Springer

KSME

Journal of Mechanical Science and Technology 25 (2) (2011) 523~536
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-010-1227-1

Verification of intelligent control of a launch vehicle with HILS †

M. Rezaei Darestani[1,*], M. Zareh[1], J.Roshanian[1] and A. Khaki Sedigh[2]

[1]*Department of Aerospace Engineering, K.N.Toosi University of Technology, Tehran, Iran*
[2]*Department of Electrical and Computer Engineering, K.N.Toosi University of Technology, Tehran, Iran*

(Manuscript Received January 20, 2010; Revised August 7, 2010; Accepted November 11, 2010)

Abstract

The reliability of an intelligent self tuning controller called the brain emotional learning based intelligent controller (BELBIC) to attitude control of a nonlinear launch vehicle (LV) simulation with hardware-in-the loop simulation (HILS) is studied. To set up the HIL system of the LV a six-degree of freedom simulation of the LV and a hydraulic actuator, which was used for the pitch channel thrust vector control (TVC) actuator of the LV, is performed. The results of the BELBIC controller with a fuzzy controller (FC) and a PID controller in this HILS of the LV to control the pitch channel of the LV have been compared.

Keywords: BELBIC; Hardware-in-the loop; Hydraulic actuator; Launch vehicle simulation

1. Introduction

The aim of this research is to make a smooth tracking of the ideal trajectory of an LV in the HILS flight. This process may not occur exactly in absence of a good controller. Here, this aim is proven with the use of an intelligent controller, the BELBIC controller, which is developed in a semi real flight of LV, HIL system. In this HIL system a hydraulic actuator is replaced with the LV pitch actuator model in the simulation. First, in the previous study the actuator model was identified [1]. Both the identified model of actuator and real actuator were controlled with a PID controller and an FC initially [2]. To specify actuator characteristics and ability, to grant all of the requirement responses of controller, comparison shows that the HIL idea works but the requirements of the HIL simulation hardware are demanding. For the case of having a good control on the LV desired attitude trajectory, use of an intelligent controller which can tune itself has much more important. The reason for using the BELBIC controller is that the proposed controllers for this system–gain scheduled PID and the FC controllers–have not the ability of self tuning and only have reasonable responses for special flight condition and bound of error. After use of these two controllers, the use of intelligent controller led us to a reasonable tracking of the desired trajectory with allowable range of nozzle deflection. Here it must be noted that the greatest advantage of the intelligent controller is that the nonlinear model of LV without any tuning difficulty of its controller gains can be guide through the desired path.

Motivated by the success in functional modeling of emotions in control engineering applications [3], the goal of this paper is to use a structural model based on the limbic system of the mammalian brain, to make a decision to control an engineering process. We have adopted a network model developed by Moren and Balkenius as a computational model that mimics the amygdala, orbitofrontal cortex, thalamus, sensory input cortex and, generally, those parts of the brain thought to be responsible for processing emotions. There are two approaches to intelligent and cognitive control: direct and indirect. In the indirect approach, the intelligent system is utilized for tuning the parameters of the controller. Here the intelligent system, the computational model termed BELBIC, is used as the controller block. The model of the proposed BELBIC structure is illustrated in Fig. (4). The BELBIC technique is essentially an action generation mechanism based on sensory inputs and emotional cues. In general, these can be vector valued, although in the benchmarks discussed in this paper for the sake of illustration, one sensory input and one emotional signal have been considered. In this case study much research has been done, which is mentioned as the following studies.

In Ref. [4] a new intelligent control approach for path tracking and collision control of a vehicle used in automated highway systems has been studied, which a modified BELBIC controller has been applied to a sixth order model of the vehicle. In Ref. [5] an algorithm for controlling first- and second-order linear systems using the brain emotional learning based

---

† This paper was recommended for publication in revised form by Associate Editor Hyoun Jin Kim

[*] Corresponding author. Tel.: +98 939 856 7602, Fax.: +9821 77791035
E-mail address: m.rezaei.d@gmail.com

intelligent controller (BELBIC) has been proposed. The algorithm proved to be able of globally asymptotically stabilizing the linear systems based on Lyapunov theorem. In Ref. [6] the particle swarm optimization algorithm is applied to design an optimum intelligent controller based on brain emotional learning. The BELBIC controller is tuned to improve the time domain parameters such as percent overshoot, steady state error, settling time and rise time of the step response of an automatic voltage regulator. In Ref. [7] intelligent control of home appliances attracted much theoretical attention, as well as becoming a major factor for industrial and economic success and rapid market penetration. In this paper, the use of two techniques which have successfully been used in other intelligent modeling and control applications is mentioned. First, the use of a neurofuzzy locally linear model system for data driven modeling of the machine and second, the use of a neural computing technique, based on a mathematical model of amygdala and the limbic system, for emotional control of the washing machine are studied. In Ref. [8] a modern intelligent control based on computational model of mammalian limbic system and emotional processes (BELBIC) for speed control of interior magnet synchronous motor (IPMSM) is presented. In this work, a novel and simple model of IPMSM motor drive control plant is achieved by using the intelligent control system, which controls motor speed accurately quite independent of motor parameters. Achieved results of the proposed plant show better operating control than the previous plant. In Ref. [9] a modern intelligent control based on a computational model of the mammalian limbic system and emotional process is developed for speed and flux control of induction motor simultaneously. In this work, a novel and simple model of induction motor driven control plant is achieved by using the intelligent control system, which controls motor speed and flux accurately, without needing to use any conventional controllers and also, quite independent of motor parameters. In Ref. [10] a theoretical analysis of on-line autonomous intelligent adaptive tracking controller based on emotional learning model in the mammalians brain (BELBIC) for aerospace launch vehicle is presented. The algorithm is very robust and fast in adaptation to dynamical change in the plant, due to its on-line learning ability. In Ref. [11] an intelligent controller is applied to govern the dynamics of an electrically heated micro-heat exchanger plant. First, the dynamics of the micro-heat exchanger, which acts as a nonlinear plant, is identified using a neurofuzzy network. The brain emotional learning based intelligent controller (BELBIC) based on PID control is adopted for the micro-heat exchanger plant. The contribution of BELBIC in improving the control system performance was shown by comparison with results obtained from a classic PID controller without BELBIC. In Ref. [12] BELBIC, which is based on the mammalian middle brain, is designed and implemented on FPGA and the obtained embedded emotional controller (E-BELBIC) is utilized for controlling a real laboratorial overhead traveling crane in model-free and embedded manner. Short time-to-market, easy testing and error handling, separating concerns, improving reusability and extendibility of the obtained models in similar applications are some benefits of the model driven development methodology. In Ref. [13] the design and evaluation of a novel approach to reactor core power control based on emotional learning is described. The controller includes a neurofuzzy system with power error and its derivative as inputs. A fuzzy critic evaluates the present situation, and provides the emotional signal. The controller modifies its characteristics so that the critic's stress is reduced. Simulation results show that the controller has good convergence and performance robustness characteristics over a wide range of operational parameters.

Now, as regard to the last studies, the following section of this paper is as follows to describe verification of intelligent control of a launch vehicle with HILS. First, the equation of motion of the LV is defined. Second, the BELBIC controller and its application in simulation are compared with the PID and Fuzzy controller. Third, the HIL system and its component are introduced. Then, PID, fuzzy and BELBIC controller performance are implemented and compared in the HILS setup. Finally, the performance of the FC and BELBIC controller setup in HILS is verified in the presence of severe atmospheric disturbance.

2. Equation of motion of the launch vehicle

2.1 Force and moment

To expedite this study the six-degree of freedom nonlinear equation of motion of the LV must be solved. Appendix 1 shows the initial conditions used to set up the LV configuration. All equations consist of three force equations and three moment equations:

$$F = F_a + F_p + F_g \tag{1}$$

$$M = M_a + M_p \, . \tag{2}$$

2.2 Velocity & angular velocity

Space launch vehicle moving equations of motion are usually simulated with a linear model of the non-linear equation of motion. The force and moment inserted to the LV is composed of Eqs. (1) and (2) which were used in the equation of motion of the LV. This model describes a reasonably realistic LV thrust vector control (TVC) airframe. The aerodynamic forces from missile datcom (MD) and environmental parameter from the International Standard Atmosphere (ISA) has been generated. The gravitational acceleration is also determined from a spherical model of the earth. The base point for the mathematical description of the LV is the following 6-DoF non-linear equations, which finally results in the entire relative (u, v, w) and angular (p, q, r) velocities of LV that completely describe the behavior of a rigid body in space, as shown in Fig. 1 [14-16]:

$$\dot{P}=QR[(I_y-I_Z)/I_x]+(L/I_x) \tag{3}$$

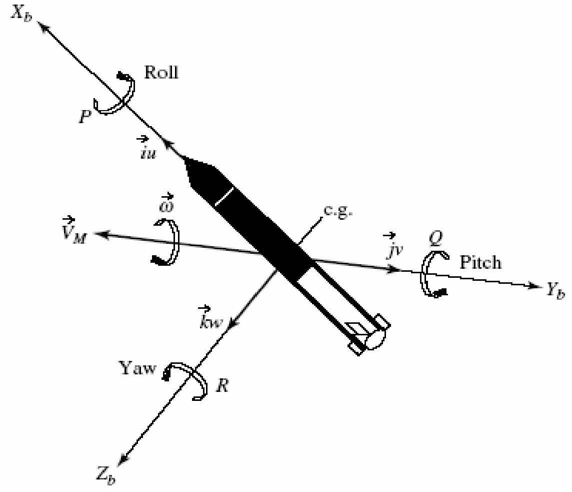


Fig. 1. Launch vehicle system of axis.

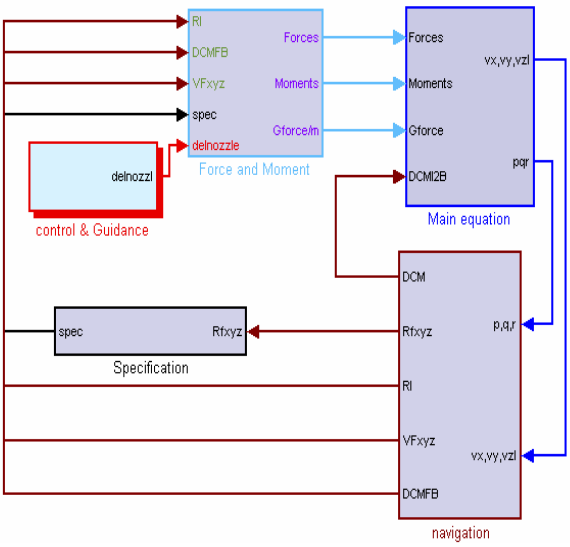


Fig. 2. 6DoF simulation of LV in Simulink.

$$\dot{Q}=PR[(I_z-I_x)/I_y]+(M/I_y) \tag{4}$$

$$\dot{R}=PQ[(I_x-I_y)/I_z]+(N/I_z) \tag{5}$$

$$\dot{u}=F_x/m+(vR-wQ) \tag{6}$$

$$\dot{v}=F_y/m+(wP-uR) \tag{7}$$

$$\dot{w}=F_z/m+(uQ-vP) \tag{8}$$

These coupled equations can be solved using numerical integration techniques which results in the angular and relative velocity of the LV in the body frame.

After transferring the angular and relative accelerations which are derived from the force and moment equations in the body axis system to the inertial axis system, the velocities u,v,w and displacement x,y,z and Euler angles φ,ϑ,ψ of the LV have been derived. These parameters have been used in the calculation of the instantaneous position of the flying vehicle in relation to its reference frame of flight. Till this step the 6 DoF equations of motion of the LV have been derived. These parameters form an open loop flight model system.

This simulation model is developed in Simulink environment which consists of five blocks as sketched in Fig. 2. These blocks perform the simulation of the LV with above-mentioned equations. In the first block the force and moment exerted on the body are determined. In the second block with solution of Eq. (3) to Eq. (8), the body acceleration in the inertial axes has been calculated. In the third block with the help of determined instantaneous relative and angular velocity of the LV the transfer matrixes which can determine the position of the LV are determined. In fourth block the local characteristics of atmosphere are determined. And finally in the last block the instantaneous position of the LV is controlled till it has a desirable tracking of the ideal trajectory. All of these processes have been done to simulate the motion of the LV in semi real simulation of flight.

Because of the inherited instability of the LV (X_{cg} lower than X_{cp}), it does not have ability to follow the desired trajectory. Here to bring into account the need of controlling the LV, a control system must be developed which has been expanded in the control and guidance block of the simulation.

3. Brain emotional learning based intelligent controller

BELBIC as a successful method in functional modeling of emotions in control engineering applications motivated us to use it in this research as a structural model based on the limbic system of the mammalian brain for decision making and control in a semi-real flight of the LV. In this structure a network model has been adopted as a computational model that mimics the amygdala, orbitofrontal cortex, thalamus, sensory input cortex and, generally, those parts of the brain thought responsible for processing emotions. There are two approaches for intelligent and cognitive control: direct and indirect. In the indirect approach, the intelligent system is used for tuning the parameters of the controller, while in the direct approach the intelligent system itself functions as the controller. This approach was proposed by Lucas as the utilizations of the direct BELBIC. Here the BELBIC controller has been used for tuning an existing classic controller, i.e., a PID controller. So, the basic performance of the system is determined by the choice of the controller block in an ideal situation, and BELBIC is responsible for tuning the parameters of the controller and, generally, to improve its performance. Excellent performance at the expense of more reasonable levels of control effort has thus been achieved, which is illustrated in Fig. 4. BELBIC is essentially an action generation mechanism based on sensory inputs and emotional cues. Obviously, these can be vector valued; one sensory input and one emotional signal have been considered. The emotional learning occurs mainly in the amygdala. The learning rule of amygdala is given in Eq. (9) [17, 18]:

$$\Delta B_a=k_1.\max(0,EC-A) \tag{9}$$

$$B_a = B_a + \Delta B_a \tag{10}$$

where B_a is the gain in amygdala connection, k_1 is the learning rate in the amygdala and *EC* and *A* are the values of emotional cue function and amygdala output at each time. The term max in the Eq. (9) is to make the learning changes monotonic, implying that the amygdala gain can never be decreased as it is modeled to occur in a biological process in the amygdala. This rule is for modeling the incapability of unlearning the emotional signal (and consequently, emotional action), which was previously learned in the amygdala. Similarly, the learning rule in the orbitofrontal cortex is as follows:

$$\Delta B_0 = k_2.(MO-EC) \tag{11}$$

$$B_0 = B_0 + \Delta B_0\ . \tag{12}$$

This model has been completely based on the original biological process. In the above equation, B_o is the gain in orbitofrontal connection, k_2 is the learning rate in orbitofrontal cortex and *MO* is the output of the entire model, where it can be calculated as the following equation:

$$MO = A - O \tag{13}$$

where *O* represents the output of the orbitofrontal cortex. In fact, by receiving the sensory input (*SI*), the model calculates the internal signals of amygdala and orbitofrontal cortex by the relations in (9) and (10) and eventually yields the output:

$$A = B_a.SI \tag{14}$$

$$O = B_0.SI\ . \tag{15}$$

As the amygdala does not have the capability to unlearn any emotional decision that it has ever learned, inhibition of any inappropriate decision is the duty of the orbitofrontal cortex. Here must noted that k_1 and k_2 may have varying characteristics during the control process. As a logical improvement these values can decrease gradually when the system performance approaches to its steady state situation. For instance, k_1 and k_2 may reduced by the factor of time sample squared. Controllers based on emotional learning have shown very good robustness and uncertainty handling properties, while being simple and easily implementable. To utilize the proposed version of the Moren–Balkenius model as a controller, it should be mentioned that it essentially converts two sets of inputs (sensory input and emotional cue) into the decision signal as its output. A closed loop configuration using this block, BELBIC controller, in the feed forward loop of the total system in an appropriate manner has been implemented. The block implicitly implemented the critic, the learning algorithm and the action selection mechanism used in functional implementations of emotionally based controllers instantaneously. The structure of the control circuit which has been implemented in this study is illustrated in Fig. (4). The implemented functions in emotional cue and sensory input blocks are given in Eqs. (14) and (15):

$$EC = |MO|.(-W_1.\dot{e}.e + W_2.|e|) \tag{16}$$

$$SI = W_3.e + W_4.\dot{e} + W_5.\int edt \tag{17}$$

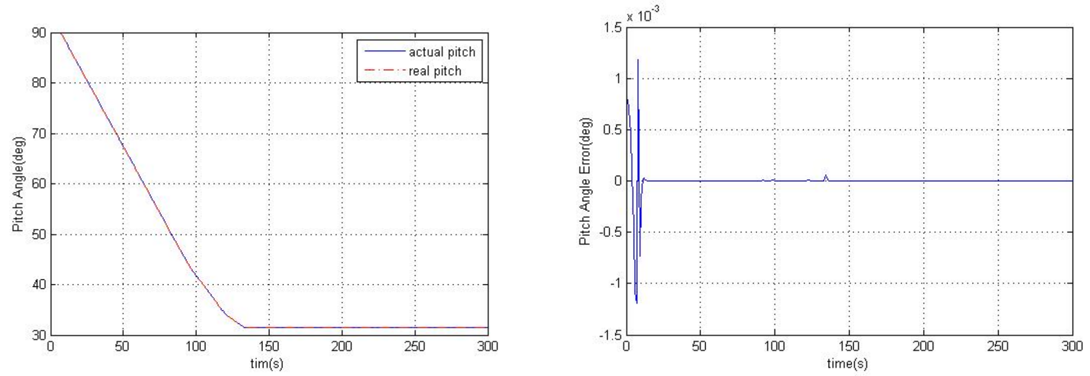
where *EC, CO, SI* and e are emotional cue, controller output, sensory input and output error and the W_1 through W_5 are the gains that must be tuned for designing a satisfactory controller. In the choice of these two signals (*EC, SI*) some principles are taken into consideration:

(1) Sensory input is a kind of control signal which in BELBIC is reinforced or punished based on emotional cues, so it should be chosen as a function of error just like a PID controller. This choice has some advantages such as the existence of a systematic way to tune the gains. In this way one can set the learning rates (k_1, k_2) equal to zero at first, and then tune the gains of sensory input as a simple PID controller and then proceed to tune the gains of the other parts of BELBIC in the direction of improving the performance of the primary sensory input signal. This method can solve the main problem of BELBIC which was the gains tuning. In addition, the controller now has more reliability because of being based on a classic controller (PID). Also the PID controller has some other advantages such as robustness to some extent, which is very desirable especially in this work with possible uncertainties in estimated model including less than enough number of neurons. Besides using this signal selection we do not need to be concerned about effect of noise on identification. So, an identification using fewer numbers of neurons can easily filter the noise while it could be used in tuning of the controller and it will certainly accelerate the online control process. It should be noted that PID gains have been tuned with Ziegler-Nicholas hand tuning method. They might not be the best, but BELBIC is expected to improve the corresponding PID controller's performance.

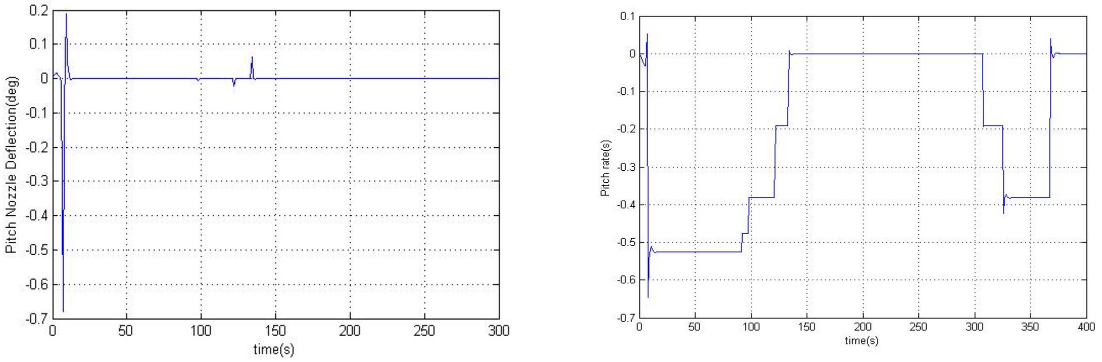
(2) When the emotional cue is a positive number, the gain of amygdala connection will be increased, and when the emotional cue is a negative number, the gain of orbitofrontal connection will be increased; a bigger emotional cue causes bigger reinforcement or punishment, so the emotional cue should increase when the absolute value of error decreases. To avoid the offset error, the emotional cue should include error in addition to its derivative but with a much smaller coefficient. Finally, the emotional cue is compared with the model output control signal (*MO*); therefore, it should have the same dimension with *MO*. Therefore, one can define the emotional cue like Eq. (14).

4. Controller setup and simulation results

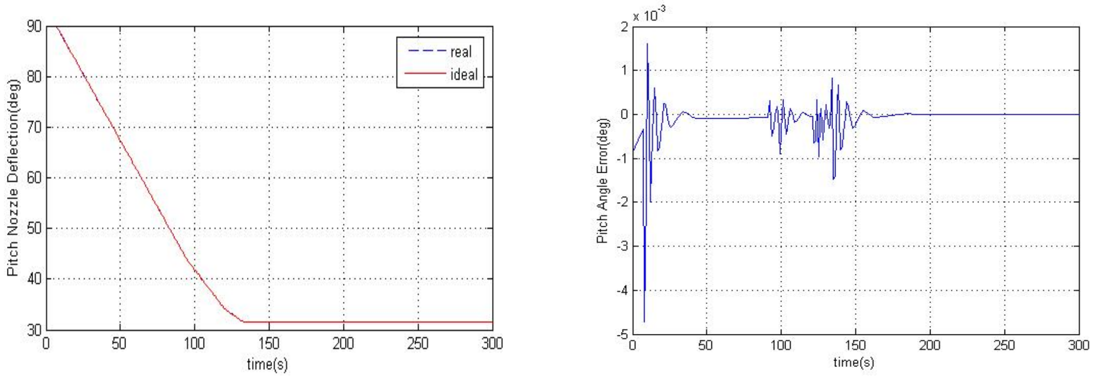
After derivation and development of the BELBIC controller, this controller has been used in the LV simulation to verify the usefulness of this controller to control the proposed complex



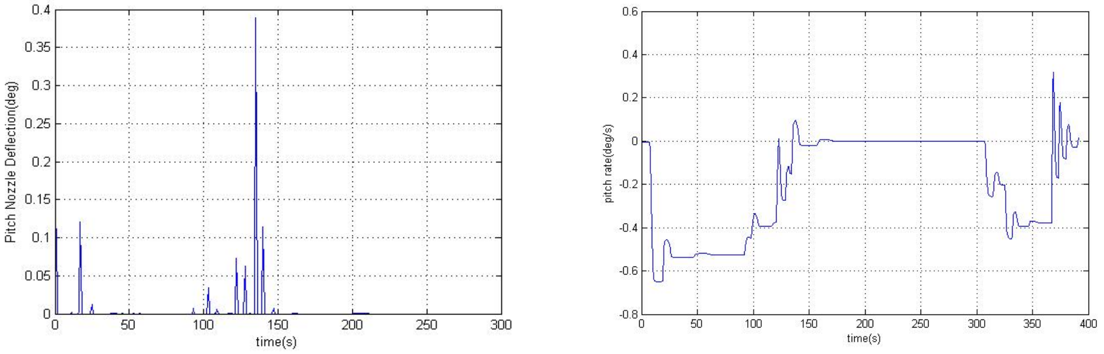
(a) BELBIC pitch angle (b) BELBIC pitch angle error



(c) BELBIC pitch nozzle deflection (d) BELBIC pitch rate



(e) FC pitch angle (f) FC pitch angle error



(g) FC pitch nozzle deflection (h) FC pitch rate

Fig. 3. LV simulation results comparison with the identified actuator model in presence of BELBIC and FC.

Table 1. Root mean square comparison of the controllers.

Root mean square error ➔	Pitch channel
BELBIC controller	2.6572e-4
Fuzzy controller	7.27e-3
PID controller	0.00164

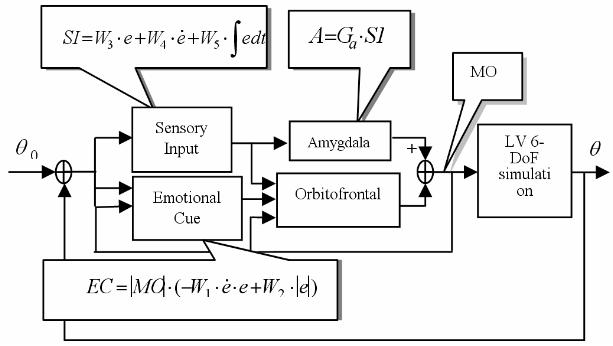


Fig. 4. Closed loop control of LV with BELBIC controller.

nonlinear system.

The result of the BEL controller in the simulation shows its ability to track the desired pitch program during LV's flight. These results are compared to FC which is implemented for the LV simulation previously in the pitch channel.

Here the first Figs. 3(a), (e) show the desired and ideal pitch angle, which granted the entire requirement of LV's guidance system. The LV is forced to track this ideal pitch program. This desired attitude comes from the obligation of the determined mission .Essential obligation in this simulation is to reach the LV to an orbit of earth. In this study no side maneuver was considered, which results in the ideal value of the roll and yaw angles without any change and only the pitch channel is considered to study. For the pitch channel of the LV an ideal pitch program is assumed. With the help of the pitch program, the LV can reach the desired orbit. To have a good tracking of the ideal pitch program a controller with the minimum error must be assumed which can track the desired attitude. In this study the PID based BELBIC controller, because of its unique properties in control of nonlinear plants, is proposed. Another reason for this selection was that this kind of BELBIC controller because of its PID based structure shows more reliability in the entire flight of LV. Also, the PID controller has some other advantages such as robustness to some extent, which is very desirable especially in this mission with possible uncertainties in estimated model. Then the result of the BELBIC controller which is used for pitch channel of the LV is compared with the FC that is designed and implemented for the same mission. The results of comparison between these two controllers for the pitch angle error in Fig. 3(b), (f) and for LV TVC nozzles are shown in Fig. 3(c), (g). The results show a better performance of the BELBIC controller in relation to the FC in the simulation. To add more to the comparison the root mean square error of these controllers in the simulation is presented, which shows a better performance of the BELBIC controller. Also note that the most advantage of using BEL controller in addition to the proposed FC is its auto-tuning characteristic during the flight period, which is very important in the control section of the LV in the flight. This specification is very important because the best situation of the FC is tuned by determination of the bound of membership functions, but the BEL controller could tune itself in the whole flight with one time determination of its gains even if severe disturbances exist.

In the following figure the block diagram of the proposed BELBIC controller which is developed for this simulation is presented. To tune this controller as mentioned in section (3), first the learning rates (k_1, k_2) in orbitofrontal and amygdala must become equal to zero; this action changes the controller structure like Eq. (16) which is a PID controller. Then tune the gains of sensory input (W_3, W_4, W_5) as a simple PID controller. Second the gains of other parts of BELBIC in the direction of improving the performance of primary sensory input signal must be tuned. So first the (W_1,W_2) gains of emotional cue must be set; second, k_1 amygdala gain might be tuned, which for the first 90sec is equal to *20* and after that is reduced to zero with time. Third, the gain k_2 of the orbitofrontal must be tuned which here has the duty of punishment in the control process. Here, this gain is set to *1* in the first *90* seconds of flight and after that is reduced to *0* by the sample time square. This method can solve the main problem of BELBIC, which was tuning the gains.

Because of good tracking and having a minimum error and the ability to control the LV intelligently, the BELBIC controller has been considered for use in the real flight of the LV.

Before use of the proposed controller in a real LV it is preferred to examine the HIL system. This real-time examination led the control designer to test the controllers in a semi-real flight simulation. This test has the unique capability that the controller designer with minimum cost and danger can find the reliability of the controller in a semi-real flight of the LV.

5. HIL system

Ideally, development of the HIL simulation is to make the same response as the real system. It means that the simulation model must be able to simulate the dynamic behavior as well as all input/outputs of the real system. In practice, an exact model is impossibly hard to achieve. In this section an HIL system for pitch channel of the LV is developed which can perform like a real LV in the pitch channel. Hardware-in-the loop (HIL) simulation has been proven a cost-effective method in design, development, modification and testing of various industrial systems. HILS has been developed primarily for military and space applications. The main benefit of the HILS technology is that it is repeatable, non-destructive and non-hazardous prototype testing, verification and validation. Engineering history shows that the main event that enabled the transfer of the HIL technology into the aerospace industrial

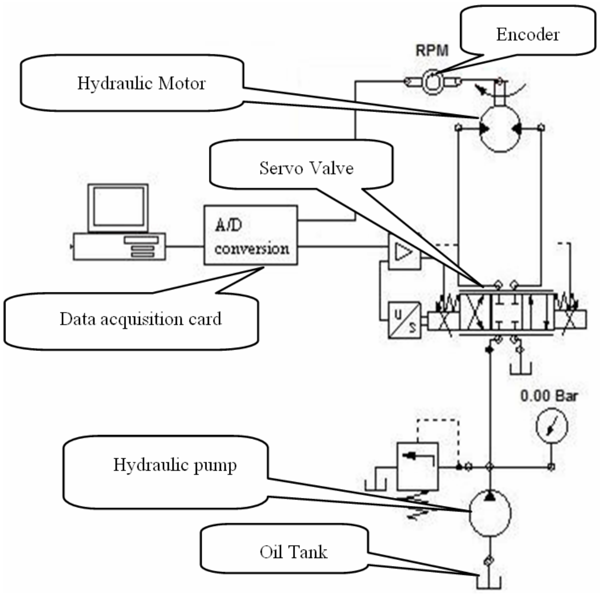


Fig. 5. Schematic loop of simulation –servo hydraulic rotating actuator.

area was the development of cost-effective preflight systems and computationally powerful processors.

5.1 Identified model of actuator

To set up the HILS a hydraulic actuator with a set pressure of approximately 70 bars and a servo-electric flapper-nozzle valve has been used. In Fig. 6 all mechanical and hydraulic parts of the HIL system in the modern control laboratory are shown. Also in Fig. 7 the closed form of the HILS is sketched. In the first step the actuator system must assure that it could exactly obey the controlling signals in simulation or in HILS.

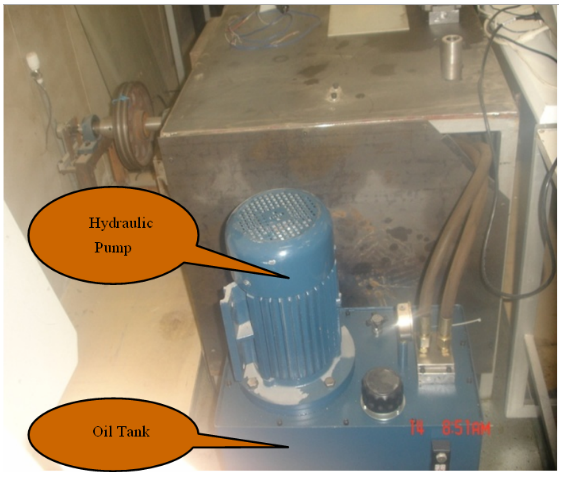
To find the actuator model and taking this model to the simulation, it was necessary to identify the actuator model. This action has been done by the use of an adaptive technique, extended least square (ELS) method in an offline style. This method takes the following linear transfer function for the actuator from the off-line input/output of the actuator [19]:

$$TF_{\text{simulation}} = \frac{\text{nozzle deflection}}{\text{controller signal}} \tag{18}$$

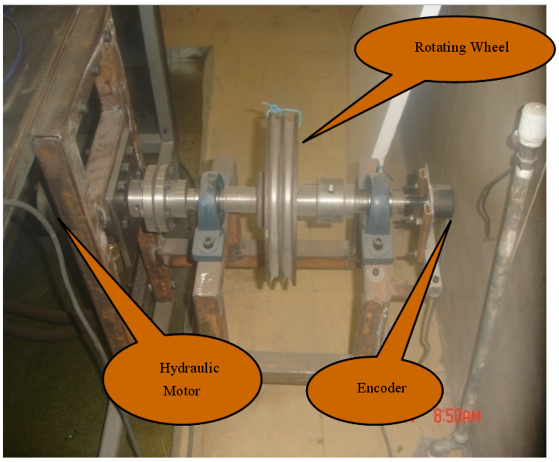
$$TF_{\text{actuator}} = \frac{s+2}{s(s+6)} . \tag{19}$$

In relation to the above derived transfer function (TF) it is obvious that this model, because of existence a pole on the imaginary axis, has an unstable property. This actuator isn't qualified for use in the simulation or in the HIL system. To use this unstable model of actuator it is required to change it to a closed loop form. This action changes the actuator model and changes it to a stable condition.

Now, separately from the main simulation an internal closed loop for the actuator model to make it tune is generated. This tuning process makes a stable condition of the actuator system. Fig. 7 shows this closed loop for actuator. So this process resulted in a stable actuator in the hardware in the loop. Fig. 8 shows the result of this closed loop stable hardware with input signals of sinusoid and pulse.



(a) Actuator system: pump-vanes



(b) Shaft connecting to the hydraulic motor as the nozzle deflector

Fig. 6. Servo hydraulic actuator system.

Here note that this off-line identification hasn't the whole detailed characteristics of the real system which might change with time. This action results in a near reality simulation of the pitch channel of LV. Now to have real time varying actuator system characteristics, a real actuator has been connected to the simulation. This connection leads to an experimental real system of LV with a real model of actuator in the pitch channel [2].

6. Launch vehicle HIL system

6.1 Actuator system

To set up a simple form of actuator connection to the MATLAB/SIMULINK to make a stable condition of the hydraulic actuator system, first the closed loop system which has been shown in Fig. 7 has been formed. The working voltage

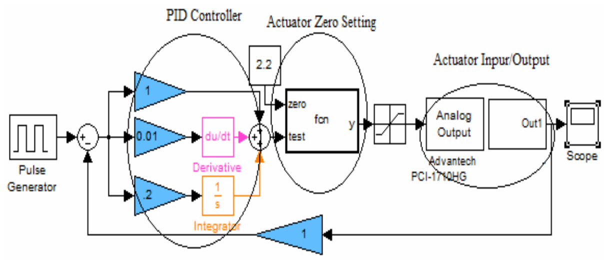
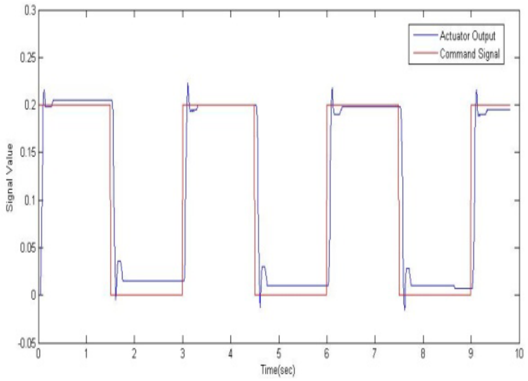
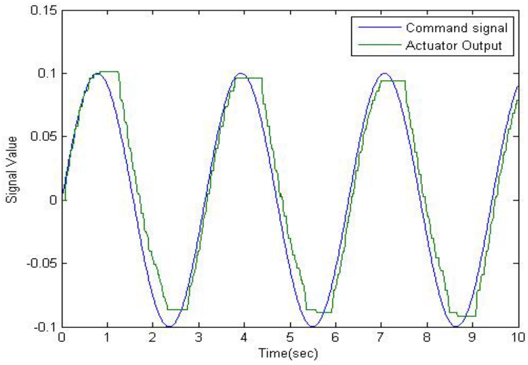


Fig. 7. Internal actuator loop.



(a) Pulse input/response of the actuator



(b) Sinuous input/response of the actuator

Fig. 8. Input/response of the actuator.

of the servo valve is between 0 to 5 volts. With a hand, tuning of the nonrotating position of the actuator (preset actuator zero) must be determined. This value takes in the determined part of actuator loop section in the simulation (actuator zero) to set the zero (working point) of the actuator. This value is always in the middle of the working voltage of the servo valve, approximately 2.5 volt. The entire controller deviation signal is acting around this point to go out to the servo valve, which point is determined as below:

The response of this actuator system to the sinusoid and pulse signals after developing it as a closed loop, the stable actuator system is shown in Fig. 8 which shows the ability of the actuator to have a good reaction and good tracking of the input signals. Through these results it is obvious that the actuator has the ability to be used in the HIL system and can obey exactly all the controlling commands of the LV TVC section [2, 20, 21].

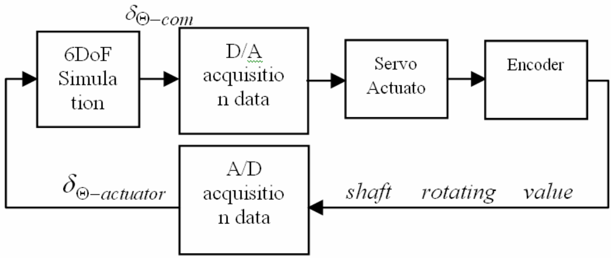


Fig. 9. HILS, connection of simulation to servo hydraulic actuator.

6.2 HIL system

To test the characteristics of the BELBIC controller in a real time space system a reasonable and cost-effective method is to develop an HIL system for the system. In this system the response of a specific hydraulic actuator and its related system is checked in section 5.1. It is determined that this system has the capability for use in a real LV flight simulation [1]. To develop the HIL system a six-degree-of-freedom simulation in SIMULINK environment was generated, which with an Analogue/Digital data acquisition card the data transfer between hardware and simulation has been done as shown in Fig. 9 [20-22].

The next step is data acquisition between the available hydraulic actuator system and simulation. With the use of available blocks in the SIMULINK/real-time windows target, data transfer has been simpler. Here a Simulink A/D card block (Advantech 1710 HGL) is doing the role of data acquisition between software, LV simulation and hardware, servo hydraulic actuator shaft output value which is measured by an encoder.

The last step is taking deflection angle data from the rotating shaft of the actuator. These data have been measured to determine the shaft rotation as the TVC deflection of the LV. The rotation angle was used to make the desired control on it to have a smooth tracking of the desired pitch of the LV. It makes the proportionate deviation of actuator. After connecting the rotating shaft, the actuator was considered as a moving TVC nozzles actuator in the simulation, which its maximum deflection is limited to 4 degrees. This procedure–data transfer between simulation and actuator shaft to measure the rotation of actuator–is done by means of an incremental encoder. This encoder is connected to the shaft of actuator. Encoder sends the binary data to the A/D card. These data contain the values from 1 (20) to 32768 (215) and a sign channel; channel no. 16; contain the value of 65536 (216). In Fig. 5 the schematic connection of the encoder to the shaft of hydraulic motor has been shown. To use the received binary data of the A/D card the summation of all ports value has been changed to the decimal value. Here total amount of shaft rotation is determined. After some experimental measurement the transfer ratio that put down this resultant revolution to the angle deflection is derived. This angle deflection is used as easily as possible to the real time simulation.

$$\text{Nozzle deflection value (radian)} = \frac{2\Pi}{24768} * \text{encoder value (revolution)} \qquad (20)$$

6.3 HILS setup based on a PID controller

First, to set up the simulation and HILS process a PID controller because of its tuning simplicity has been employed, which has the following results in HILS [1]. The tuning process of this PID controller with Ziegler-Nichols frequency response method (Ziegler & Nichols in Åström & Hägglund, 1995) comes as the following steps:

(a) Increase the proportional gain until the system oscillates; that gain is the ultimate gain K_u.

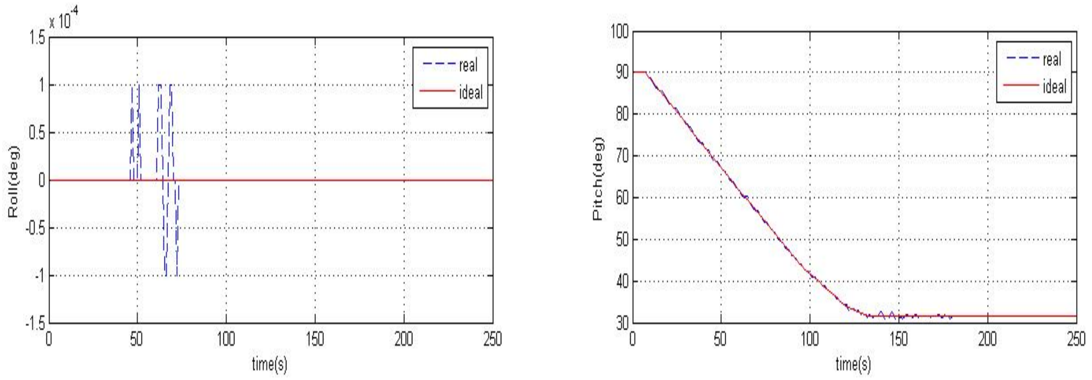
(b) Read the time between peaks T_u at this setting.

(c) Table 2 gives approximate values for the controller gains.

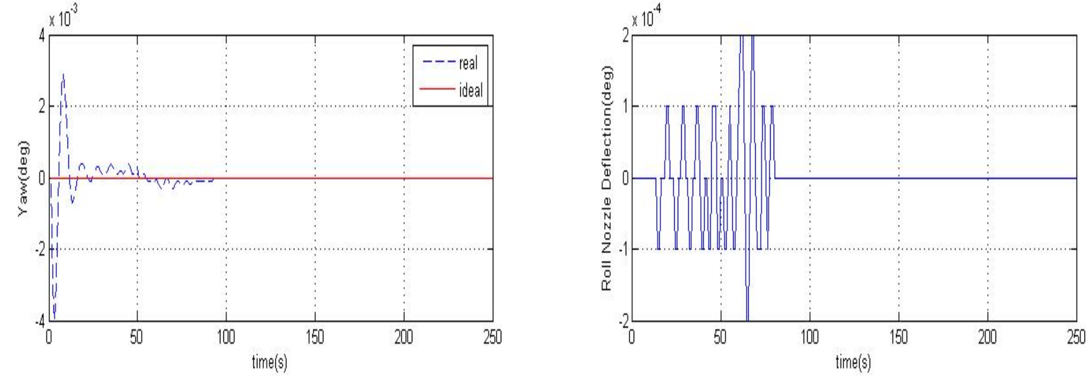
Table 2. Tunning of PID controller.

Controller	K_p	T_i	T_d
P	$0.5K_u$		
PI	$0.45K_u$	$T_u/1.2$	
PID	$0.6K_u$	$T_u/2$	$T_u/8$

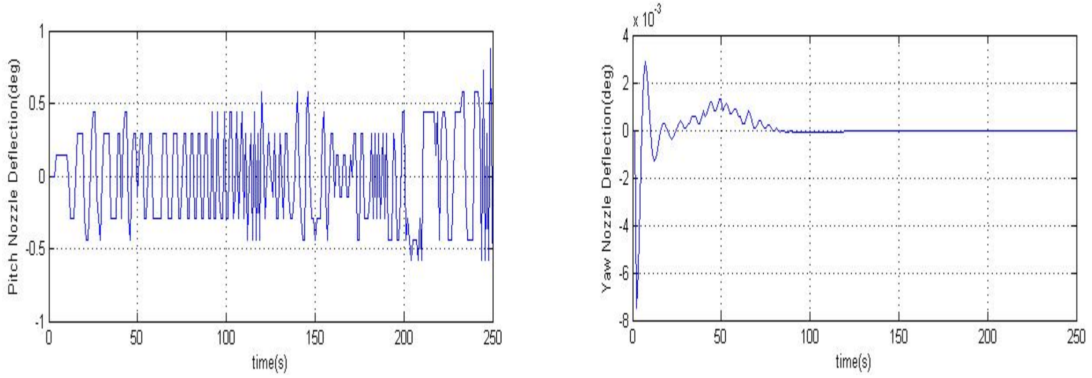
After setting up the PID controller, the results which come in Fig. 10, show that the roll-pitch-yaw angle tracking of the LV in HILS in presence of PID controller has made a good enough tracking for all channels. It must be mentioned that



(a) Roll angle (b) Pitch angle

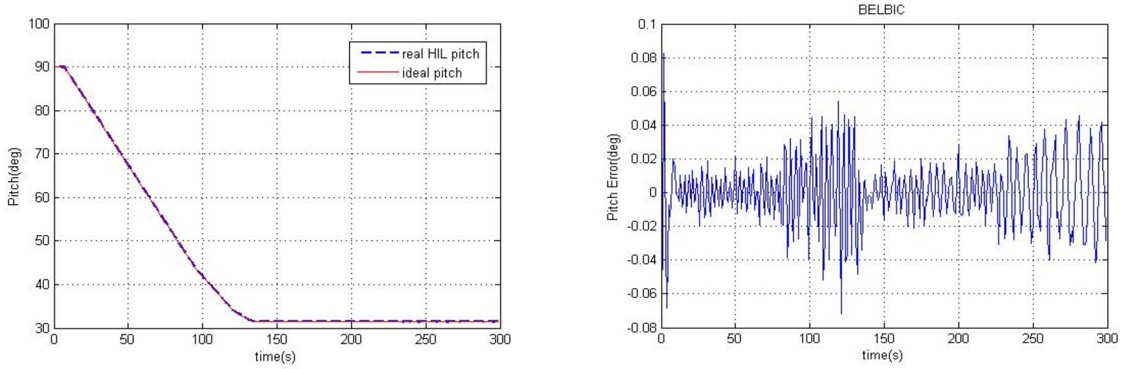


(c) Yaw angle (d) Roll nozzle deflection

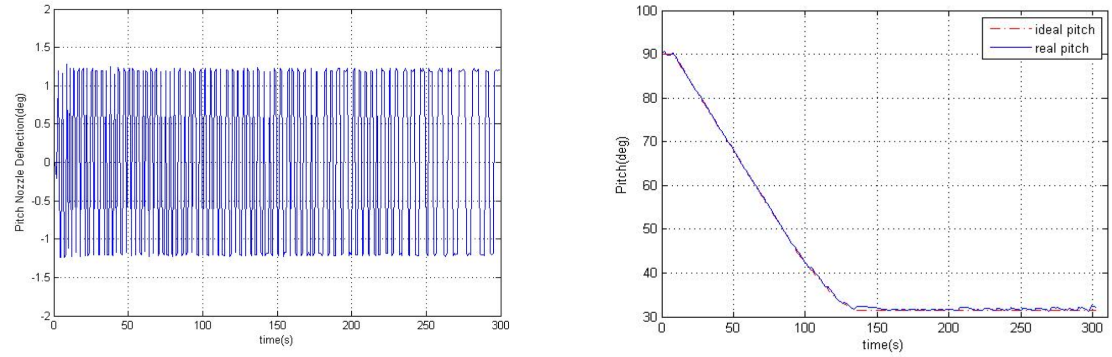


(e) Pitch nozzle deflection (f) Yaw nozzle deflection

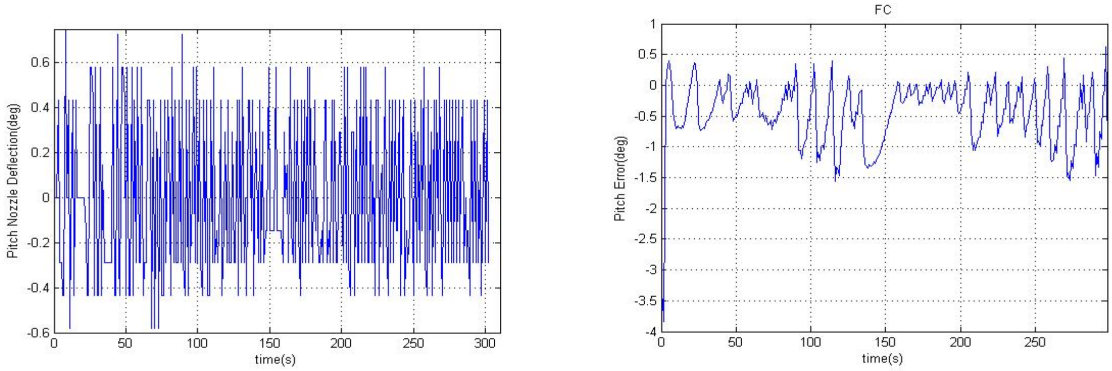
Fig. 10. HILS results in presence of PID controller.



(a) BELBIC pitch angle (b) BELBIC pitch angle error



(c) BELBIC pitch nozzle deflection (d) FC pitch angle



(e) FC pitch nozzle deflection (f) FC pitch angle error

Fig. 11. BEL controller in comparison with FC in HILS.

these results were in presence of a coupling effect between these channels of the LV. Also because of coupling in channels the tracking performance in relation to the dynamics of actuator approximately remains unchanged. But the results of using the PID controller show unpredicted behavior in HILS, especially in pitch nozzle deflection because of accumulated error of the system between actuator and simulation; this classic controller couldn't have a satisfactory behavior till the end of the process. This problem and other difficulties of the classic controller made us enthused to employ the modern control strategies to overcome these difficulties. Here the following results come to have a comparison in employing PID controller with the modern controllers that has been implemented in the next part.

6.4 The designed BELBIC controller in the HILS

In this section, the BELBIC controller verification with HILS, the process of developing the BELBIC controller in the HIL system to determine the ability of this controller in the online real time control of the LV, is studied. After setting up the HILS system mentioned in section (5.2) the BEL controller was developed and tuned to use in the HIL system to test its reliability in the real flight of LV in relation to the initially used PID and fuzzy controller. The proposed controller is determined in Fig. 4. This controller as mentioned in section (3) is based on the PID controller. In this way to tune this part of controller gains by setting the learning rates (k1, k2) equal to zero, the gain of sensory input as a simple PID controller

Table 3. Root mean square comparison of the controllers.

Root mean square error ➔	Pitch channel
BELBIC controller	2.46e-4
Fuzzy controller	4.994e-3
PID controller	0.010100

was tuned and we then proceeded to tune the gains of the other parts of BELBIC in the direction of improving the performance of the primary sensory input signal. This method can solve the main problem of BELBIC, which was the tuning of the gains. For this system the gains k_1 and k_2 were considered equal to 10 and 0.5. For this system the bound of nozzle deflection was considered equal to $\pm 1.5 \deg$ whom the controller output must not exceeded this value. After tuning the SI part the performance of BEL controller must improve to the HILS. This leads to determine the gains of EC (W_1, W_2) and amygdala and then orbitofrontal. This process is done and k_1, k_2 must decrease to zero after some time so that the gains have been tuned. The result of testing this controller showed that the BELBIC controller has a good tracking of the desired pitch program of the LV with minimum error in relation to the FC, which had a better performance from PID controller in the HIL system. The results are shown in Fig. 8. The proposed FC generation is mentioned in the appendix 3 [23, 24].

The results showed that the nozzle deflection in the BELBIC controller sometimes reaches a higher value of deflection than FC. But with higher nozzle deflection and less tracking error, the BEL controller can control the LV from the beginning to the end of flight and does not diverge.

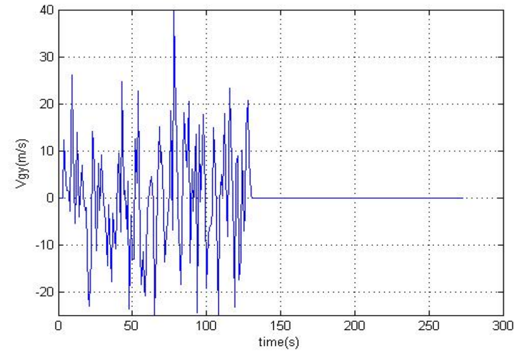
The comparison between BELBIC and FC in Fig. 11 shows the high capability of the BEL controller to have a smooth tracking of the ideal LV attitude in HILS in addition to the simulation. Finally, the root mean square (RMS) errors of these two kinds of controller are compared with each other. This comparison shows that the BELBIC has a twentieth RMS error less than in relation to the FC in the HIL system and very good tracking of the pitch attitude of the LV.

6.5 The effect of disturbance in the HIL system robustness

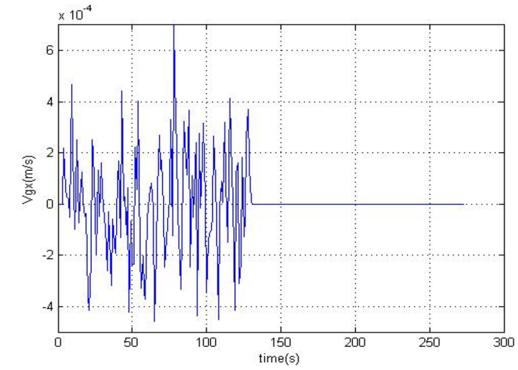
In this study after setting up HILS with a PID control and comparing this with an FC and BELBIC controller, to demonstrate the robustness of the proposed BEL controller in HIL system, a disturbance model has been considered of the atmosphere which is generated from the Von Karman gust model of atmosphere to test the BEL controller in the HILS. The test is developed for the worst condition of Von Karman model of gust, which is a thunderstorm so that the specific characteristics of this gust model are as follows [14]:

$$G_u(s) = \frac{\sqrt{K_u}}{s+\lambda_u} \tag{21}$$

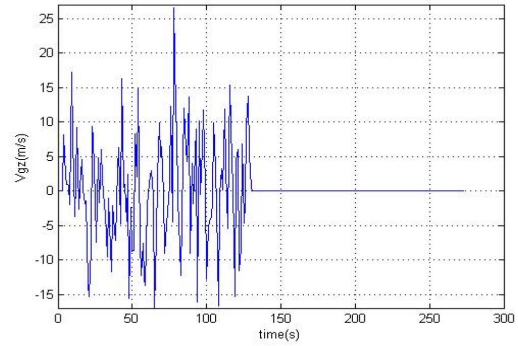
$$G_v(s) = \sqrt{K_v} \cdot \frac{s+\beta_v}{(s+\lambda_v)^2} \tag{22}$$



(a) X direction of gust velocity



(b) Y direction of gust velocity



(c) Z direction of gust velocity

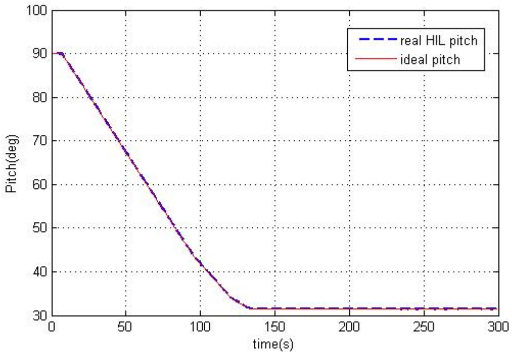
Fig.12. Von Karman thunderstorm model of atmosphere in the inertial axis.

$$G_w(s) = \sqrt{K_w} \cdot \frac{s+\beta_w}{(s+\lambda_w)^2}. \tag{23}$$

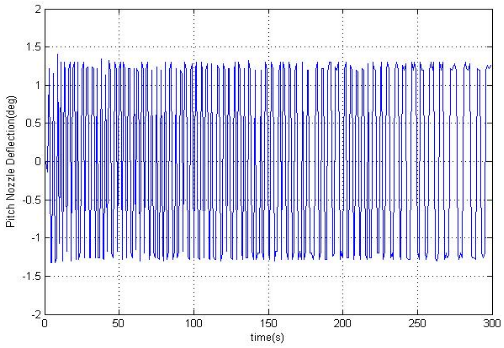
To generate such gust model, after derivation of disturbance transfer functions ($G_i(s)$) the following setup must be generated:

With development of this kind of gust model and inserting the white noise to the gust transfer function, the gust model is generated; Fig. 12 shows the characteristics of this gust model in the three axes of motion which it has been inserted to the simulation for the 10 to 120 second of flight.

After developing this wind model, the specified wind velocities in relation to the earth coordinate have been transferred to the same body coordinate velocity in the flight simu-



(a) Pitch angle



(b) Pitch nozzle deflection

Fig. 13. distributed HILS in presence of disturbance.

lation in the HILS. Finally, the exerted wind velocity determines the effect of wind disturbance on the LV in the HILS; these results are in Fig. 13.

Here this procedure determines the robustness of the BELBIC controller in HILS. The results of this system of the HILS in presence of the gust are shown in Fig. 13 and without inserting the wind in Fig. 11(a), (c). These results indicate that in the presence of severe wind turbulence the maximum deflection of the pitch nozzle actuator is not exceeded more than 1.5 degrees and a smooth tracking of the pitch channel with complete control of the LV to the end of mission has been determined.

7. Conclusion

This paper deals with an experimental HILS to verify the reliability of the designed BELBIC controller, which was used to control the TVC nozzle actuator of the LV. This actuator, with much inherent uncertainty, drift, noise and disturbance, could be used in this complicated experimental HILS setup of the LV TVC of the pitch channel. In this experience first in the simulation, the specification and reliability of the BELBIC controller was determined, which indicated more reliability and good tracking of the BEL controller in relation to the PID control and FC. Then after assurance of reliability of this controller in the simulation, the proposed BELBIC controller was designed and verified with HIL system in comparison with the PID controller and FC. After some experiences the robustness of this controller against severe atmosphere wind model in HILS was determined. This experience with the semi-real flight of LV determines obvious reliance of the use of the BEL controller in the real time LV flight period. The greatest advantage of the BEL controller in relation to the proposed PID and fuzzy controller is its auto-tuning and robust characteristics in presence of severe disturbances, which for aerospace vehicles has a vital importance. Use of this auto tuning, self learning, robust intelligent controller in the launch vehicles, which must have a reliable performance in attitude tracking during their nominal trajectories to orbit, is one of the most important cases for research. These properties lead the LV designer to control the LV exactly through to the ideal trajectory. This minimum deviation leads to minimum fuel consumption, which is a critical problem in weight balance of the LVs to carry much more payload to the orbit.

Nomenclature

F_a : Aerodynamic force (N)
F_p : Propulsion force (N)
F_g : Gravity force (N)
M_a : Aerodynamic moment (N.m)
M_p : Propulsion moment (N.m)
$\phi,\ \theta,\ \psi$: Roll ,pitch ,yaw angles of LV (deg)
q_0, q_1, q_2, q_3 : Quaternion parameter
$\dot{p},\dot{q},\dot{r}; p,q,r$: Angular acceleration and velocity of LV in body frame (rad/s)
I_x, I_y, I_z : Inertial momentum of LV (kg.m)
$\dot{u},\dot{v},\dot{w}\,; u,v,w$: Relative acceleration and velocity of LV (m/s^2), (m/s)
x,y,z : Position of LV in inertial frame (m)
G_a : The amygdala connection gain
EC : Emotional Cue
A : Amygdala output
k_1 : Amygdale learning rate
G_o : Gain in orbitofrontal connection
k_2 : Learning rate in orbitofrontal cortex
MO : Model Output
O : Orbitofrontal cortex Output
SI : Sensory Input
Z : Zero
NB : Negative Big
NM : Negative Medium
PB : Positive Big
PM : Positive Medium

Reference

[1] M. Rezaei Darestani, M. Zareh and J. Roshanian, hardware in the loop set up for TVC control of a launch vehicle pitch channel, 8th *Iranian conference of aerospace* (2009).

[2] Mahdy Rezaei Darestani, Mehran Zareh Eshghdust, Jafar Roshanian, Ali Nahvi, A Hardware-in-the Loop Experimental Set Up for a Launch Vehicle Actuator, AIAA-2009-6653, *AIAA SPACE 2009 Conference and Exposition*, Pasadena,

California, Sep. 14-17 (2000).

[3] J. Moren and C. Balkenius, A Computational Model of Emotional Learning in The Amygdala: From animals to animals *Proc. 6th International conference on the simulation of adaptive behavior,* ambridge, Mass., The MIT Press (2000).

[4] S. Jafarzadeh, R. Mirheidari, M. R. Jahed Motlagh and M. Barkhordari, Designing PID and BELBIC Controllers in Path Tracking and Collision Problem in Automated Highway Systems, *2008 10th Intl. Conf. on Control, Automation, Robotics and Vision* Hanoi, Vietnam, 17-20 December (2008).

[5] S. Jafarzadeh, M. R. Jahed Motlagh, M. Barkhordari and R. Mirheidari, A New Lyapunov Based Algorithm for Tuning BELBIC Controllers for a Group of Linear Systems, *16th Mediterranean Conference on Control and Automation Congress Centre*, Ajaccio, France, June 25-27 (2008).

[6] Sima Valizadeh, Mohammad-Reza Jamali and Caro Lucas, A Particle-swarm-based Approach for Optimum Design of BELBIC Controller in AVR System, *International Conference on Control, Automation and Systems,* 2008 Oct. 14-17, Seoul, Korea, COEX (2008).

[7] Rasoul Mohammadi-Milasi, Caro Lucas and Babak Nadjar Araabi, Intelligent Modeling and Control of Washing Machine Using LLNF Modeling and Modified BELBIC, *2005 International Conference on Control and Automation (ICCA2005),* June 27-29, Budapest, Hungary (2005).

[8] E. Daryabeigi, Gh. Arab markadeh and C. Lucas, Interior Permanent Magnet Synchronous Motor (IPMSM), with a developed Brain Emotional Learning Based Intelligent Controller, *Electric Machines and Drives Conference 2009, IEMDC '09. IEEE International* (2009) 1633-1640.

[9] E. Daryabeigi, Gh. Arab Markadeh and C. Lucas, Simultaneously, Speed and Flux Control of a Induction Motor, with Brain Emotional Learning Based Intelligent Controller (BELBIC), *Electric Machines and Drives Conference 2009, IEMDC '09. IEEE International* (2009) 894-901.

[10] Ali Reza Mehrabian, Caro Lucas and Jafar Roshanian, Aerospace launch vehicle control: an intelligent adaptive approach, 9 December 2005, *Aerospace Science and Technology,* 10 (2006) 149-155.

[11] Hossein Rouhani, Mahdi Jalili, Babak N. Araabi, Wolfgang Eppler and Caro Lucas, Brain emotional learning based intelligent controller applied to neurofuzzy model of micro-heat exchanger, Institute of Data Processing and Electronics, Forschungszentrum Karlsruhe, Germany, *Expert Systems with Applications,* 32 (2007) 911-918.

[12] M. R. Jamali, A. Arami, M. Dehyadegari, C. Lucas and Z. Navabi, Emotion on FPGA: Model driven approach, *Expert Systems with Applications,* 36 (2009) 7369-7378.

[13] Sima Seidi Khorramabadi, Mehrdad Boroushaki and Caro Lucas, Emotional learning based intelligent controller for a PWR nuclear reactor core during load following operation, *Annals of Nuclear Energy,* 35 (2008) 2051-2058.

[14] Donald McLean, Automatic Flight Control System, *prentice Hall international Ltd. (*1990).

[15] George M. Siouris, Missile guidance and control systems, *Springer-Verlag New York, Inc.* (2004).

[16] Peter H. Zipfel, Modeling and Simulation of Aerospace Vehicle Dynamics, *AIAA* (2000).

[17] Hossein Rouhani, Mahdi Jalili, Babak N. Araabi, Wolfgang Eppler and Caro Lucas, Brain emotional learning based intelligent controller applied to neurofuzzy model of micro-heat exchanger, *Expert Systems with Applications*, 32 (3) (2007) 911-918.

[18] R. M. Milasi, C. Lucas, B. N. Arrabi, T. S. Radwan and M. A. Rahman, Implementation of Emotional Controller for Interior Permanent Magnet Synchronous Motor Drive, *Industry Applications Conference 2006, 41st IAS Annual Meeting. Conference Record of the 2006 IEEE,* Volume 4 (2006) 1767-1774.

[19] M. Zareh, M. Rezaei Darestani and J. Roshanian, comparison of different identification method for a hydraulic actuator, *7th Iranian conference of aerospace* (2008).

[20] M. Linjama, T. Virvaloa, J. Gustafsson, J. Lintulab, V. Aaltonen and M. Kivikoski, Hardware-in-the-loop environment for servo system controller design, tuning and testing, *Microprocessors and Microsystems*, 24 (1) (2000) 13-21.

[21] Kresimir, Cosi, Ivica Kopriva, Todor Kosti, Miroslav Slami and Marijo Volarevi Ó, Design and implementation of a hardware-in-the loop simulator for a semi-automatic guided missile system, *Simulation Practice and Theory*, 7 (2) (1999) 107-123.

[22] Y. Kim, C.-O. Lee, An experimental study on the optimization of controller gains for an electro-hydraulic servo system using evolution strategies, *Control Engineering Practice*, 14 (2) (2006) 137-147.

[23] Jan Jantzen, Tuning of Fuzzy PID Controllers, *Technical University of Denmark, Department of Automation*, Tech. report no 98-H 871 (fpid) (1998).

[24] S. Y. Lee and H. S. Cho, A fuzzy controller for an electro-hydraulic fin actuator using phase plane method, *Control Engineering Practice*, 11 (6) (2003) 697-708.

Appendix 1

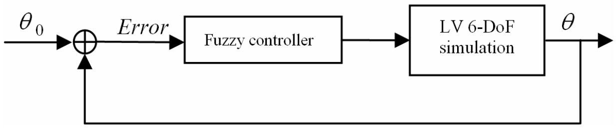
Initial characteristics of the Launch Vehicle

I_{x_0} (kg.m^2)	196,000
I_{y_0} (kg.m^2)	50,000
I_{z_0} (kg.m^2)	15,000
M_{total} (kg)	130,000
Thrust (ton)	180
Length (m)	32
Diameter (m)	4.5

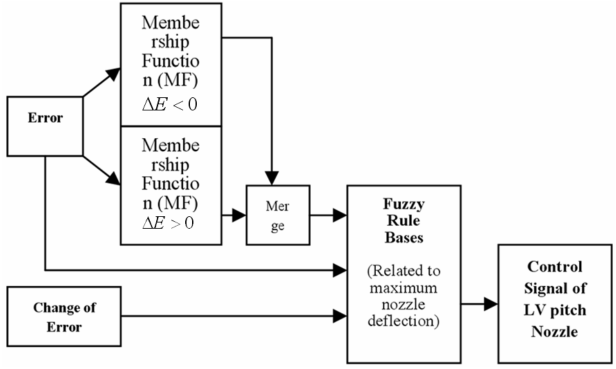
Appendix 2

Fuzzy controller implemented in HILS

(i) Fuzzy control of LV [4]



(ii) Fuzzy controller detail block



(iii) Fuzzy rule bases in output

CE \ E	Neg	Zero	Pos
Neg	NB*MF	NM*MF	Z*MF
Zero	NM*MF	Z*MF	PM*MF
Pos	Z*MF	PM*MF	PB*MF

Appendix 3

Wind disturbance parameter

$$L_u = L_v = L_w = 580m$$

$$\sigma_u = \sigma_v = \sigma_w = 7.0 m.s^{-1}$$

$$\beta_{u,v,w} = \frac{U_0}{\sqrt{3}L_{u,v,w}}$$

$$\lambda_{u,v,w} = U_0 / L_{u,v,w}$$

$$K_u = \frac{2U_0\sigma_u^{\ 2}}{L_u\pi}$$

$$K_v = \frac{3U_0\sigma_v^{\ 2}}{L_v\pi}$$

$$K_w = \frac{3U_0\sigma_w^{\ 2}}{L_w\pi}$$

Mahdy Rezaei Darestani received the B.Sc. degree in the Aerospace engineering from the Science and research branch of Azad University, Iran in 2006. He continued his studies as the M.Sc. candidate in the Aerospace engineering in the K.N. Toosi University of Technology, Iran and received the degree in 2009. His interest is about real time simulations, generation and application of new control methods in the real time systems. His research focuses on the adaptive control, fuzzy control, intelligent control, navigation and flight simulation. Now, He is a PhD student at K.N. Toosi University of Technology from 2009.

Mehran Zareh received the B.Sc. degree in the mechanical engineering from the University of Birjand, Iran in 2006. He continued his studies as the M.Sc. candidate in the aerospace engineering in the K.N. Toosi University of Technology, Iran and received the degree in 2009. His M.Sc. research involved application of robust adaptive control in the flight dynamics. His research focuses on the adaptive control, robust control, optimal control and flight simulation. He honored the best researcher of the year in 2010 at K.N. Toosi University of Technology.

Jafar Roshanian received his BS in mechanical engineering from K.N. Toosi University of Technology in Tehran in 1990, and attended the Moscow state Technical University (MSTU) in 1993. He spent six years at MSTU as a postgraduate student, MSc and PhD in flight dynamics from this university. He joined the aerospace engineering department of K. N. Toosi University in 1999 where he is presently a Professor and Dean of Aerospace Engineering Department.