

Autopilot Design for an Autonomous Vehicle under 6-Degree Motion

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Abstract: Autopilot technique in fluid dynamics is value able from last decade due to under water environmental activities; include navigation, control, defense, communication. Autonomous under water vehicle stability criteria is tough task to achieve due to involvement of fluid dynamics. Wave encounter with the head of submarine cause nonlinearity in AUV's movement. In this paper we become familiar with the techniques of analysis & controller design for AUV's by implementation of Control Law Design (CLD) possessing Pole Placement Technique (PPT).

Keywords: autopilot, fluid dynamics, optimization, PID controller, pole placement

1. Introduction

Unmanned underwater vehicle (UUV's) is getting popularity in last 2-3 decades, under observation submersible vehicle is of autonomous type. Many other kinds such as remotely operated vehicle (ROV's) tethered, autopilot, single shot ROV's (SSR's) has been used before. Submarine follows low depth motion as its control in deep seas is hard to achieve. Main problem with this system is wave encounter, which cause 6-degrees motion in AUV's. Control is basically to achieve a desired response of a system. Many ways would be considered to get stability as stability is just to change pole location in a pole zero map. Addition of zeroes & poles is one way to get ordered design and is ancient technique. Standard tools such as MATLAB & SIMULINK are used now a days for controller designs.

Here we will 1st observe stability criteria in these kind of vehicles which is applicable design in linear motion. After estimating damping & stability criterion, we will move towards its controller design. Also there is possibility to add more zeroes & poles in given system to fulfill stability criterion, but alternative technique is adopted.

In this proposed design after an introductory description of State Space Model (SSM) of a specified submersible vehicle, the response of model due to impulse & constant applied inputs is considered. System may or may not b controlled so a check for system behavior for controller design is adopted. Real time system with PID controller and description of state variables in ODE's also included.

2. Analysis of Time Domain Responses

Fig.1 shows how the fore and aft dive planes are used during a dive. At the start of the dive the aft plane is rotated upwards so that the stern of the boat is forced upwards. The fore hydroplanes are rotated downwards thus forcing the bow of the boat down. During the dive the aft hydro planes are moved to the neutral position and the dive angle is controlled with the fore hydroplanes only.

Close to the required depth, the aft planes are rotated down and the fore planes up to level off the boat. At slow speeds

the depth of the boat is maintained by the fore planes only. During the first dive, the water level in the main trim tanks is adjusted to obtain a neutral buoyancy so that the required depth can be maintained with a nearly horizontal position of the hydroplanes same as observed in the real model of a hydro plane.

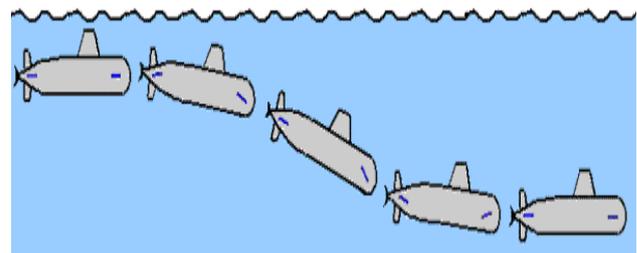


Figure 1: dive plane bow(δ_b) & stern(δ_s) angles during a drive.

Table 1: parametric notation of 6-degree's of freedom.

DOF	Auv's dynamics	Forces and moments	Linear & angular velocities	Positions & Euler angles
1	Motion in x-direction(surge)	x	U	X
2	Motion in y-direction sway)	Y	V	Y
3	Motion in z-direction(heave)	Z	W	Z
4	Rotation about x-axis(yaw)	K	P	Φ
5	Rotation about y-axis(pitch)	M	Q	Θ
6	Rotation about z-axis(roll)	N	r	Ψ

Submarine models are correspond to the equation of motion of the six degrees of freedom (DOF) vehicle. Dynamic models are same as aeronautical parameters [1],[2],[4],and[5], a linearized model can be derived from equation of motion of a submarine which is reported in [18]. For instance state space (time domain) model is obtained by taking constant buoyant conditions as following in (Fig.1)

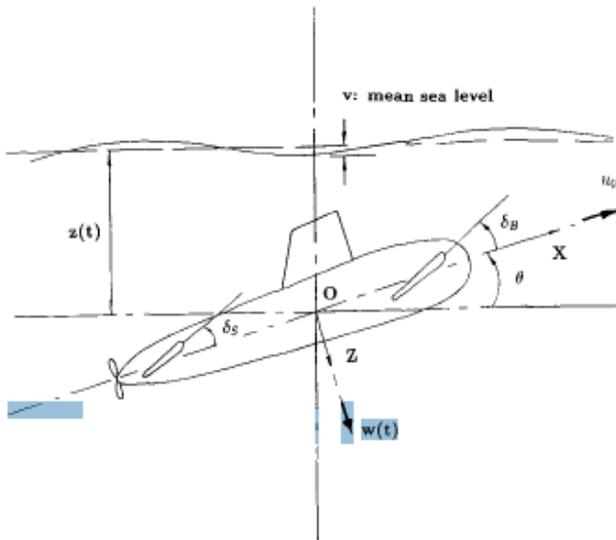


Figure 3: submarine as hydroplane model with parameters.
 $x = AX + BU$
 $y = CX + DU$
 $X = [w \ q \ z \ \theta]^T, Y = [z \ \theta]^T, U = [\delta_b \ \delta_s]$

$$A = \begin{bmatrix} -0.038 & 0.896 & 0 & 0.0015 \\ 0.0017 & -0.092 & 0 & -0.0056 \\ 1 & 0 & 0 & -3.086 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$B = [-0.0075 \ -0.023 \ ; \ 0.0017 \ -0.0022 \ ; \ 0 \ 0 \ ; \ 0 \ 0]$$

$$C = [0 \ 0 \ 1 \ 0 \ ; \ 0 \ 0 \ 0 \ 1]$$

Where,
 W=the heave velocity.
 Q=pitch rate.
 Z=the submarine depth.
 Θ=the pitch angle.
 Δb=the bow hydroplane angle.
 Δs=the stern hydroplane angle.
 System has two inputs and two outputs, four transfer functions G_{11}, G_{12}, G_{21} & G_{22} are possible. Given system is linear time invariant; no variable is time dependent. Using MATLAB lti (linear time invariant) viewer, resulting impulse & step responses are given below:

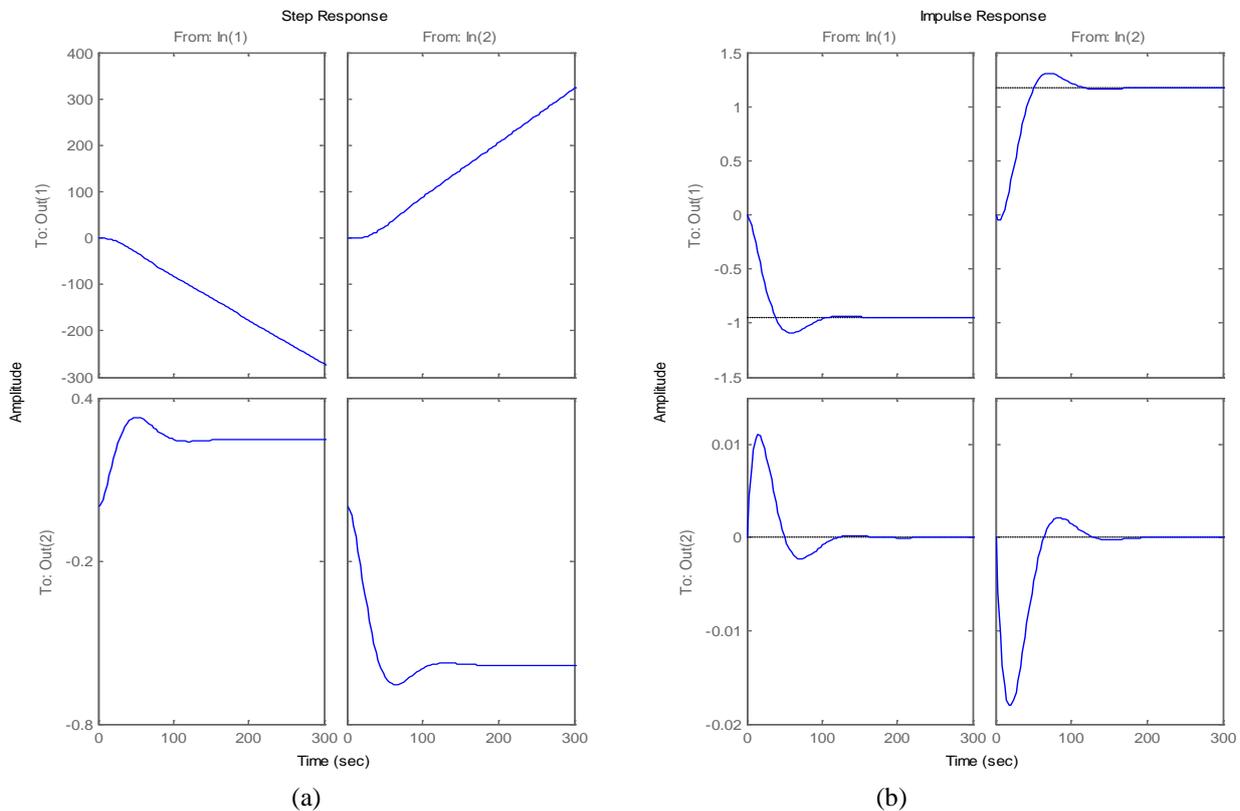


Figure 4: (a) step response of state space model. (b) impulse response of state space model.

Here,

Step response shows that

- With time, by applying constant input which is bow angle (δ_b) causes the decrease in depth, submarine moves towards surface.
- Application of constant stern angle (δ_s) Causes the depth to increase; submersible vehicle moves towards bottom.
- If bow angle (δ_b) is considered constant input, then it cause pitch angle first to increase then settle down at a constant value.

- Applying stern angle (δ_s) as constant input, it causes pitch angle to decrease and then establish a steady state position.

3. Controllability & Observability Criteria

Eigen values of given system is mentioned through CCF & OCF & also through general form of A.

$$M = \begin{pmatrix} -0.0075 & -0.0230 & 0.0018 & -0.0011 & -0.0002 & 0.0002 & 0.0000 & 0.0000 \\ 0.0017 & -0.0022 & -0.0002 & 0.0002 & 0.0000 & -0.0000 & -0.0000 & -0.0000 \\ 0 & 0 & -0.0075 & -0.0230 & -0.0034 & 0.0057 & 0.0003 & -0.0003 \\ 0 & 0 & 0.0017 & -0.0022 & -0.0002 & 0.0002 & 0.0000 & -0.0000 \end{pmatrix}$$

This system is controllable as rank (A)= 4 Which means that all rows are linearly independent. It is possible to control the response of system as all state variables are involved in the controllability matrix. This criterion leads us towards controller design.

$$O = \begin{pmatrix} 0 & 0 & 1.0000 & 0 \\ 0 & 0 & 0 & 1.0000 \\ 1.0000 & 0 & 0 & -3.0860 \\ 0 & 1.0000 & 0 & 0 \\ -0.0380 & -2.1900 & 0 & 0.0015 \\ 0.0017 & -0.0920 & 0 & -0.0056 \\ -0.0023 & 0.1689 & 0 & 0.0122 \\ -0.0002 & 0.0044 & 0 & 0.0005 \end{pmatrix}$$

This system's output is full filled Observability criteria as rank (O)=4 ,which shows that we are able to estimate output response. Controller design is not possible without

inspection of the controllability criteria. Our system is controllable so next step is to controller design.

4. Optimization through PID controller

Proposed SSD is linearized model of submersible vehicle. PID controller is applied in a case if noise is negligible. In real models derivative parameter is not used as it boost up the effects of noise, which leads towards nonlinear behavior, PID controller design is applicable to LTI systems only. SIMULINK is used as a tool for this system as in (Fig.5) $y = k_p r + k_d D(r) + k_i \int r dt$

In frequency domain it becomes as

$$Y = (k_d s^2 + s k_p + k_i) / s$$

Here,
 K_d =differential gain.
 K_p =proportional gain.
 K_i =integral gain.

Tuning of PID controller involved the values of these parameters set as to achieve desired response.

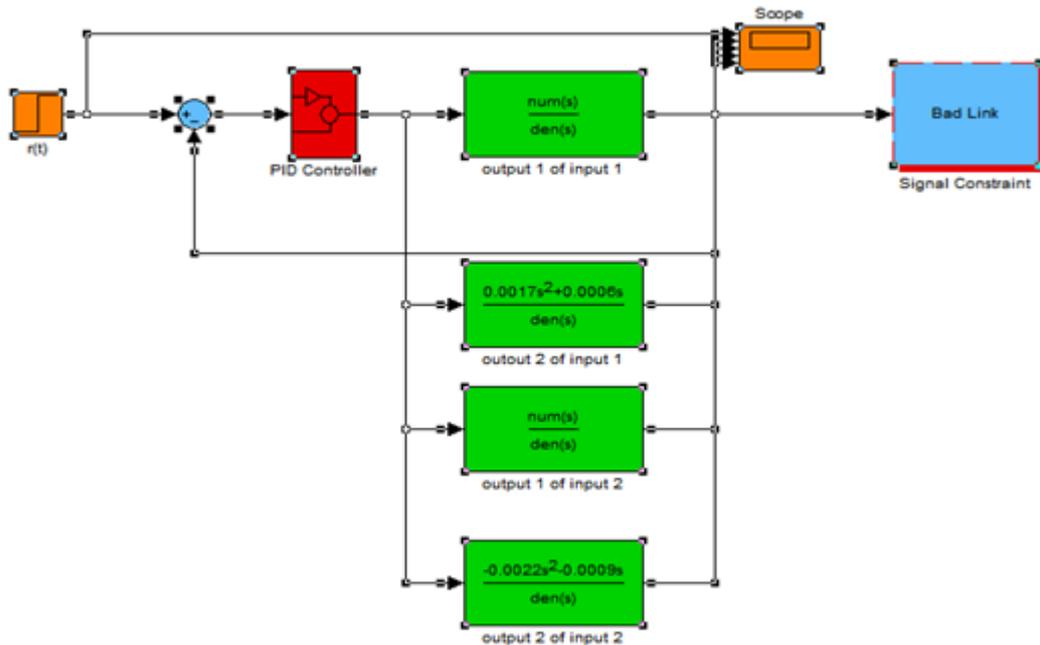


Figure 5: optimization of system by using PID controller

Optimized model of controller could be achieved by tuning PID. Values of proportional, derivative & integral gains are adjusted to achieve a controlled or desired output.

Ordinary diff. equations are of order one describe state variable derivatives in relation with state variables & inputs. We can estimate values of state variables of our system by using MATLAB graphical tools.

5. Ordinary Differential Equations (ODE's) of State Space System

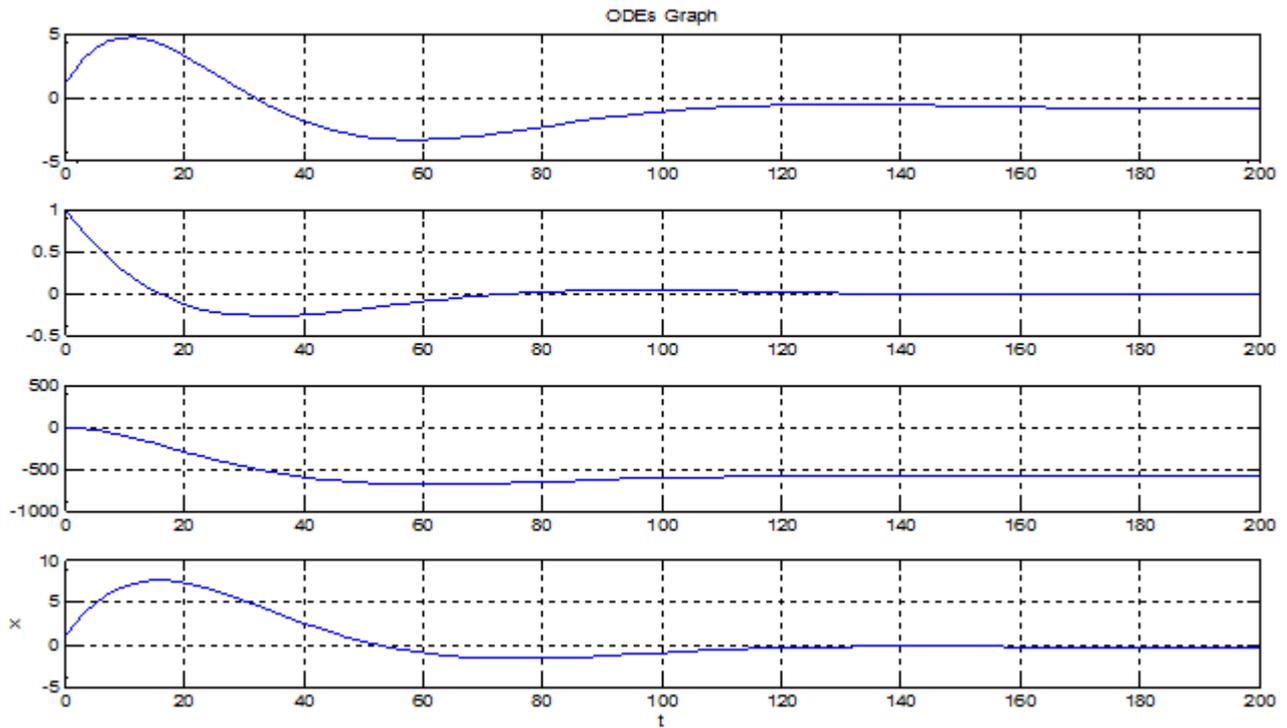


Figure 6: state variables in the form of ODE's

ODE's shows state variables which are heave velocity, pitch rate, depth & pitch angle. Graph shows relationship of their derivatives with state variables.

6. Controller Law Design

Control law design (CLD) is a technique to place the system poles at desired values. Pole positions determine the stability of a linear systems. So by changing pole positions we may control the system stability. We designed a controller for the system which state space model has already mentioned above but input (U) is changed as $u=r-kx$; here $r=0$ so $u=-kx$
 $X=ax+b(-kx)=(a-bk)x$
 $Y=cx+d(-kx)=(c-dk)x$

Eigen values of $[a-bk]$ are new poles of system by adjusting values of 'k' we could change $[a-bk]$ matrix , which leads us to desired pole location. estimation of system stability will

easy to perform. Pre existing Poles of the given system are following.

- 0
- 0.0336 + 0.0471i
- 0.0336 - 0.0471i
- 0.0627

Desired pole locations are at:

- 0.034+.4j,
- 0.034+.4j
- 0.0627+.3j,
- 0.0627+.3j,

Manually values of k could find by comparing coefficients of polynomials of Det $[SI-A+BK]$ & desired poles. Using matlab tool the k matrix can be find as,

- 6.0779 78.9991 -8.5771 83.4378
- 0.4527 57.6794 -1.9478 -13.0765

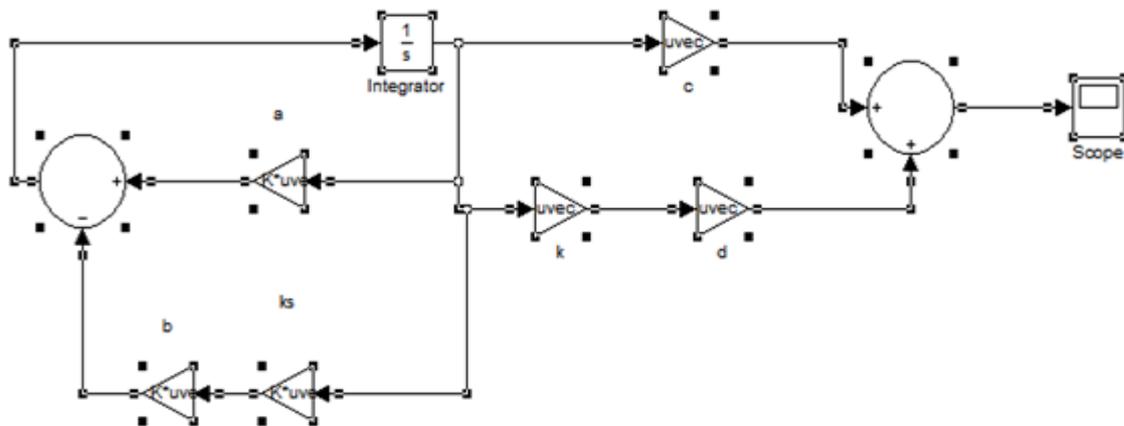


Figure 7: Simulink model for controller using pole placement technique.

Use this [k] into the simulink diagram & get out put as 'y'. This is desired system response.

7. Conclusion

PID Controller design in this paper is specifically cope with the difficulties related to optimization of a system. Proposal of controller contains all three gain values that are self adjusted. This is best to use for an LTI system, having no noise. Otherwise derivative gain of controller is set as zero. PID is used for transfer functions (frequency domain representation) showing the output to input relation.

Pole placement technique is also valid for linier models. By adjusting gains, we are able to get desired Eigen values. Controller law design is applicable to state space (time domain) models.

Unmanned under water vehicles is just like aeronautical or spacecrafts operational mediums. Parametric resemblance shows analogy in structure, usage & principles. Multi-tiered software architectures are becoming defect standard in the defense industry for realization (Command, Control, Communications Computer, Information, Surveillance and Reconnaissance) systems. Naturally, unmanned platforms, and hence UUVs will get advantage of such implementations. Several considerations arise for the realization of such architectures in the unmanned platforms. In order to achieve rapid development and broad maintenance capabilities, robust open source components shall be identified. Certainly, the robustness of these components will also be critical regarding the run time performance of these mission critical vehicles.

References

- [1] J. Feldman, "Revised standard submarine equations of motion," Naval Ship Research and Development Center, Wash. DC, Tech. Rep. D TNSRDC-SPD-0393-09.
- [2] M. Gertler and G. R. Hagen, "Standard equations of motion for submarine simulation," Naval Ship Research and Development Center, Wash. DC, Tech. Rep. R NSRDC2510.
- [3] A. R. J. M. Lloyd, "Submarine Dynamics," Lecture notes, Defence Research Agency, Haslar, Gosport, U.K.
- [4] J. B. Spencer, "Stability and control of submarines. Parts I-IV," *Reprint of the Royal Naval Scient@ Service*, vol. 23., pp. 187-205, 265-281, 1241 S. J. Williams and W. B. Marshfield, "HW multivariable design of a submarine depth control system," *Inst. of Meas. and Contr., Symp. Appl.*
- [5] DISSANAYAKE, M. W. M. G., NEWMAN, P., CLARK, S., DURRANY-WHYTE, H. F., CSORBA, M. A solution to the simultaneous localization and map building (SLAM) problem. *IEEE Transactions on Robotics and Automation*, 2001, vol. 17, no. 3, p. 229 - 241.
- [6] SOZER, E. M., STOJANOVIC, M., PROAKIS, J. G. Underwater acoustic networks. *IEEE Journal of Oceanic Engineering*, 2000, vol. 25, no. 1, p. 72 - 83.
- [7] SOMARAJU, R., SCHILL, F., A communication module and] RUIZ, I. T., REED, S., PETTILOT, Y.,

- BELL, J., LANE, D. M. 345. *ea Keeping-Ship Behavior in Rough* [19] T. Miyake and K. Takahashi, "Application of optimal control theory to submarine control system," *N.E.C., Research and Development*, no. 25, pp. 45-53, Apr. 1972.
- [8] R. J. Martin., L. Valavani, and M. Athans, "Multivariable control of a submersible using the LQGLTR design methodology," in *Proc. Am. Contr. Con\$, Seattle, WA, June 1986.*
- [9] R. J. Richards and D. P. Stoten, "Depth control of a submersible vehicle," *Int. Shipbuilding Progress*, vol. 81, pp. 30-39, 1981.
- [10] M. J. Ruth, "Application of p-synthesis to control design for a submersible *Weather ehicle*," Lecture notes from MUSYN, Robust Control Short Course, CA, Arcadia, Sep. 1989.
- [11] RODRIGUES, L., TAVARES, P., PRADO, M. Sliding mode control of an AUV in the diving and steering planes. In *Proceedings of the MTS/IEEE Oceans'06 Conference*. Fort Lauderdale (FL, USA), 1996, p. 576 - 583.
- [12] SOYLU, S., BUCKHAM, B. J., PODHORODESKI, R. P. A chattering-free sliding-mode controller for underwater vehicles with fault tolerant infinity-norm thrust allocation. *Ocean Engineering*, 2008, vol. 35, no. 16, p. 1647 - 1659.
- [13] CACCIA, M., VERUGGIO, G. Guidance and control of a reconfigurable unmanned underwater vehicle. *Control Engineering Practice*, 2000, vol. 8, no. 1, p. 21 - 37.