System Identification of Small Scale Helicopter using Invasive Weed Optimization on Flight Data

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Abstract: This paper presents the System Identification through dynamic modelling of scale model Helicopter UAV using Invasive Weed Optimization (IWO) algorithm. The Helicopter used is in this experiment is an Align TREX 550 flybarless helicopter with main rotor diameter of 1.2 meters. A flybar is used commonly on model scale helicopters and in this experiment a flybarless helicopter is used which is increasing in popularity for its mechanical simplicity and fast response. The identification is done using actual flight data for hovering condition and a complete dynamic model is obtained. A comparison of the results of IWO and GA shows the accuracy of the identified model by IWO over the more commonly used GA.

Keywords: **Helicopter UAV, System Identification, Evolutionary algorithms in control and identification**

1. INTRODUCTION

Model-scale Helicopters are aerial robots that are popular for their vertical take-off and land capabilities and their dexterity in cruise flight. This makes it a highly-sought after platform for unmanned aerial vehicles (UAVs). However, helicopters are mechanically complex and their dynamic behaviour is highly nonlinear. Implementing mathematical model through first principles of helicopter have only been partially successful in understanding the full capabilities of helicopter UAVs (H-UAVs) as much as it has been used by its full-sized counterpart. This complexity arises due to its high sensitivity towards control inputs, external perturbations and a high degree of inter-axis coupling. These behaviours make autonomous flight of helicopters still far from reality. From control system point of view, Helicopters are multi input-multi output (MIMO) systems. Metaheuristic algorithms as of now have been most successful in identifying a model that is practically close enough to the degree of accuracy required for such highly nonlinear and unstable platforms to be autonomous as shown by Lei et al. We have chosen genetic algorithm (GA) and invasive weed optimization (IWO) algorithm to identify the state-space parameters for an H-UAV.

Genetic Algorithm is a nature-inspired metaheuristic method, commonly adopted to solve many optimization problems. This falls under a larger class of algorithms which supplies satisfactorily good solutions especially with incomplete or imperfect information or limited computation capacity. In this method, a population of solutions, called Phenotypes or Individuals, of an optimization problem is evolved towards better solutions by mimicking the natural selection process in a genetic level which involves crossovers and mutations. There are two variants of the genetic algorithm based on the encoding of the chromosome: Binary-Coded GA and Real-Coded GA. Binary-coded GA was employed in to solve the present problem as it is more nature-identical than the latter. System identification using genetic algorithm has been extensively dealt by K.Kristinsson et.al.

Invasive Weed Optimization (IWO) algorithm was first proposed by A.R.Mehrabian et.al., which was inspired by the vigorous and invasive growth habits of weeds which posed a threat to cultivated plants. The highly adaptive, robust and random nature of the weed's colonizing behaviour is used in this algorithm which makes it a powerful optimization tool.

Fig. 1. TREX 550 used for collecting flight data

2. HELICOPTER UAV DESCRIPTION

The Align TREX 550 helicopter used is a 550 size helicopter capable of 3D flight and is mainly used in hobby and sports flying. It does not use a traditional flybar as used by the majority of the scale-model helicopters available commercially. Flybars provide a negative feedback to the lateral and longitudinal motion of the aircraft due to the Coriolis force. The TREX 550 uses an electronic flybar that makes use of a micro electro-mechanical system (MEMS) gyroscope, so that the motion feedback can be tuned according to requirements, either to maximize agility while sport flying or maximize stability for beginners.

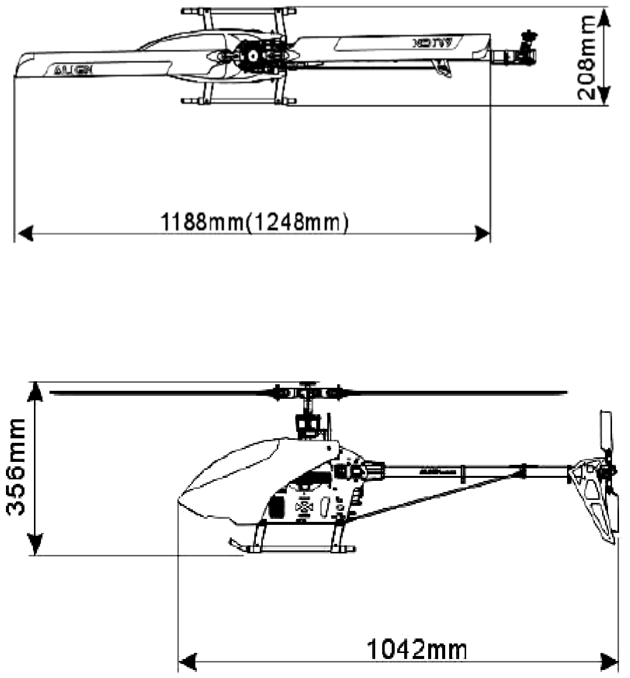

Fig. 2. TREX 550 physical characteristics

2.1 H-UAV Instrumentation

Indian Institute of Science's TREX 550 H-UAV is equipped with state-of-the-art sensor equipment that produce high quality flight-data, which has been presented in the paper by K.V.Aditya et al. The core of the on-board systems is a Pixhawk flight controller board. The Pixhawk houses a number of sensors that have been proven to provide good quality data apt for system identification. It contains a 3-axis gyroscope (which gives rates *p*, *q*, *r*), an accelerometer (which gives airframe accelerations a_x, a_y, a_z) and a magnetometer. Apart from this, a GPS module is also connected to the Pixhawk. A separate 3-axis gyro is installed to serve as an electronic flybar. The data is logged onto a micro-SD card mounted on the Pixhawk board at the rate of 100 Hz.

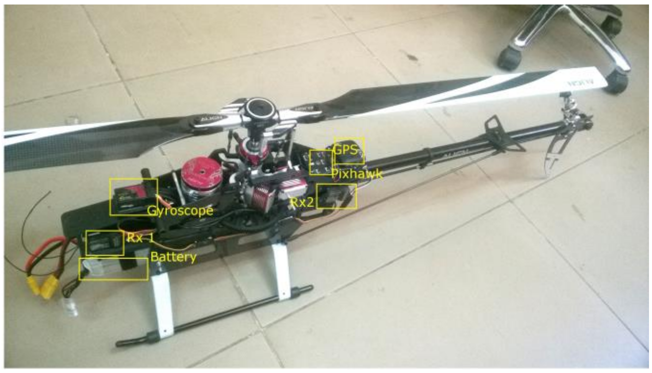

Fig. 3. TREX 550 instrumentation

3. FLIGHT TEST PROCEDURE

In order to excite the full range of responses from the H-UAV, the pilot is required to provide specific inputs. As the system identification is in the time-domain, a doublet input manages excite all the motions and states. The inputs were given by the pilot for both lateral and longitudinal directions keeping the pedal input for directional corrections. The both the tests were conducted in the hover condition with a fixed collective and motor rpm.

As suggested by M.B Tischler et.al, to get good quality data, instrumentation (sample rate and bandwidth) must be carefully selected so that its dynamic response has little effect on the identified overall dynamic response. The characteristics of the sensors and filters are known so that their effects can be incorporated in the analysis. To obtain good quality data, flight tests were conducted during periods of minimum ambient wind and turbulence. Steady winds of less than 2.57 m/s (5 knots) are desirable when the helicopter is in hover because measured response distortion resulting from recording equipment, sensor and filter dynamics, and atmospheric disturbances all degrade the precision and accuracy with which the real vehicle dynamics can be identified.

4. STATE-SPACE MODEL

The state-space model of an H-UAV has been adopted from the paper on system identification of small-scale helicopter by M.Bernard et al.

$$\dot{x} = Ax + Bu \tag{1}$$

The state space equation is formulated as depicted in (1). Where the *A* and *B* matrices are illustrated in Table 3 and Table 4 respectively, *x* is the state vector and *u* is the input vector. A few differences between the Yamaha R-50 helicopter used by them and the TREX 550 used in this paper are:

- The R-50 has a flybar whereas the TREX 550 is flybarless.

- The R-50 incorporates flapping of blades for uniform lift distribution whereas TREX 550 uses changes in blade pitch to achieve the same.

The parameters *c* and *d* in the state matrix correspond to stabilizer bar feedback in the longitudinal and lateral axes respectively. For the TREX 550, the flybar is an electronic element whose feedback is provided by the gyroscope. The parameters *a* and *b* are the flapping angles of the blade in the R-50 but for the TREX, the blade pitch angle provides for *a* and *b* by linear interpolation of the radio inputs.

5. METAHEURISTICS ON FLIGHT DATA

Metaheuristic techniques like genetic algorithm (GA) and particle swarm optimization (PSO) have been widely used in the field of system identification due to their powerful optimization technique. Invasive Weed Optimization (IWO) is a fairly recent entrant into the family of nature-inspired techniques. IWO is compared with GA due to their similar natural selection based model of optimization. The following sub-section discusses how the IWO algorithm was employed to identify the state-space parameters of the H-UAV model.

5.1 Invasive Weed Optimization (IWO)

Step 1: *Initialization*: A finite number of initial solutions or seeds are deposited randomly over a search space. Each seed contains 40 variables corresponding to the 40 parameters in the adopted state-space model.

Step 2: *Assigning the Fitness/Cost to Each Individuals*: The Cost function is defined by a combination of two methods: the Least squares method and the Population Pearson correlation coefficient.

The method of least squares minimizes the sum of the squared residuals, where the residual is the absolute difference between the actual output and the estimated output.

$$S = \sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{2}$$

Where r_i is the residual, y_i is the actual data and $\hat{y}_i$ is the estimated data.

The Population Pearson correlation coefficient of two sets of data is a measure of their frequency correlation or rather their “shape fitness”. Consider data sets *A* and *B* have *N* scalar observations each, then the Pearson correlation coefficient is defined as in (3).

$$\rho(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i - \mu_A}{\sigma_A}\right)\left(\frac{B_i - \mu_B}{\sigma_B}\right) \tag{3}$$

Where σ_A *and* σ_B are standard deviations of sets *A* and *B* respectively and μ_A and μ_B are the means of *A* and *B* respectively.

And the total Cost is expressed as in (4)

$$Z = \frac{S}{\rho^2} \tag{4}$$

With this as a basis, probabilities are assigned to each of the individuals in the population by the method shown in (5).

$$P_i = 1 - \frac{Zi}{\sum_{j=1}^{N} Z_j} \tag{5}$$

Step 3: *Reproduction*: Every seed grows into a flowering plant which in turn deposits its own seeds. But the number of seeds each flowering plant can deposit linearly varies from the minimum possible seeds to the maximum possible seeds based on its fitness value. In other words, the plant with a higher fitness score can deposit the maximum number of seeds.

Step 4: *Spatial Dispersal*: The spawned seeds are distributed randomly over the search space by normally distributed random number with zero mean and varying variance. The variance varies as expressed in (6)

$$\sigma_{iter} = \frac{(iter_{max} - iter)^n}{iter_{max}}\left(\sigma_{initial} - \sigma_{final}\right) + \sigma_{final} \tag{6}$$

Where $iter_{max}$ is the maximum number of iterations and σ_{iter} is the standard deviation of the current iteration and *n* is the nonlinear modulation index.

This ensures that the probability of dropping a seed in a distant area decreases nonlinearly at each iteration which groups fitter plants and eliminates weak ones.

Step 5: *Competitive Exclusion*: Initially all the seeds are allowed to grow unchecked till it reaches the population limit. Once the population limit is reached, a function to eliminate plants with poor fitness gets called. This function ranks all the seeds in the population with their parents’ ranks and eliminates weeds with lower fitness and allows newer seeds to fill the population. This way plants with low fitness scores are allowed to survive if their offspring gives a high fitness score.

5.2 Results

Each flight data output is compared to its estimated value and the correlation between the two data sets is calculated and scored from 0 to 1 where 1 score is achieved when a data set exactly correlates with the other. We can observe from Table 1 that the IWO algorithm provides better correlation score when compared to the traditional GA for every output parameter. We can also observe that the greatest difference in the correlation presents itself in the lateral velocity (*u*), roll rate (*p*) and roll angle (ϕ). This shows that the IWO is highly efficient in predicting the lateral dynamics of the H-UAV than the GA. Though the difference in longitudinal dynamics correlation score is low, there is a noticeable similarity between the IWO and GA results in the plots of longitudinal velocity (*u*), pitch rate (*q*), and pitch angle (θ) which is shown in appendix B.

Table 1. Performance Comparison

	GA	IWO
u	0.7732	0.8517
v	0.7235	0.8209
p	0.7791	0.85
q	0.7641	0.7685
r	0.66	0.6711
ɵ	0.7768	0.7860
ϕ	0.8318	0.9005

A few of the parameters which were identified using the IWO algorithm have been presented in Table 2. Where Xu is the longitudinal velocity derivative, Yv is the lateral velocity derivative, Bd and Ac are electronic stabilizer bar-rotor coupling derivative, Lu, Lv, Mu, Mv are angular speed derivatives which are responsible mainly for the phugoid instability in hover condition, Nped is the yaw control derivative, Nv is the lateral velocity effect due to tail rotor, Zw is the heave damping derivative, Zcol is the heave control sensitivity coefficient, and T_f is the bare-rotor time constant.

Table 2. Identified Parameters

Parameters	Values
Xu	1.0845
Yv	-1.3166
Lu	3.7164
Lv	2.3703
Mu	-1.4641
Mv	4.1149
T_f	12.0950
Ac	0.0724
Bd	-1.5359
Zw	-18.9351
Nv	0.8455
Zcol	-41.2789
Nped	36.5245

6. CONCLUSIONS

The state-space model for the H-UAV was successfully identified using IWO and it has provided a more accurate model than the one given by the traditional GA. This shows that IWO is a powerful tool in system identification.

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Appendix A. STATE-SPACE SYSTEM

$$
\begin{bmatrix}
X_u & 0 & 0 & 0 & 0 & -g & X_a & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & Y_v & 0 & 0 & g & 0 & 0 & Y_b & 0 & 0 & 0 & 0 & 0 \\
L_u & L_v & 0 & 0 & 0 & 0 & 0 & L_b & L_w & 0 & 0 & 0 & 0 \\
M_u & M_v & 0 & 0 & 0 & 0 & M_a & 0 & M_w & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\tau_f & 0 & 0 & -1 & A_b & 0 & 0 & 0 & A_c & 0 \\
0 & 0 & -\tau_f & 0 & 0 & 0 & B_a & -1 & 0 & 0 & 0 & 0 & B_d \\
0 & 0 & 0 & 0 & 0 & 0 & Z_a & Z_b & Z_w & Z_r & 0 & 0 & 0 \\
0 & N_v & N_p & 0 & 0 & 0 & 0 & 0 & N_w & N_r & N_{rfb} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_r & K_{rfb} & 0 & 0 \\
0 & 0 & 0 & -\tau_s & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & -\tau_s & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1
\end{bmatrix}
$$

Table 3. Matrix A of the state-space system

$$
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & Y_{ped} & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & M_{col} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
A_{lat} & A_{lon} & 0 & 0 \\
B_{lat} & B_{lon} & 0 & 0 \\
0 & 0 & 0 & Z_{col} \\
0 & 0 & N_{ped} & N_{col} \\
0 & 0 & 0 & 0 \\
0 & C_{lon} & 0 & 0 \\
D_{lat} & 0 & 0 & 0
\end{bmatrix}
$$

Table 4. Matrix B of the state-space system