covariance matrices. The filter performance is not involved with substantial restriction occurs by using classic KF.

II. VERTICAL CHANNEL MECHANIZATION

This section deals with the formulation of true barometric altitude model in non-standard atmosphere conditions and developing vertical channel damping loop. The barometric altimeter is affected in a large degree by the atmosphere physics. So, it must be calibrated. In the standard atmosphere, the barometric altitude is obtained as follows [1].

$$H_p = \frac{T_0}{L}\left[\left(\frac{P_s}{P_0}\right)^{-\frac{LR}{g}} - 1\right] + H_0 \tag{1}$$

where, the temperature and the pressure at sea level are specified by T_0 and P_0, respectively. In standard atmosphere these variables are assumed to be $288.15\,(°K)$, $101.325\,(kPa)$. L, R, and g are the constant lapse rate, universal gas constant, and gravity constant, respectively. H_0 is taken 0 for sea level data, and P_s stands for the pressure measured by the barometer. For non-standard atmosphere, the constant lapse rate assumption remains valid [15]. However, the temperature and the pressure assumptions cannot be guaranteed as a real atmosphere system. Applying scale factor, s and bias, b as calibration parameters, the barometric altitude compensation is achieved by the following equation of non-standard atmosphere.

$$H \cong H_P + s(H_P - H_0) + b \tag{2}$$

where, H is the calibrated barometric altitude under non-standard atmosphere condition. The scale factor and the bias parameters are defined as follows.

$$s = \frac{\Delta T}{T_0} \tag{3}$$

$$b = \frac{RT_0}{g}\left(\frac{\Delta P}{P_0}\right) \tag{4}$$

In (3) and (4), ΔT and ΔP denote the deviation of true temperature and true pressure at sea level from the corresponding fixed values of standard condition, respectively. To compute the true values of local sea level temperature and pressure around tests region, the following model is used.

$$\begin{aligned} T_t &= T_s + L\,H_P \\ P_t &= P_s + \rho g\,H_p \end{aligned} \tag{5}$$

where, T_t and P_t represent the true temperature and the pressure at sea level, respectively. T_s and P_s are the measured values by sensors.

In many positioning and navigation applications accurate altitude information is required. The main goal of the vertical channel mechanization is to minimize the errors of altitude and down-ward vertical velocity. Through damping loop, the vertical channel data of INS is integrated with aiding barometric system known here as Air-data. The feedback block diagram of damping loop in Fig. 1 shows how the computed data of INS vertical channel are stabilized.

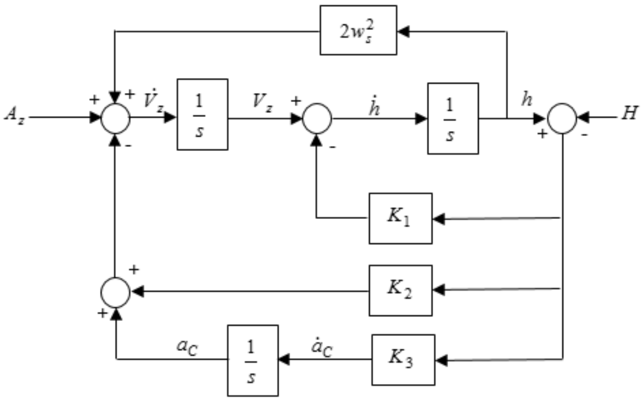

Fig.1 Block diagram of vertical channel damping loop.

The corresponding dynamical equation of the damping loop can be written as follows.

$$\begin{aligned} \dot{h} &= V_Z - K_1(h - H) \\ \dot{V}_Z &= A_Z - a_C + 2w_s^2 h - K_2(h - H) \\ \dot{a}_C &= K_3(h - H) \end{aligned} \tag{6}$$

where, V_Z, h and H stand for vertical velocity, true height and calibrated barometric altitude of non-standard atmosphere condition, respectively. A_Z denotes the measured acceleration along vertical channel. The parameters, a_C and w_s are the outputs of compensator and Schuler frequency, respectively. The feedback gains, K_1, K_2 and K_3 should be determined in such a way that leads to minimized error between the estimated and the reference values of vertical velocity. GA based computation algorithm for optimal values of feedback gains is explained in complete details in the following section.

III. ERROR COMPENSATION BY GA METHOD

In this section, a new binary GA method is proposed. As a matter of fact, GPS and barometer are used as aiding systems of the integrated INS to estimate and compensate its vertical channel errors. The vertical velocity component of GPS system, V_G^{obs} is considered as the reference signal and the value computed by (6), V_Z^{a} is considered as the estimated value. The mismatch between the N number of reference and estimated values is designated based on the following cost function.

$$J_O \equiv \sum (V_{Gi}^{obs} - V_{Zi}^{a})^2 \qquad i = 1, 2, \ldots, N \tag{7}$$

where, the summation extends over the observation grid points by the GPS over a time window of at least one volume scan period. So the problem is formulated as a binary genetic algorithm, and the objective of this problem is minimizing the cost function of (7).

GA operates through a simple but important iteration in four main steps [13]: the creation of population of strings, the evaluation of each string, the selection of the best or fittest strings and finally the genetic manipulation to create the new population of strings. The algorithm starts with initial random sets of individuals called the initial population. The objective function (7) for each individual is evaluated. On the basis of this evaluation, a new set of population is created according to three major genetic operators including selection, crossover and mutation in addition to four control parameters of population size, selection pressure, crossover rate and mutation rate. The procedure is iteratively repeated until a defined terminating condition is reached and satisfied.

- **Selection**

Selection is one of the three major genetic operators that chooses a chromosome from the current generation's population to be included in the population of next generation. Selection operator includes tournament, roulette wheel, top percent and best selection sections. In the tournament step of designed algorithm, a small subset of chromosomes is picked randomly and the chromosome with the lowest cost in this subset becomes a parent.

- **Crossover**

Crossover is an operator that combines two chromosomes to produce a new chromosome [16]. The major idea in crossover is that the child may be better than parents. The crossover operator includes one-point, two-point and uniform operation. Crossover occurs according to definable crossover probability. In the proposed GA filter, the one-point method is used and the crossover probability (P_c) is defined as a fixed value of 0.9.

- **Mutation**

Mutation is a genetic operator that alters one or more gens of a selected chromosome. Mutation points are randomly selected among the $(N_{pop} \times N_{bits})$ bits in the population matrix. If the selected gen in a single point mutation changes from 1 to 0 or conversely, new individuals are created and added to the population. Mutation occurs during evolution according to a certain mutation probability. In the presented algorithm, the relationship between the mutation probability and the generation number is considered as follows [17].

$$p_m = \frac{1}{240} + \frac{0.11375}{2^t} \qquad (8)$$

where, p_m denotes the mutation probability and t is the generation number.

Block diagram of Fig. 2 shows the main structure of the proposed GA algorithm of vertical channel filter.

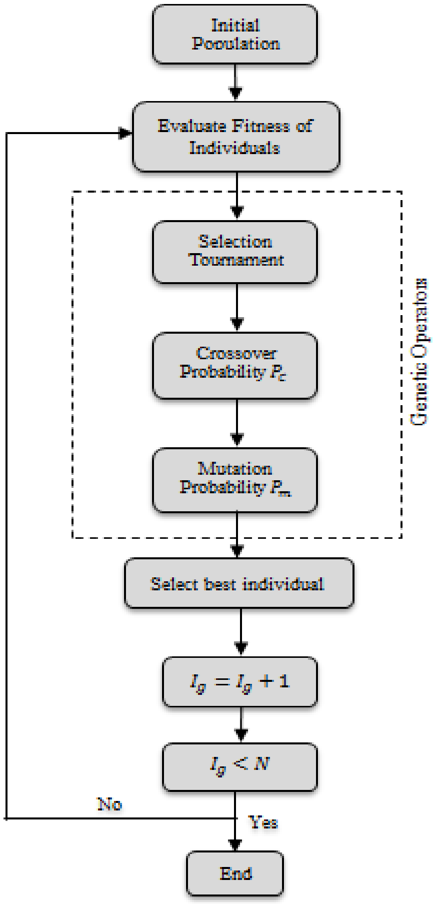

Fig.2 Block diagram of binary GA for vertical channel error compensation.

The proposed GA algorithm of vertical channel filter is summarized in five main steps as follows.

Step 1: The algorithm's parameters comprising of chromosome length, number of initial population, crossover probability (P_c) and number of generation (*N*) are initialized.

Step 2: For the initial population, the gains of vertical damping loop, K_1, K_2 and K_3 are generated.

Step 3: The objective function of (7) is evaluated for each chromosome. In this step, the best individual and also the individuals that have the least parameter distance from the best individual are reserved. The distance between the i^{th} individual and the best individual is calculated as:

$$d^i = \sum_{k=0}^{p_n} (P_k^i - P_k^{\max})^2 \qquad (9)$$

where, p_n shows the total number of parameters. P_k^i and $P_k^{\max}$ stand for the k^{th} parameter of individual *i*, and the k^{th} parameter of the best individual, respectively.

Step 4: The iterative generation, I_g is set. For $I_g < N$, considering the crossover probability condition, crossover operation is done for two selected chromosomes and two children are generated. Furthermore, considering the mutation probability condition, mutation operation is done for the selected pair and another two children are generated. Then, the fitness of the new individuals is calculated and the dominant individuals of the population are updated.

Step 5: I_g is set to $(I_g + 1)$. If $I_g < N$, the algorithm is repeated from step 3. Otherwise, the process is stopped and the best solution is achieved.

Applying the presented algorithm, the feedback gains of vertical channel damping loop are determined and the true height is estimated.

IV. IMPLEMENTATION AND EESULTS

In this section, the proposed GA filter algorithm for integrated barometric altitude is experimentally verified. Vehicular tests have been performed using "ADIS16407" IMU-barometer sensors and a "Vitans" integrated INS with a "Garmin 35" GPS [18], as shown in Fig. 3. The required temperature and raw pressure data are provided by corresponding sensors of ADIS16407 system. Considering the full scale ranges of the sensors, the pressure data are determined in the interval between 10 *mbar* and 1200 *mbar* and the vertical acceleration data could be measured in the interval -10g to 10g.

Fig.3 Block diagram of vertical channel damping loop.

Vehicular tests have been executed by experienced colleagues in navigation field. Along the mountain road tests, the vehicle’s altitude is changed in large range intervals and therefore enriched calibration data are provided.

A. Compensated Barometric Altitude

In this section, the obtained altitude by the proposed compensation method of the barometric altimeter according to nonstandard atmosphere is compared with that of the traditional barometric altitude produced by Vitans system. Both the compensated barometric altitude presented in section II, and the barometric altitude of Vitans system with respect to the GPS altitude data are shown in Fig. 4.

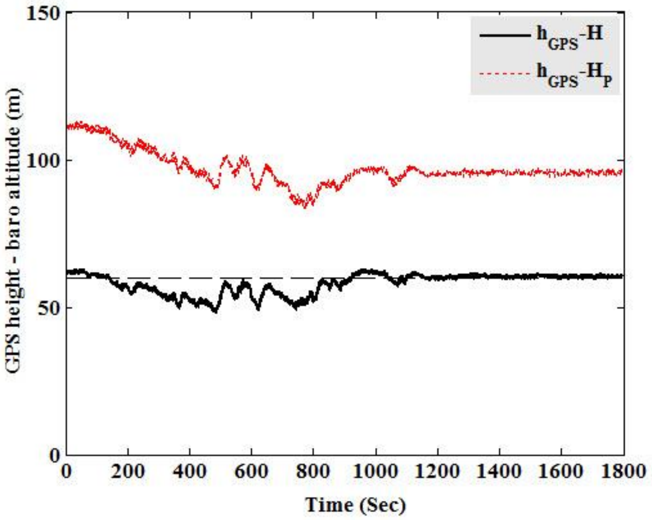

Fig.4 Compensated barometric altitude and vitans' barometric altitude with respect to GPS height.

According to Fig. 4, the error of corrected barometric altitude with respect to that of GPS is approximately 60 m. Using WGS84 data which is the most commonly recognized model of the world geodetic system, the sea level altitude in the test region is 60 m above the mean sea level. Therefore, considering the fact that the GPS gives its altitude with respect to the mean-sea level, the compensated altitude of the non-standard atmosphere is significantly accurate. Consequently, the barometric altitude correction algorithm based on non-standard atmosphere gives near-accurate altitude in comparison to the reference GPS data.

B. Implementation of GA

In this section, the proposed genetic algorithm method presented in section III is experimentally verified using the vehicular test data. In the GA, random initial populations are generated for the gains of vertical damping loop. The optimal gains of the damping loop are obtained through the GA as follows.

$$\begin{aligned} K_1 &= 3.00 \\ K_2 &= 0.6452 \\ K_3 &= 0.8710 \end{aligned} \tag{10}$$

By comparing the estimated height with respect to that of the GPS receiver in Fig. 5, the tracking performance of the GA based damping loop of vertical channel mechanization is assessed. The illustrated result during the vehicular test shows the valuable estimation performance of the proposed algorithm. It can be obviously inferred from Fig. 5 that the proposed GA method in the paper results in a relatively accurate estimation of vertical channel height with respect to the reference GPS height.

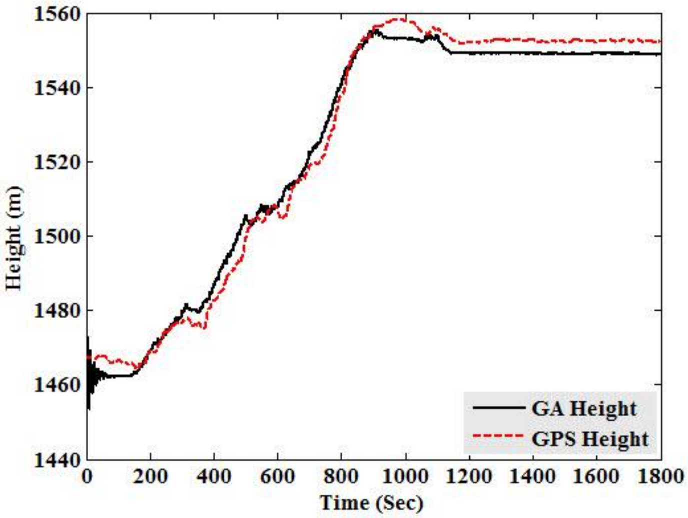

Fig.5 Estimation of vertical channel altitude for vehicular test using GA method.

C. Comparison with Kalman Filter

To legitimize the estimation performance of the proposed GA-based method, the vertical height is also estimated through KF algorithm. Using dynamical equations (6) the following dynamics of the vertical channel error is utilized in the implementation of KF [8].

$$\begin{aligned} \delta\dot{V}_Z &= 2w_s^2\delta h + A_Z + w(t) \\ \delta\dot{h} &= \delta V_Z \end{aligned} \tag{11}$$

where, $w(t)$ represents Gaussian noise signal. Moreover, the bias of the barometer sensor is considered as a first order Gauss-Markov process modeled as [19]:

$$\dot{b}(t) = -\beta b(t) + \sqrt{2\beta\sigma^2}\, w(t) \tag{12}$$

In (12) β and σ are the correlation time and the standard deviation of zero-mean white noise process, $w(t)$, respectively. The dynamical model of (11) and (12) can be rewritten in the following state space model.

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{13}$$

where, the state vector, $\mathbf{x}$ and the input vector, $\mathbf{u}$ are determined as follows.

$$\begin{aligned} \mathbf{x} &= \begin{bmatrix} \delta V_z & \delta h & b \end{bmatrix}^T \\ \mathbf{u} &= \begin{bmatrix} A_z & w(t) \end{bmatrix} \end{aligned} \tag{14}$$

Using (11) and (12), the matrices A and B are obtained as:

$$\mathbf{A} = \begin{bmatrix} 0 & 2w_s^2 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -\beta \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{2\beta\sigma^2} \\ 0 & 0 \end{bmatrix} \tag{15}$$

The following measurement equation is used in KF estimation algorithm.

$$h = H + \delta h - b + v_a \tag{16}$$

where, v_a represents measurement noise signal. KF algorithm is imposed on the continuous-time linear dynamic system represented by (13) and the measurement (14). In Fig. 6, the performance of the GA-based vertical channel damping method is compared to the result of KF algorithm.

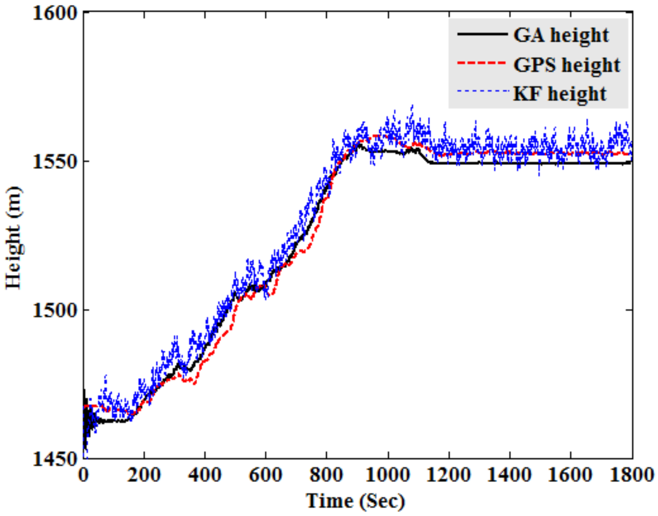

Fig.6 Comparison of GA and KF methods in estimation of vertical channel altitude.

As shown in Fig. 6, the proposed GA method yields a superior tracking compared to KF method. Furthermore, in the estimated height by the GA-based method the oscillation effect of noises has been removed, perfectly. This result becomes more significant by regarding the main advantage of GA method in which no zero-mean Gaussian noise assumption is required.

V. CONCLUSION

In many navigation applications, accurate altitude information is required. The main goal of vertical channel mechanization is to minimize the errors of vertical height and velocity. In this paper, based on binary genetic algorithm, a new algorithm has been proposed for vertical channel error compensation. vehicular test has been performed and the proposed algorithm for integrated barometric altitude was experimentally verified. The tests are executed in maneuvering conditions of the vehicle in mountain roads. It can be inferred from the results that the algorithm has a good performance for estimating the vertical channel height with an acceptable range of precision. For a fair comparison, the vertical channel height was also estimated through KF algorithm. The test results elucidate the superiority of GA method in tracking of accurate altitude compared to KF algorithm. Using GA method, the oscillation effect of noises on the estimated height has been removed, perfectly. Taking into account the limitation of zero-mean Gaussian noise assumption in KF, the results of GA method becomes more significant.

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