JAST, 2018;11(2):1-7

AIR FUEL RATIO CONTROL USING DELAY RESISTANT CLOSED LOOP REFERENCE MODEL ADAPTIVE CONTROL

Yıldıray YILDIZ

Department of Mechanical Engineering,
Bilkent University, 06800 Ankara, Türkiye,
yyildiz@bilkent.edu.tr

Received: *07th March 2018* ***Accepted:*** *27th April 2018*

ABSTRACT

The focus of this paper is the air fuel ratio control of spark ignited engines. It is known that for an efficient removal of the pollutants from the exhaust gases, air fuel ratio has to be kept within a narrow band around the stoicometric ratio, which represents the condition where the air amount is perfectly matched with the fuel amount for a complete burn. The main challenges for this control problem are the inherent time delay of the system and uncertain dynamics. In this paper, employment of a high performance adaptive controller, which explicitly compensates for the delays without causing excessive oscillations, is proposed. The performance of this controller is demonstrated via simulation studies. To emphasize the importance of delay compensation, the controller is compared with the closed loop model reference adaptive controller, which do not have explicit delay compensation.

Keywords: *Air Fuel Ratio Control, Adaptive Control, Time Delays, Closed Loop Reference Models.*

İÇTEN YANMALI MOTORLARDA HAVA YAKIT ORANININ ZAMAN GECİKMELERİNE DAYANIKLI KAPALI DÖNGÜ REFERANS MODELLİ UYARLAMALI KONTROLÜ

ÖZET

Bu makalenin konusu buji ateşlemeli içten yanmalı motorların hava yakıt karışımı kontrolüdür. Egzoz gazlarındaki çevre kirliliğine sebep olan maddelerin verimli bir şekilde temizlenebilmesi için hava yakıt karışımının tam yanmanın sağlanacağı seviyelerin çok dar bir bandında tutulması gerektiği bilinmektedir. Bu kontrol problemini zorlaştıran iki ana etken sistemdeki zaman gecikmeleri ve belirsiz dinamiklerdir. Bu makalede bu problemin çözümü için yüksek performanslı ve zaman gecikmelerini telafi eden, telafi ederken de aşırı salınımlara sebep olmayan bir uyarlamalı kontrolcü kullanılması önerilmektedir. Bu kontrolcünün performansı simülasyon çalışmaları ile gösterilmiştir.

Anahtar Kelimeler: *Hava Yakıt Karışımı Kontrolü, Uyarlamalı Kontrol, Zaman Gecikmeleri, Kapalı Çevrim Referans Modelleri.*

1. INTRODUCTION

Controlling the air fuel ratio (AFR) of internal combustion engines is important to keep the pollutants in reasonable levels and to provide a comfortable ride. It is known that the efficiency of pollutant removal makes a peak for a stoicometric AFR, which represents a perfect matching of air and fuel amounts for a complete burn, and drops quickly outside a narrow region around this burn ratio. There exist several methods proposed in the literature, both linear and nonlinear, to obtain a satisfactory AFR control [1-10]. The importance of a careful AFR control is emphasized in [11].

Two of the main challenges that make the task of a precise AFR control difficult are 1) time varying delays and 2) uncertainties. Time delays are a result of the time required for the combustion process to be completed and the time required for the exhaust gases to reach the exhaust gas oxygen sensor. These delays depend on the engine speed and therefore they are time-varying. Uncertainties are originating due to uncertain wall wetting dynamics, degradation of moving parts and the estimation errors occurring, for example, in the estimation of the air amount entering the engine. The major disturbance source is the purging of the fuel accumulated in the carbon canister that is used for storing the fuel gas evaporating from the fuel tank.

In this study, a high performance adaptive controller designed for explicit compensation of time delays is proposed to be employed for AFR control. The controller merges the advantages of the previously proposed “Adaptive Posicast Controller” (APC)[12], which is designed for uncertain plants with time delays, and the “Closed-loop Reference Model (CRM) Adaptive Controller” [13], which is proposed as a high performance adaptive controller. The main working principle of the APC is predicting the future behavior of uncertain dynamics and using these predictions in the feedback loop, which eliminates the effect of time delays. CRM adaptive controller, on the other hand, uses the tracking error in its reference model which helps to damp undesired oscillations due to high controller gains. APC is previously employed for AFR and idle speed control problems [14]-[16]. In this work, a high performance adaptive controller designed by combining these two controllers is utilized for the control of AFR. To emphasize the importance of explicit time delay compensation, the results are compared with the case where CRM adaptive controller is used for the control problem. The adaptive controller exploited in this work is used by author earlier for the gas generator pressure control problem [17]. In this work, this controller will be utilized for AFR control.

The organization of the paper is as follows: The plant model is introduced in Section 2. Controller design is presented in Section 3. The simulation results are provided in Section 4 and the Conclusion is given in Section 5.

PLANT MODEL

Air Fuel Ratio (AFR) open loop plant block diagram is given in Fig. 1. In this plant, the input is the injected fuel and the output is the AFR measurement. The amount of air that is mixed with the fuel is represented by “A”. After the fuel is injected, it passes through the wall wetting dynamics and after a division by the amount of air, AFR is formed. The measurement, however, is obtained after the time delays and universal exhaust-gas oxygen (UEGO) sensor dynamics.

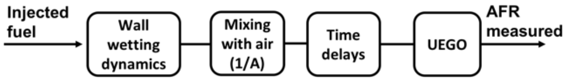

Figure 1. AFR open loop plant block diagram.

The transfer functions used to obtain the model described above is given below:

1.1. Wall Wetting Dynamics

The transfer function for wall wetting dynamics is given as

$$DI(s) = \frac{1+(1-X)as}{as+1} \tag{1}$$

where X is the amount of injected fuel that sticks to the wall and $\boldsymbol{a}$ is the time constant of fuel evaporation from the wall. According to this dynamics, when the fuel is injected, some of it evaporates immediately while the rest sticks to the wall and then evaporates from the wall in time [1].

1.2. UEGO Sensor Dynamics and Time Delays

Sensor dynamics consists of a first order transfer function and a time delay in series to this transfer function:

$$UE(s) = \frac{K}{bs+1} e^{cs}, \tag{2}$$

where, K is a constant, b is the sensor time constant and c is the time-delay.

1.3. Model Used for Controller Design

To simplify the controller design, AFR control system's plant model can be approximated to a first order transfer function with a unity gain and a time delay in series:

$$G(s) = \frac{1}{ds+1} e^{zs}, \tag{3}$$

where d is the time constant of the plant and z is the total time delay. The model provided in (3) is used only for the controller design. For the simulations, the plant model described in detail in sections 2.1 and 2.2. is used.

2. CONTROLLER DESIGN

In this section, delay resistant closed loop reference model adaptive controller is explained. First, the two control approaches, Adaptive Posicast Controller (APC) and Closed Loop Reference Model (CRM) adaptive controller, that are used to obtain the delay resistant controller is explained. The details of the stability proof of APC are provided in [12].

2.1. Adaptive Posicast Controller (APC)

APC is a controller developed for time delay systems with parametric uncertainties [12]. The dynamics of the target system for this controller is given as

$$\begin{aligned} y(t) &= G_p(s)u(t-\tau), \\ G_p(s) &= \frac{k_p N_p(s)}{D_p(s)}, \end{aligned} \tag{4}$$

where y, u and τ represents the output of the plant, input to the plant and the input time delay, respectively. $G_p(s)$ is a transfer function with stable zeros but not necessarily stable poles. It is assumed that the relative degree of this plant is equal to or smaller than 2. It is assumed that the value of the time delay and the sign of the transfer function gain k_p are known. The locations of the poles and zeros, however, can be unknown. The reference model to be followed is given as

$$y_m(t) = G_m(s)r(t-\tau), \quad G_m(s) = \frac{k_m}{D_m(s)}, \tag{5}$$

where r and k_m are the reference trajectory and reference model gain, respectively. $D_m(s)$, on the other hand, is designed by the control engineer to specify the desired dynamics for the plant. The degree of $D_m(s)$, should be the same as $G_p(s)$ in (4). State space description of the AFR system is given as

$$\begin{aligned} &\dot{x}(t) = Ax(t) + bu(t-\tau), \quad y(t) = h^T x(t), \\ &\dot{\omega}_1(t) = \Lambda\omega_1(t) + lu(t-\tau), \\ &\dot{\omega}_2(t) = \Lambda\omega_2(t) + ly(t), \end{aligned} \tag{6}$$

where A and Λ are $n \times n$ matrices. (Λ, b) is also assumed to be a controllable pair.

The controller to be used is given as [12]:

$$\begin{aligned} u(t) = {} & a_1^T(t)\omega_1(t) + a_2^T(t)\omega_2(t) \\ & + \int_{-\tau}^{0} \rho(t,\sigma)u(t+\sigma)d\sigma + k(t)r(t), \end{aligned}$$

$$\theta \equiv [a_1 a_2 \ \ k]^T, \quad S \equiv [\omega_1 \omega_2 \ \ r]^T, \quad e_t = y - y_m$$

$$\dot{\theta}(t) = -\Psi e_t S(t-\tau),$$

$$\frac{\partial\lambda(t,\sigma)}{\partial t} = -\psi(\sigma) e_t \mathrm{u}(t+\sigma-\tau), \tag{7}$$

where $\Psi \in R^{(2n+1)x(2n+1)}$ is the adaptation rate matrix and the scalar $\psi(\sigma)$ is also representing the adaptation rate. It can be shown [12] that this controller stabilizes the plant (6).

2.2. Delay Resistant Closed Loop Reference Model Adaptive Controller

The main difference between the APC and the delay resistant closed loop reference model adaptive controller is that in the latter one, the reference model (5) is modified to include the tracking error($e = y - y_m$) as feedback. State space representation of the modified reference model is given as:

$$\begin{aligned} \dot{x}_m(t) = {} & A_m x_m(t) + b_m r(t-\tau) + L(y_p(t) \\ & - y_m(t)) \\ y_m(t) = {} & h_m^T x_m(t), \end{aligned} \tag{8}$$

where $x_m \in R^n, y_m \in R, A_m \in R^{nxn}$ and b_m, L, $h_m \in R^n$. The reference model equations can also be given as

$$y_m(t) = G_m(s)r(t-\tau) + G_L(s)e_1(t) \tag{9}$$

where $e_1 = y - y_m$ is the tracking error between the plant output and the reference model output. The transfer functions used in (9) can be defined as

$$G_m(s) \equiv h_m^T(sI - A_m)^{-1}b_m = k_m \frac{Z_m(s)}{R_m(s)},$$
$$G_L(s) \equiv h_m^T(sI - A_m)^{-1}L = k_L \frac{Z_L(s)}{R_m(s)}, \tag{10}$$

where $R_m(s)$ is a monic polynomial with degree n, and $Z_m(s)$ and $Z_L(s)$ are monic polynomials of degree $n-1$. k_m and k_L are the real gains of the transfer functions. It can be shown that the closed loop system is stable with the controller (7) controlling the plant (4), where the reference model is given in (8), if the variable L in (8) is selected such that the following transfer function is strictly positive real [17]

$$G_e(s) = \frac{Z_m(s)}{R_m(s) - k_L Z_L(s)} \tag{11}$$

3. SIMULATION RESULTS

In this section, the performance of the delay resistant closed loop reference model adaptive control is demonstrated in the simulation environment. To emphasize the value of explicit delay compensation, the proposed controller is compared with the closed loop reference model adaptive controller without delay compensation.

The parameter values used in the simulation study are provided in Table 1. These values are used to simulate sensor and wall-wetting dynamics given in (1) and (2), respectively. The amount of air A introduced for mixing (see Fig. 1) is also given in the table.

Table 1. Numerical values of plant parameters.

a	X	A	K	b	c
1	0.3	0.4	1	1	0.3

When there is a perfect match between the air and fuel amounts during burning, this fuel/air ratio is called the stoichiometric ratio and corresponds to 0.068 (Correspondingly, air/fuel stoichiometric ratio is14.7.) Fuel/air ratio normalized by the stoichiometric value is called the equivalence ratio. In this section, we use the *deviations* from the equivalence ratio in the simulation results and we will use the symbol Φ to represent this deviation. For example, when the equivalence ratio is 1.1, we will use $\Phi = 0.1$.

Figure 2 presents the performance of a well-tuned delay resistant closed loop reference model adaptive controller. The performance is not surprising since the controller is tuned according to known dynamics. When the delay compensating part of the controller is omitted, and hence a closed loop reference model controller is obtained, the performance drop can be observed in Fig. 3. In Fig. 4, the performance of the delay resistant controller is seen when the delay in the system is increased 20% and the time constant of the wall-wetting dynamics is decreased by 10%. As demonstrated in the figure, the performance of the delay resistant controller is not considerably affected after the introduction of these uncertainties. In Fig. 5, the performance of the controller is shown when the delay compensation is omitted, using the same plant uncertainties, where it is seen that the performance drops dramatically. To test the limits of the delay resistant controller, we increased the delay value by 100% while keeping the 10% wall-wetting dynamics time-constant uncertainty and the results are presented in Fig. 6. It is seen that even after a large uncertainty is introduced, the delay resistant controller can still provide a reasonable tracking performance. It is noted that in these figures, the feedback control signal variation represents the deviation of the control signal from the stoicometric ratio conditions.

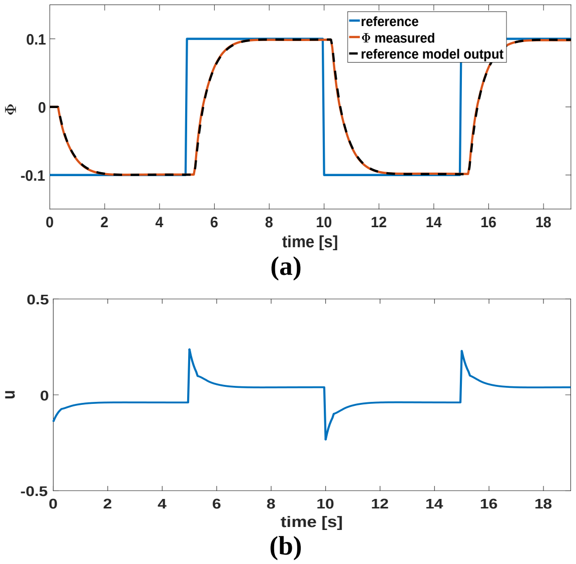

Figure 2. (a) Delay resistant closed loop reference model controller performance – tuned for known dynamics, **(b)** Feedback control signal variation.

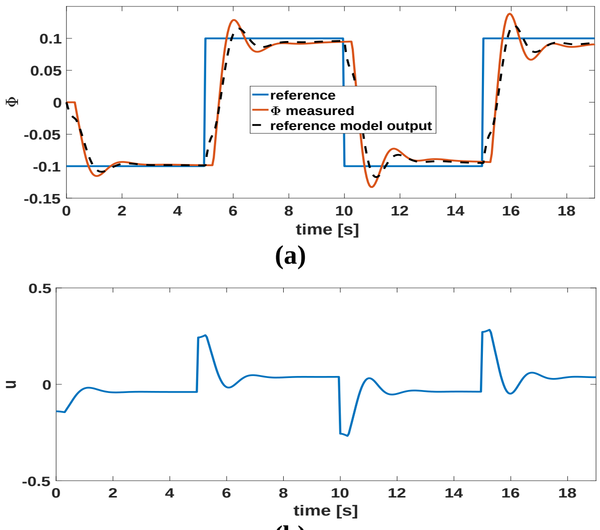

Figure 3. (a) The performance of the closed loop reference model adaptive controller that is obtained by omitting delay compensation part of the well-tuned delay resistant controller, **(b)** Feedback control signal variation.

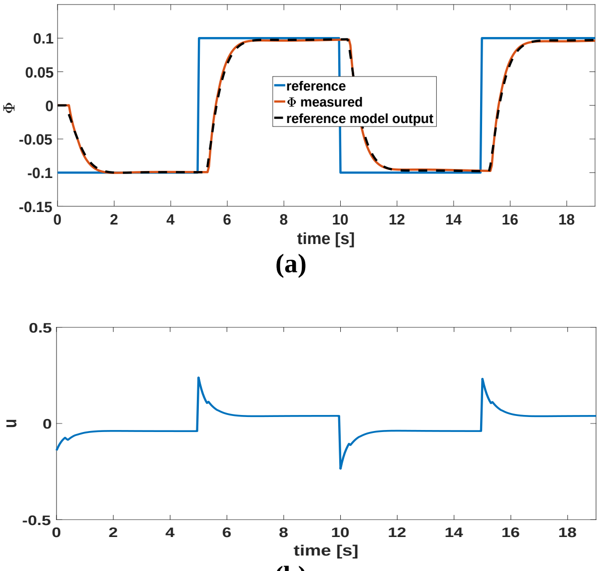

Figure 4. (a) Delay resistant closed loop reference model controller performance when the uncertainty introduced to the plant dynamics are 1) 20% delay uncertainty and 2) 10% wall-wetting time constant uncertainty, **(b)** Feedback control signal variation.

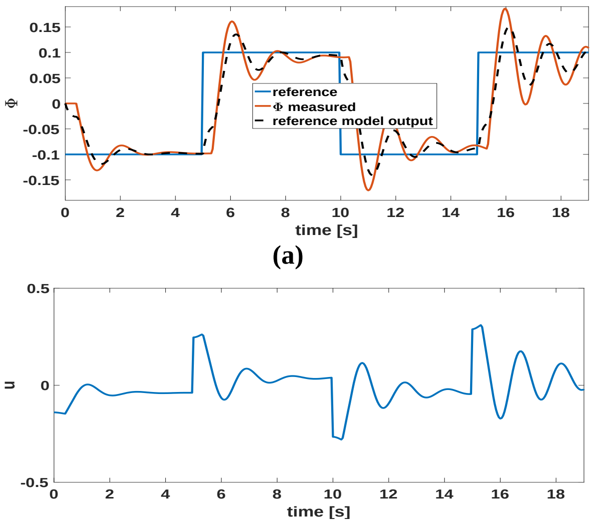

Figure 5. (a) The performance of the closed loop reference model adaptive controller that is obtained by omitting delay compensation part of the well-tuned delay resistant controller, with uncertain plant dynamics in the loop, **(b)** Feedback control signal variation.

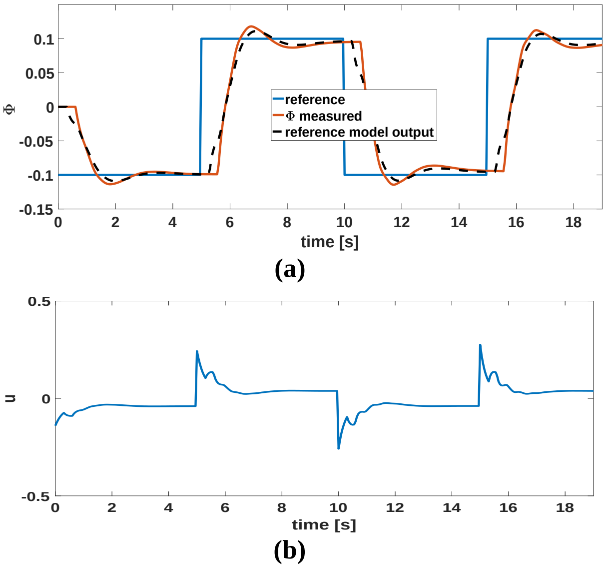

Figure 6. (a) Delay resistant closed loop reference model controller performance when the uncertainty introduced to the plant dynamics are 1) 100% delay uncertainty and 2) 10% wall-wetting time constant uncertainty, **(b)** Feedback control signal variation.

4. CONCLUSIONS

In this study, an implementation of the delay resistant closed loop reference model adaptive controller for air fuel ratio control is presented. This controller merges the advantages of the adaptive posicast controller that the author developed earlier and a recently developed closed loop reference model adaptive controller. The adaptive posicast controller introduces delay compensation for uncertain plants and closed loop reference model adaptive controller enables performance improvement via higher adaptation rates without introducing undesired oscillations. To emphasize the importance of delay compensation, the exploited controller is compared with a closed loop reference model adaptive controller, which does not have delay compensation, in the simulation environment. The simulation results demonstrate that the delay resistant controller can provide a reasonable tracking performance even after a large uncertainty is introduced in plant dynamics, but the performance drops dramatically once the delay compensation part is removed.

5. REFERENCES

[1] Guzzella, L. ve Onder, C. H. “Introduction to modeling and control of internal combustion enginesystems,” *Springer-Verlag*, Berlin Heidelberg, 2010.

[2] Onder, C. H. ve Geering, H. P. “Model-based multivariable speed and air-to-fuel ratio control of an SI engine,” *SAE*, No 930859, 1993.

[3] Powell, J. D., Fekete, N. P. ve Chang, C. F., “Observer-based air–fuel ratio control,” *IEEE Control Systems Magazine*, Cilt 18, No 5, 72–83, 1998.

[4] Rupp, D., Onder, C., ve Guzzella, L., “Iterative adaptive air/fuel ratio control,” *Advances in automotive control*, Seascape Resort, USA, 2008.

[5] Zhang, F., Grigoriadis, K., Franchek, M., ve Makki, I., “Linear parameter varying lean burn air–fuel ratio control for a spark ignition engine,” *Journal of Dynamic Systems, Measurement, and Control*, Cilt 129, No 4, 404–414, 2007.

[6] Sharma, N., Bhasin, S., Wang, Q., ve Dixon, W. E., “Predictor-based control for an uncertain Euler–Lagrange system with input delay,” *Automatica*, Cilt 47, No 11, 2332-2342, 2011.

[7] Ebrahimi, B., Tafreshi, R., Masudi, H., Franchek, M., Mohammadpour, J., ve Grigoriadis, K., “A parameter-varying filtered PID strategy for air–fuel ratio control of spark ignition engines,” *Control Engineering Practice*, Cilt 20, No 8, 805-815, 2012.

[8] Tafreshi, R., Ebrahimi, B., Mohammadpour, J., Franchek, M. A., Grigoriadis, K., ve Masudi, H., “Linear dynamic parameter-varying sliding manifold for air–fuel ratio control in lean-burn engines,” *IET Control Theory & Applications*, Cilt 7, No 10, 1319-1329, 2013.

[9] Ebrahimi, B., Tafreshi, R., Mohammadpour, J., Franchek, M., Grigoriadis, K., ve Masudi, H., “Second-order sliding mode strategy for air–fuel ratio control of lean-burn SI engines,” *IEEE Transactions on Control Systems Technology*, Cilt 22, No 4, 1374-1384, 2014.

[10] Ashok, B., Ashok, S. D., ve Kumar, C. R., “A review on control system architecture of a SI engine management system,” *Annual Reviews in Control*, Cilt 41, 94-118, 2016.

[11] Gürbüz H., Akçay, İ. H., Öz, A., “İçten Yanmalı Motorlarda Çalışma Nokta Metodu ile Yanma Kontrolü,” *Electronic Journal of Vehicle Technologies*, Cilt 1, No. 2, 31-49, 2009.

[12] Yildiz, Y., Annaswamy, A., Kolmanovsky, I. V., ve Yanakiev, D., “Adaptive posicast controller for time-delay systems with relative degree $n* \leq 2$,” *Automatica*, Cilt. 46, No. 2, 279-289, 2010.

[13] Gibson, T., Annaswamy, A. ve Lavretsky, E., “On Adaptive Control with Closed-Loop Reference Models: Transients, Oscillations, and Peaking,” *IEEE Access*, Cilt. 1, pp. 709-717, 2013.

[14] Yildiz, Y., Annaswamy, A. M., Yanakiev, D., ve Kolmanovsky, I., “Spark ignition engine fuel-to-air ratio control: An adaptive control approach,” *Control Engineering Practice*, Cilt. 18, No 12, 1369-1378, 2010.

[15] Yildiz, Y., Annaswamy, A. M., Yanakiev, D., ve Kolmanovsky, I., “Spark-ignition-engine idle speed control: An adaptive control approach,” *IEEE Transactions on Control Systems Technology*, Cilt. 19, No 5, 990-1002, 2011.

[16] Yildiz, Y., Annaswamy, A., Yanakiev, D. ve Kolmanovsky, I., “Automotive powertrain control problems involving time delay: An adaptive control approach,” *ASME Dynamic Systems and Control Conference*, Ann Arbor, Michigan, 2008.

[17] Alan, A., Yildiz, Y. ve Poyraz, Ü, "Adaptive Pressure Control for Use in Variable-Thrust Rocket Development," arXiv preprint arXiv:1705.01849, 2017.

VITAE

Assistant Professor Yildiray Yildiz received his B.S., M.S and PhD degrees in Mechanical Engineering from the Middle East Technical University in 2002, in Mechatronics from Sabanci University in 2004 and in Mechanical Engineering with a Mathematics minor from Massachusetts Institute of Technology in 2009, respectively. He worked as a postdoctoral scholar from 2009 to 2010 and as an Associate Scientist from 2010 to 2014 at NASA Ames Research Center, employed by the University of California. He joined Bilkent University in 2014 as an Assistant Professor and has been directing Bilkent Systems Laboratory since then. His research interests are system dynamics and controls, human-machine interactions and applications in automotive, aerospace and robotic systems.