Performance Maximization of Tactical Unmanned Aerial Vehicles via Integrated Passive and Active Morphing

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***Abstract*— In this conference paper integrated passive and active morphing methodology is used on tactical unmanned aerial vehicles (TUAVs) in order to maximize autonomous flight performance. For this drive dynamic modeling of TUAVs produced in Erciyes University Faculty of Aeronautics and Astronautics Model Aircraft Laboratory is followed in order to get state-space models and a simulation model. This TUAV called as ZANKA-III is 50 kg, has range of around 3000 km, endurance of around 28 h, and ceiling altitude of around 12500 m. Von-Karman turbulence modeling is benefited in order to model atmospheric turbulence in simulation environment. A stochastic optimization method namely simultaneous perturbation stochastic approximation (i.e. SPSA) is applied in order to get optimum morphing parameters (e.g. assembly position of tailplane to fuselage and extension ratio of wing span).**

***Index Terms*— Tactical Unmanned Aerial Vehicles (TUAVs), Autonomous Flight, Performance, Morphing, Stochastic Optimization.**

I. INTRODUCTION

For the preceding four and five decades *U*nmanned *A*ir *V*ehicles (UAVs) have been broadly used for military operations as well as in commercial invitations because of the fact that they owe numerous superiorities with respect to the classical manned vehicles. Some of these advantages are having cheap manufacturing and cheap operating, having flexibility in configuration depending on customer demand and also not risking the pilot's life on interesting missions. UAVs have also been applied in aerial agriculture such as crop monitoring and spraying, photography such as film and video, and coast guarding such as coastline and see-lane etc. with civilian purposes. They have additonally been applied during military tasks. For example, they have been benefited for navy such as decoying missiles by the emission of artificial signatures and shadowing enemy fleets, army such as reconnaissance and surveillance of enemy activity and air force such as radar system jamming and destruction and airfield base security. In Ref. [1] many other UAV applications, are given. Too many different scientific research about UAV design and control have been lately applied (such as Ding, Liu and Hsiao; 2013 [2]; Drak et al. 2014 [3]; Filippis, Guglieri, Quagliotti, 2014 [4]; Hadi et al. 2014 [5]).

In conventional approach, a model of the any physical system will be controlled (e.g. fixed wing TUAV, VTOL UAV, helicopter UAV etc.), also named as the "plant", is given a priori to the control system design engineer having no effect on this model's conceptual and detailed design.

Nonetheless, it is well-known fact that the plant design problem and control system design problem are so relevant (see Grigoriadis et al., 1993 [6]; Grigoriadis et al., 1996 [7]). Some minor changes in UAV parameters may develop autonomous performance noticeably such as in Krog et al., 2004 [8]; Park et al., 2008 [9]; Qun and Hong-quang, 2011 [10]. The classical consecutive methodology: first of all, design the plant, and second design the control system, does not share the best overall design (see Grigoriadis et al., 1993 [6]; Grigoriadis et al., 1996 [7]). Elegantly, the system required to be controlled and the control system should be simultaneously designed such that a given objective (i.e. cost function) is minimized, while there are rigid constraints on the plant and control system parameters. In this conference article this idea is followed and a tactical passive and active morphing UAV (i.e. ZANKA-III) manufactured in Erciyes University, Faculty of Aeroanutics and Astronautics and a PID based hierarchical autopilot system are simultaneously designed through wing and horizontal tail parameters and additionally autopilot P, I, D parameters in order to minimize a cost function consisting of performance parameters, i.e. maximum overshoot, settling time and rise time during trajectory tracking.

This is the *first conference article* simultaneously designing a both passive and active morphing TUAV and autopilot system for autonomous flight performance maximization. Furthermore, for this motivation a stochastic optimization method (i.e. SPSA, simultaneous perturbation stochastic approximation) is *first time* assisted and using it, optimal results are found safely and fast. Additonally, simultaneous design idea during both passive and morphing case increases autonomous flight performance noticeably, hence less overshoot, less settling time and less rise time are obtained during reference trajectory tracking.

II. PROPERTIES OF UAV

In Figure 1 morphing wing and airframe of ZANKA-III, fully active + passive morphed wing + fully passive + no active morphed horizontal tail case and no active + passive morphed wing + no passive + active morphed horizontal tail case are summarized, respectively.

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(a)



(b)



(c)

Fig. 1. (a) Morphing wing and airframe of TUAV (b) Fully-active+passive morphed wing + Fully-passive and non-active morphed HT TUAV (c) Non-active+passive morphed wing + Non-passive+active morphed HT TUAV

Some properties of our manufactured TUAV are given in Table 1.

Table I: Some Properties of TUAV

Total Weight	50 kg
Payload	15 kg (5 kg of fuel)
Length and Width	4 m wing span 2.188 m longitudinal length
Engine Power (HP)	18 Hp
Maximum Range	2550 km
Maximum Endurance	28.7 sa
Speed For Maximum Endurance	88. 9 km/sa
Ceiling Altitude	12792 m

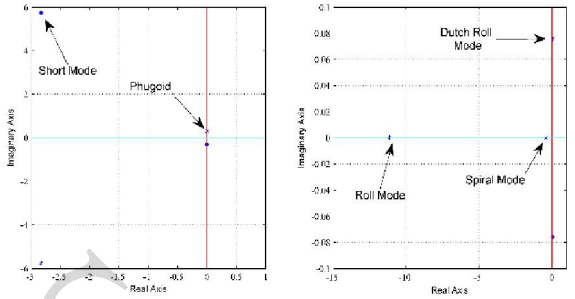
III. SIMULATION MODEL

In Eqs. (1-2) longitudinal and lateral state-space models for TUAV are given, respectively.

$$\begin{bmatrix}\Delta\dot{u}\\ \Delta\dot{w}\\ \Delta\dot{q}\\ \Delta\dot{\theta}\end{bmatrix}=\begin{bmatrix}X_u & X_w & 0 & -g\\ Z_u & Z_w & u_0 & 0\\ M_u+M_{\dot{w}}Z_w & M_w+M_{\dot{w}}Z_w & M_q+M_{\dot{w}}u_0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\Delta u\\ \Delta w\\ \Delta q\\ \Delta\theta\end{bmatrix}+\begin{bmatrix}X_{\delta_T} & X_{\delta_e}\\ Z_{\delta_T} & Z_{\delta_e}\\ M_{\delta_T}+M_{\dot{w}}Z_{\delta_T} & M_{\delta_e}+M_{\dot{w}}Z_{\delta_e}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\Delta\delta_T\\ \Delta\delta_e\end{bmatrix} \quad (1)$$

$$\begin{bmatrix}\Delta\dot{v}\\ \Delta\dot{p}\\ \Delta\dot{r}\\ \Delta\dot{\phi}\end{bmatrix}=\begin{bmatrix}Y_v & Y_p & -(u_0-Y_r) & -g\cos(\theta_0)\\ L^*_w+\frac{I_{xz}}{I_x}N^*_v & L^*_p+\frac{I_{xz}}{I_x}N^*_p & L^*_r+\frac{I_{xz}}{I_x}N^*_r & 0\\ N^*_v+\frac{I_{xz}}{I_z}L^*_v & N^*_p+\frac{I_{xz}}{I_z}L^*_p & N^*_r+\frac{I_{xz}}{I_z}L^*_r & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}\Delta v\\ \Delta p\\ \Delta r\\ \Delta\phi\end{bmatrix}+\begin{bmatrix}0 & Y_{\delta_r}\\ L^*_{\delta_a}+\frac{I_{xz}}{I_x}N^*_{\delta_a} & L^*_{\delta_r}+\frac{I_{xz}}{I_x}N^*_{\delta_r}\\ N^*_{\delta_a}+\frac{I_{xz}}{I_z}L^*_{\delta_a} & N^*_{\delta_r}+\frac{I_{xz}}{I_z}L^*_{\delta_r}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\Delta\delta_a\\ \Delta\delta_r\end{bmatrix} \quad (2)$$

In Figure 2 longitudinal and lateral flight dynamics modes of our TUAV are given, respectively. There were qualitative and quantitative match between our modes and literature results ([8-11]). Therefore, it is decided that our modeling approach is correct.



(a) (b)

Fig. 2. (a) Longitudinal and (b) Lateral Flight Dynamics Modes

For our both theoretical and practical (with real-time flight tests) TUAV studies traditional PID based hierarchical autopilot system is selected (see Refs. [12] and [13]). This type of system benefits three layers PID controller to succeed waypoint navigation. In Figure 3 detailed version of any PID-based hierarchical autopilot system is illustrated.

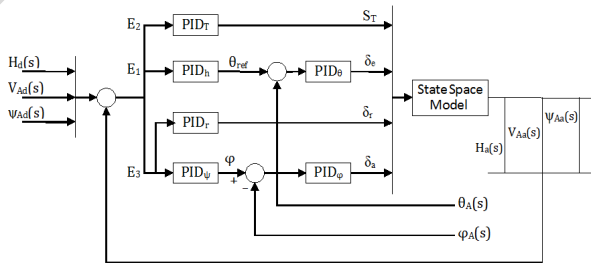


Fig. 3. PID Based Autopilot Structure

IV. OPTIMIZATION AND ALGORITHM

Since there is complex dependency between cost function and the constraints on the optimization variables (18 P-I-D gains and 2 TUAV passive morphing parameters and 2 TUAV active morphing parameters, total of 22 parameters), computation of cost function derivatives with respect to these parameters is not analytically possible. This advocates the demand of certain stochastic optimization techniques. For solving this specific problem we choose a certain stochastic optimization method named as SPSA (abbreviation of simultaneous perturbation stochastic approximation), which

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was effectively applied in similar very complex constrained optimization problems earlier (see Sultan, 2010 [14]; Oktay 2012 [15]; Oktay and Sultan 2012 [16]). SPSA has many superiorities w.r.t. the other existing method in the literature.

First of all, SPSA is not expensive since it applies only two evaluations of the objective in order to guess the gradient (see Spall 1992 [17]). Additionally, it is also effective in solving constrained optimization problems (see see Sultan, 2010 [14]; Oktay 2012 [15]; Oktay and Sultan 2013 [16]).

V. RESULTS AND DISCUSSION

Both passive and active morphing TUAV (i.e. ZANKA-III) and autopilot system tracking pitch attitude are simultaneously designed in order to minimize cost function consisting of autonomous flight performance parameters using SPSA. For this conference article the ZANKA-III our TUAV was tracking a 5 degrees of pitch angle and there were a PID controller parameters and two passive morphing and 2 active morphing parameters (i.e. wing and horizontal tail) during this optimization problem. In Fig. 4 cost minimization during using SPSA and relative energy save at each iteration are given. The relative energy save ***%J*** is around %45. Accomplishment of used autopilot system when there exists turbulence on the system is also searched. In Fig. 5 the closed loop system responses when there exists pure turbulence on the system are given. From this figure it can be seen that when there is also turbulence on the system, the autopilot system is able to track reference trajectory efficiently. Additionally, other states do not experience catastrophic behavior (fast and large oscillations) during pitch trajectory tracking. Finally, while there is constraint on control surface (+-30 degrees for elevator), it is also possible for desired trajectory tracking.

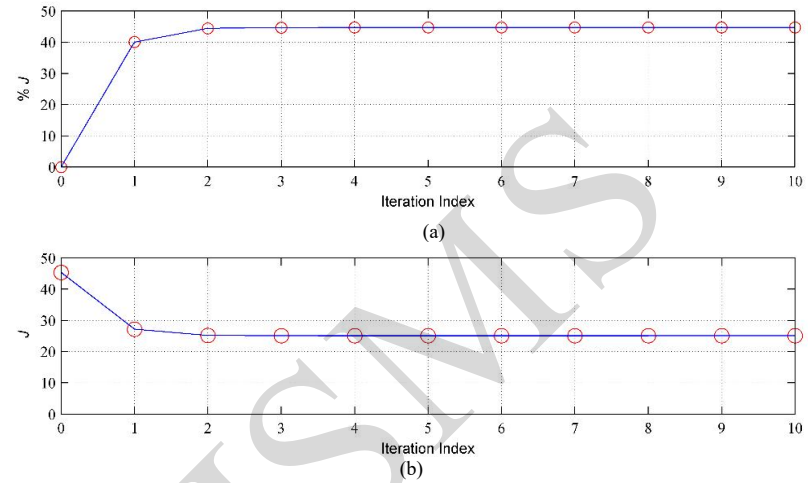
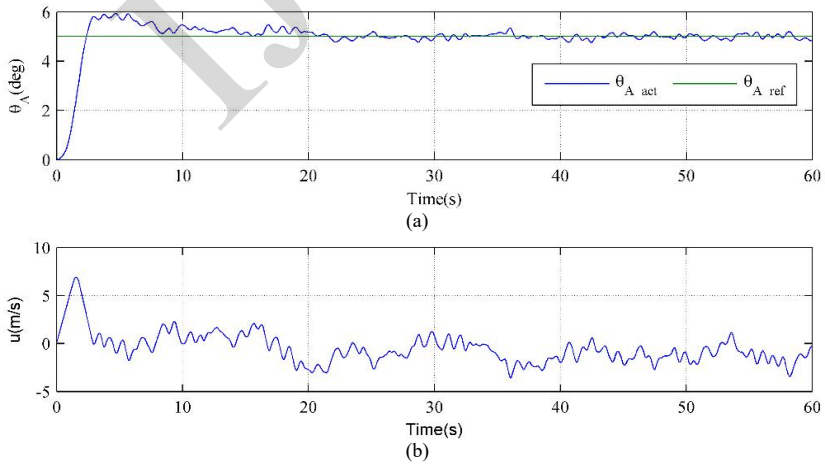


Fig. 4. (a) Relative Energy Save and (b) Energy Minimization with SPSA



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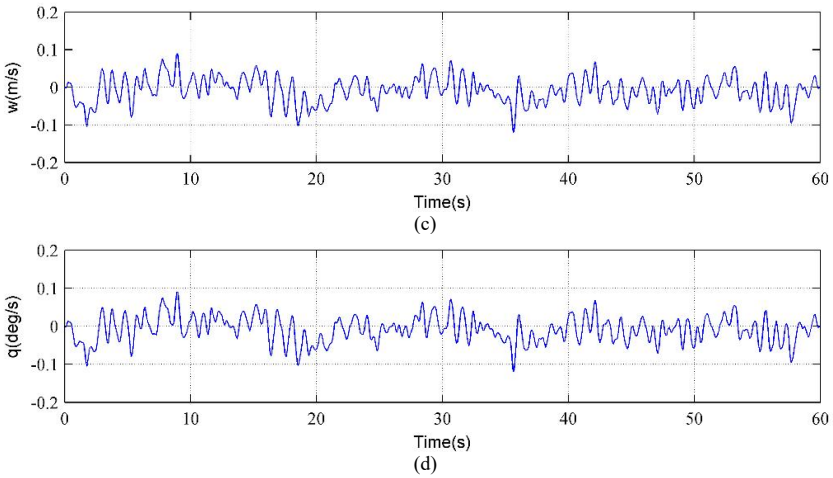


Fig. 5. (a, b, c, d) Closed Loop Longitudinal Responses when Turbulence exists

VI. CONCLUSIONS

Simultaneous passive and active morphing tactical unmanned aerial vehicle (TUAV) (total of 50 kg) and autopilot system design is researched in order to improve autonomous flight performance of UAVs. A PID based hierarchical autopilot system is used for this conference article. A stochastic optimization method namely simultaneous perturbation and stochastic approximation (i.e. SPSA) is benefited for autonomous performance maximation. Vital improvement in flight performance (around %45) is obtained using simultaneous passive and active morphing UAV and autopilot system design idea.

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REFERENCES

[1] R. Austin, Unmanned aircraft systems, Wiley, 2010.

[2] Dink, Y., Liu, Y. C., and Hsiao, F. B. The application of extended Kalman filtering to autonomous formation flight of small UAV system. Aircraft Engineering and Aerospace Technology. 1(2), 154-186.

[3] A. Drak, M. Hejase, M. ElShorbagy, A. Wahyudie, A. and H. Noura, "Autonomous formation flight algorithm and platform for quadrotor UAVs", International Journal of Robotics and Mechatronics. 1(4), 124-132, 2014.

[4] L. D. Filippis, G. Guglieri and F. B. Quagliotti, "A novel approach for trajectory tracking of UAVs", Aircraft Engineering and Aerospace Technology: An International Journal. 86 (3), 198 – 206, 2014.

[5] Hadi, G., Varianto, R., Trilaksono, B., and Budiyono, A. 2014. Autonomous UAV System Development for Payload Dropping Mission. Journal of Instrumentation, Automation and Systems. 1(2), 72-77.

[6] Grigoriadis, K. M., Carpenter, M. J. Zhu, G., and Skelton, R. E. 1993. Optimal Redesign of Linear Systems. Paper presented at Proceedings of the American Control Conference, San Francisco, CA.

[7] Grigoriadis, K. M., Zhu, G., and Skelton, R. E. 1996. Optimal Redesign of Linear Systems. Journal of Dynamic Systems, Measurement and Control. 118 (3), 598–605.

[8] Nelson, R. C. 2007. Flight Stability and Automatic Control. 2nd ed., McGraw-Hill, New York, chapters 2-6.

[9] Zagi-The original R/C EPP foam wing homepage (2015), http//:www.zagi.com.

[10] Vural, S. Y. and Hajiyev, C. 2008. Autopilot system design for a small unmanned aerial vehicle. MS thesis, Istanbul Technical University, Istanbul, Turkey.

[11] Vural, S. Y. and Hajiyev, C. 2013. LQR controller with Kalman estimator applied to UAV longitudinal dynamics. Scientific Research Journal. 4, 36-41.

[12] Chao, H., Cao, Y., and Chen, Y. Q. 2007. Autopilots for Small Fixed-Wing Unmanned Aerial Vehicles: A Survey. Paper presented at IEEE International Conference on Mechatronics and Automation, Harbin, China.

[13] Jang, J. S., Liccardo, D. 2006. Automation of small UAVs using a low cost mems sensor and embedded computing platform.

[14] Sultan, C. 2010. Proportional damping approximation using the energy gain and simultaneous perturbation stochastic approximation. Mechanical Systems and Signal Processing. 24, 2210-2224.

[15] Oktay, T. 2012. Constrained control of complex helicopter models. PhD Dissertation, Virginia Tech.

[16] Oktay, T. and Sultan, C. (2013), "Simultaneous helicopter and control-system design," Journal of Aircraft, Vol. 50, No. 3, pp. 32-47.

[17] Sadegh, P. and Spall, J. C. (1998), "Optimal random perturbations for multivariable stochastic approximation using a simultaneous perturbation gradient approximation", IEEE Transactions on Automatic Control, 43(10), pp. 1480-1484.

[18] U.S. Military Handbook MIL-HDBK-1797, 19 December 1997.

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