V_k \tag{2}$$

where X_k is the $n \times 1$ state vector at time t_k, ϕ_k is the $n \times n$ state transition matrix from X_k to X_{k+1}, $W_k \sim N(0, Q_k)$ is the $n \times 1$ process error vector (a white sequence with a specific covariance-based function is assumed), Z_k is the $m \times 1$ measurement vector at time t_k, H_k is the $m \times n$ matrix which creates an ideal relation (without any noises) between measurement and state vectors at time t_k and $V_k \sim N(0, R_k)$ is the $m \times 1$ error vector (a white sequence is recognized with covariance structure and is supposed as W_k with cross correction equal to zero). The KF recursive equations are:

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1} \tag{3}$$

where K_k is called Kalman gain. The estimation process is updated as:

$$\hat{X}_k = \hat{X}_k^- + K_k (Z_k - H\hat{X}_k^-) \tag{4}$$

where "^" and "-" denote estimated state and prior to measurement incorporation, respectively. By calculating the corresponding covariance matrix using optimum estimation, we will have:

$$P_k = (I - K_k H_k) P_k^- \tag{5}$$

Consequently, optimum state estimation and covariance matrix are resulted for the next time step.

$$X_{k+1}^- = \phi_k \hat{X}_k \tag{6}$$

$$P_{k+1}^- = \phi_k P_k \phi_k^T + Q_k \tag{7}$$

4. Genetic Algorithm

GA is an effective searching method in a very wide and huge space. It affects getting an optimum result that it is probably not possible to achieve in a person's life. GAs are far more different from primitive optimization methods. In these algorithms, the design space must be changed into the genetic representation. Therefore, GAs deal with a series of encoded variables. The advantage of using encoded variables is that it can be possible to encode continuous functions like discrete functions. GA is based on random processing or more specifically it is based on guided random process. Therefore, random operators of searching space are examined in a comparative way. Basically, in order to use GA these three important concepts must be defined. If these three sections are defined correctly, GA will certainly function properly and it is finally possible to improve the performance of the system by applying some changes.

Objective function: In each problem, the purpose is to maximize or minimize a parameter or parameters. Therefore the objective function is determined using mathematical relations and proper weighing to solve the problem.

Searching space: The purpose of problem solving is to find the best result among different results. The space of all probable states is called searching space. Each result could be represented by a value which determines its propriety. Searching for a result means finding an extremum result within the searching space.

Operators of GA: After achieving the objective function and encoding the population, it is the time for operators of GA to start functioning. In a simple GA, the following three main operators including reproduction, merging and mutation operators are usually used.

Reproduction is usually the first step which is applied to the population. In this method, a series of genes are selected as a parent in the population which will result in generating children by merging. Based on the theory of the fittest, the best individuals should be selected in order to generate the best next generation. Correspondingly, the reproduction operator is sometimes called selecting operator. There are different selection methods in GA to select genes, but the purpose for all of them is to select strings with high average between current population and producing multiple copies of them and putting them in a place, which is called reproduction pool based on a probable form.
After the reproduction stage is complete, a population of the fittests is generated. In fact reproduction function has selected a set of the best strings (colony), but it has not generated new strings. For this reason, merging function is applied to reproduction pool in order to produce new better strings. The purpose of merging is to search the parameter space and to preserve hidden information in strings as much as possible.

Mutation of a bit is to change between 0 and 1 and vice versa bit by bit which is done based on a small probability like P_m. In mutation stage a random number between 0 and 1 is produced. If the produced number is less than P_m then the output is considered as true and otherwise it is considered as false. If the output is true for each bit, the bit will change, otherwise it will remain unchanged.
Bits of a string are mutated independently; it means that mutation of a certain bit does not affect the probability of other bits. In a simple GA, this function is considered as a secondary operator to preserve the information which might be missing. For example, consider that all bits of strings in a population in a certain range are zero and optimum solving method needs one 1 in that point, while merging operator can not generate 1 in that situation. Therefore, in order to generate 1, mutation function is used. In the following sections objective function and the operators which are used in this paper are explained.

5. KF Parameters Tuned using GA

In order to utilize KF, it is necessary to know the accurate mathematical model. However, it is impossible to achieve an accurate model due to lots of uncertainties existing in GPS including errors of the time-variant disturbance, parameter perturbation in mathematical model and unknown statistical properties of noise existing in the system. These factors will result in estimate error in KF, even they make it unstable.
In order to achieve the best filtering performance, the two parameters, that is, system model parameter error variance matrix Q_k and measurement noise sequence variance matrix R_k must be optimized by GA [13]. The objective function J will reach the minimum value by using the combination of best filtering effect. The objective function J is described as follow:

$$J = \sqrt{RMS_x^2 + RMS_y^2 + RMS_z^2} \tag{8}$$

in which RMS_x, RMS_y and RMS_z are effective errors of x, y and z, respectively. The traditional parameter optimization method based on calculations is derived from the assumption that the resolving function is continuous and differentiable, but in practice the continuous and differentiable condition of the function is not fulfilled and results in several solutions and heavy noise.
Compared to traditional methods, GA is not influenced by continuous and differentiable condition, and it can solve many complex problems, which can not be done using traditional methods. It possesses extensive adaptability and good robust performance, and it is easily applicable in parallel tasks. The operators which are used in the implemented GA in this paper are mentioned in the following section:

Step 1: Population: The algorithm starts at the first place with a set of random results, which is called population. These results are used to generate next new population anticipating a better population than the previous ones, because the methods are used for selecting new populations with respect to their propriety. Therefore, the best ones have more chances to reproduce. This process repeats until final conditions are met (to achieve the best results). After doing different experiments, the size of population was decided to contain 165 subjects in this paper.

Step 2: Reproduction: Between available methods to select genes and to merge them the tournament method has been selected. This method is similar to a tournament in the nature, in which a small subset of genes is selected randomly and competes with others. Finally, one of them wins with respect to its propriety in this tournament and then it is copied in the mating pool as a new parent and this process repeats until all parents will be generated in the new population.

Step 3: Crossover: Crossover options specify how the GA combines two individuals, or parents, to form a crossover child for the next generation. In this paper, the heuristic method has been selected after considering different merging methods.

Step 4: Mutation: After merging strings, it is the time to mutate. Mutation is useful for preventing quick convergence and helping the search algorithm to escape from being trapped in positional minimums. On the other hand, this function is used to preserve different states of genes and to be distinct in a population. The mutation which is used in this paper is mutation adapt feasible. The feasible region is bounded by the constraints and inequality constraints. A step length is chosen along each direction so that linear constraints and bounds are satisfied.

Step 5: Migration: Migration options specify how individuals move between subpopulations. Migration occurs if we set population size to be a vector of length greater than 1. When migration occurs, the best individuals from one subpopulation replace the worst individuals in another subpopulation. Individuals that migrate from one subpopulation to another are copied. They are not removed from the source subpopulation. Migration wraps at the ends of the subpopulations. That is, the last subpopulation migrates into the first, and the first may migrate into the last.

Step 6: Stopping criteria: Stopping criteria determine what causes the algorithm to terminate. We can specify the following options:

- **Function generations:** Specifies the maximum number of iterations for the GA to perform. The adjusted value in this paper is 80.
- **Function stall generations:** The algorithm stops if the weighted average change in the fitness function value over stall generations is less than the function tolerance. The adjusted value in this paper is 70.
- **Function stall time limit:** The algorithm stops if there is no improvement in the best fitness value for an interval of time in seconds specified by stall time. The adjusted value in this paper is 2000 seconds.

6. Experimental Results

Data collection is highly important in assessing the utmost performance and efficiency of the method suggested in this paper. Such a process was carried out in the center for Computer Control and Fuzzy Logic Research Lab in Iran University of Science and Technology. Fig. 1 depicts the hardware used in data collection process.
According to the hardware shown in Fig. 1, the serial GPS receiver data are passed through TTL-RS232 converter to change their levels from TTL to RS232 standard and make it ready to be connected to the computer. It should be noted that the keyboard on this hardware board is used for the purpose of setting GPS receiver's programmable parameters such as, the output protocol of receiver's serial ports (NMEA or Binary) and data transmission rate (4600 or 9600 bit/s) [14].

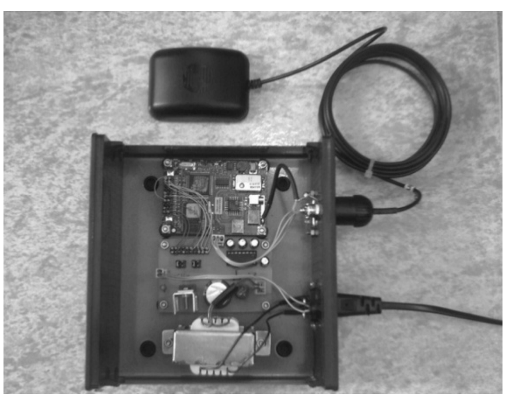

Fig. 1: GPS receiver board

The technically significant features of the GPS receiver used in data collection process include 5-channel GPS receiver, capable of keeping track of up to 9 satellites, capable of reducing SA effect in static mode, functioning with both active and inactive antennas, capable of position measuring with maximum accuracy in SPS mode, capable of selecting satellites and making satellite's view angle narrow and capable of updating information in each second.
Considering the precision and the convergence rate, filtering result J is adopted as an objective function. Two parameter matrixes, system model parameter error variance matrix Q_k, and measurement noise sequence variance matrix R_k are regarded as the optimal parameters for KF which make J reach the minimum value. Table 1 reveals the features of the GA which is utilized in this paper.

Table 1: Features of the GA utilized in this paper

Parameter	Features
Population size	165
Generations	80
Stall gen limit	70
Stall time limit	2000
Initial population	R1,R2,R3
Mutation function	Adapt feasible
Selection function	Tournament
Crossover function	Heuristic

The optimal values of Q_k and R_k were put in KF relation and the filtering experiment was carried out on 1000 data which were obtained from the aforementioned GPS. Figures 2 to 5 represent the real, predicted and prediction error values of the component position errors for 1000 experimental data sets using KF tuned by GA in SA error turned on and turned off states.

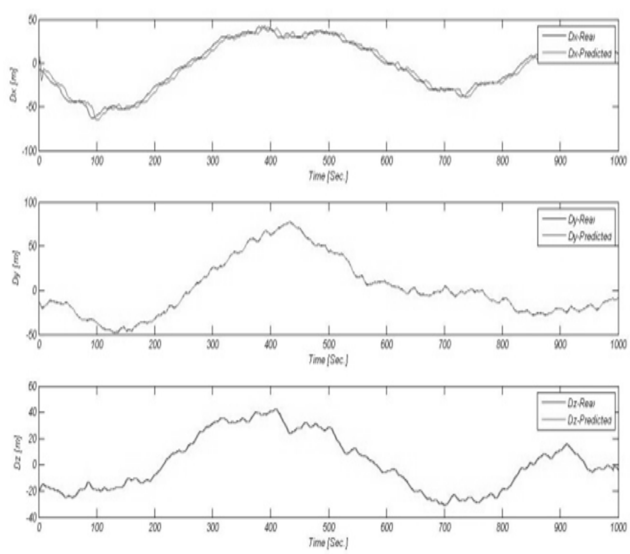

Fig. 2: The results of 1000 prediction for component positions using KF tuned by GA (SA on)

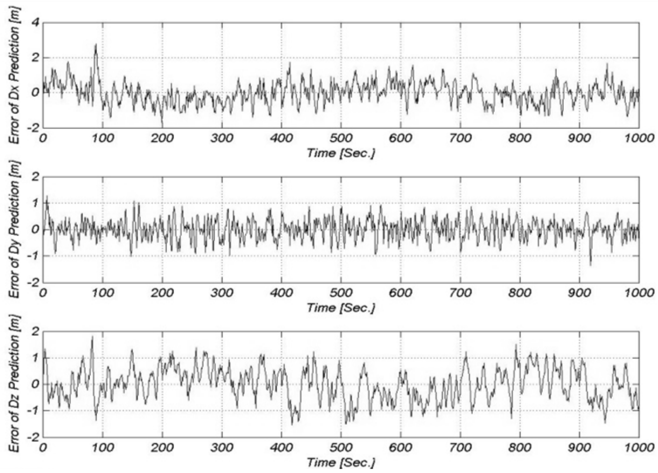

Fig. 3: The results of 1000 prediction error for component positions using KF tuned by GA (SA on)

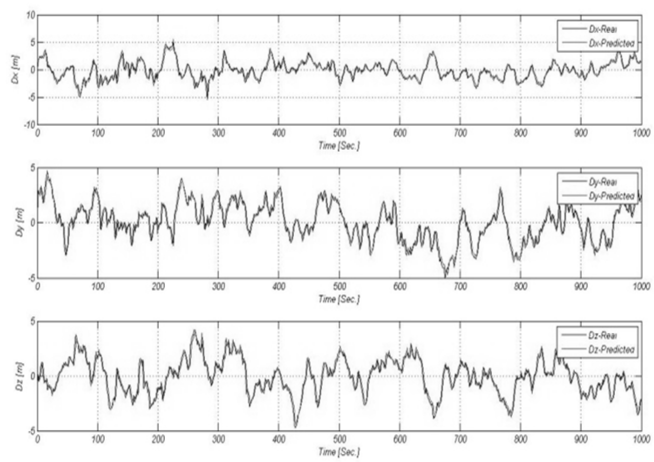

Fig. 4: The results of 1000 prediction error for component positions using KF tuned by GA (SA off)

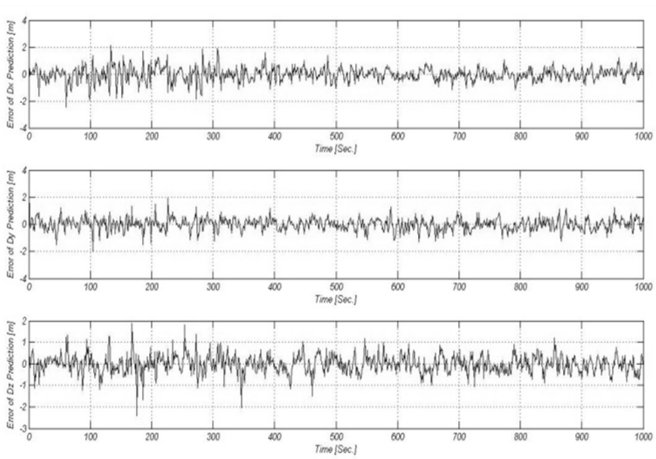

Fig. 5: The results of 1000 prediction error for component positions using KF tuned by GA (SA off)

Tables 2 and 3 depict the statistical features of estimation errors for 1000 tests which were performed on experimental data. According to the results illustrated in Tables 2 and 3, it is noticeable that the RMS errors in estimation error in component positions using KF tuned by GA in SA on and off modes reduced to less than 1 and 0.9 meters, respectively. The results from tests carried out on real data show that the functionality of KF tuned by GA in estimating components of position errors is independent of the effect of SA errors which is one of the advantages of KF tuned by GA.

References [15,16] predict DGPS corrections using traditional KF. As shown in Table 4, the KF tuned by GA has better accuracy than traditional KF for DGPS corrections prediction. There are few papers that predict the DGPS corrections using KF. The proposed KFs in this paper have more accuracy than them.

Table 2: The maximum, minimum, average and RMS error values for 1000 estimation using KF adapted with GA (SA off)

Parameters	X	Y	Z
Maximum	2.1349	3.0893	1.8759
Minimum	-2.4570	-2.0089	-2.4190
Average	0.0145	-0.0091	0.0045
RMS	0.5170	0.4546	0.4256
Total RMS	**0.8093**		

Table 3: The maximum, minimum, average and RMS error values for 1000 estimation using KF adapted with GA (SA on)

Parameters	X	Y	Z
Maximum	2.7732	1.2690	1.8113
Minimum	-1.7061	-2.4190	-1.5343
Average	0.0188	-0.0048	-0.0221
RMS	0.6268	0.3815	0.6044
Total RMS	**0.9507**		

Table 4: Comparing DGPS corrections prediction accuracy using proposed method and traditional KF

Prediction Method	Accuracy (SA on)	Accuracy (SA off)
Traditional KF [15,16]	1.4380	0.8108
KF tuned by GA	0.9507	0.8093

7. Conclusions

Regarding the increasing development in using GPS and their pivotal roles in various fields including business and the military, improvement in their measurement accuracy and data security in these systems are considered not only as theoretical issues, but also as vital necessities in these systems. In this paper, the way of utilizing a low cost GPS receiver as an accurate positioning device was discussed.

Moreover, a KF-based GA was proposed. The experimental results using real data which were gathered in test fields, affirm the high potential of these methods to obtain precise positioning information. The results reveal that it is possible to reduce position RMS error in single-frequency GPS receivers to less than 1 meter, especially when SA is in on mode, the effective error value improves to 0.4873 meter utilizing KF adapted with GA as compared to traditional KF.

References

[1] K. D. McDonald, "The Modernization of GPS: Plans, New Capabilities and the Future Relationship to Galileo", Journal of Global Positioning System, Vol.1, No.1, pp.1-17, 2002.

[2] M. R. Mosavi, "GPS Receivers Timing Data Processing using Neural Networks: Optimal Estimation and Errors Modeling", Journal of Neural Systems, World Scientific, Vol.17, No.5, pp.383-393, 2007.

[3] P. Misra, B. P. Burke and M. M. Pratt, "GPS Performance in Navigation", Proceeding of the IEEE, Vol.87, No.1, pp.65-85, 1999.

[4] K. Kobayashi, Ka C. Cheok, K. Watanabe and F. Munekata, "Accurate Differential Global Positioning System via Fuzzy Logic Kalman Filter Sensor Fusion Technique", IEEE Transactions on Industrial Electronics, Vol.45, No.3, pp.510-518, 1998.

[5] A. Indriyatmoko, T. Kang, Y. J. Lee, G. I. Jee, Y. B. Cho and J. Kim, "Artificial Neural Networks for Predicting DGPS Carrier Phase and Pseudo-Range Correction", Journal of GPS Solutions, Vol.12, No.4, pp.237-247, 2008.

[6] B. W. Parkinson, J. J. Spilker Jr, P. Axelrad and P. Enge, "Global Positioning System: Theory and Applications", The American Institute of Aeronautics and Astronautics, 1996.

[7] R. Yarlagadda, I. Ali, N. Al-Dhahir and J. Hershey, "GPS GDOP Metric", IEE Proc.-Radar, Sonar Navig., Vol.147, No.5, pp.259-264, 2000.

[8] O. Øvstedal, "Absolute Positioning with Single-Frequency GPS Receivers", Journal of GPS Solutions, Vol.5, No.4, pp.33-44, 2002.

[9] G. Seeber, F. Menge and C. Volksen, "Precise GPS Positioning Improvements by Reducing Antenna and Site Dependent Effects", Advances in Positioning and Reference Frames, IAG Symposium, Vol.118, pp.237-244, 1997.

[10] K. Deergha Rao, "An Approach for Accurate GPS Navigation with SA", IEEE Transactions on Aerospace and Electronic Systems, Vol.34, No.2, pp.695-699, 1998.

[11] D. Simon, "Optimal State Estimation: Kalman, H. Infinity and Nonlinear Approches", John Wiley, 2006.

[12] W. S. Chaer, R. H. Bishop and J. Ghosh, "A Mixture-of-Experts Framework for Adaptive Kalman Filtering", IEEE Transactions on Systems, Man and Cybernetics - Part B: Cybernetics, Vol.27, No.3, pp.452-464, 1997.

[13] J. Yan, D. Yuan, X. Xing and Q. Jia, "Kalman Filtering Parameter Optimization Techniques Based on Genetic Algorithm", IEEE Conference on Automation and Logistics, pp.1717-1720, 2008.

[14] "Zodiac GPS Receiver Family Designer's Guide", Rockwell Semiconductor Systems, GPS-33, 1996.

[15] M. R. Mosavi, "Comparing DGPS Corrections Prediction using Neural Network, Fuzzy Neural Network and Kalman Filter", Journal of GPS Solutions, Vol.10, No.2, pp.97-107, 2006.

[16] M. R. Mosavi, A. Nakhaei and Sh. Bagherinia, "Improvement in Differential GPS Accuracy using Kalman Filter", Journal of Aerospace Science and Technology, Vol.7, No.2, pp.139-150, 2010.

Mohammad-Reza Mosavi (Corresponding Author) received his B.S., M.S., and Ph.D. degrees in Electronic Engineering from Department of Electrical Engineering, Iran University of Science and Technology (IUST), Tehran, Iran in 1997, 1998, and 2004, respectively. He is currently faculty member of Department of Electrical Engineering of IUST as associate professor. He is the author of about 120 scientific publications on journals and international conferences. His research interests include Artificial Intelligent Systems, Global Positioning Systems, Geographic Information Systems and Remote Sensing.