Fuzzy logic estimator implemented in observation-tracking device control

Michal Sobolewski
Faculty of Mechatronics and Machine Design, Kielce University of Technology, Kielce, Poland
Norbert Grzesik
Aviation Faculty, Polish Airforce Academy, Deblin, Poland
Zbigniew Koruba
Faculty of Mechatronics and Machine Design, Kielce University of Technology, Kielce, Poland, and
Michal Nowicki
Industrial Institute for Automation and Measurements PIAP, Warsaw, Poland

Abstract

Purpose – Nowadays, various methods of observation from unmanned aerial vehicles (UAV) are being widely developed. There are many ways of increasing the amount of information retrieved from captured material. Unfortunately, hardware solutions consume a lot of energy, which is unacceptable in UAV applications, as it can have direct impact on the observing time on UAV. Those kinds of problems have been identified during the development phase of stabilizing platform in Polish Research Space Centre in Warsaw. As a result of that fact, energy saving control methods have been implemented, which estimates quality of stabilization process for the observation-tracking device (OTD).

Design/methodology/approach – Mathematical model has been designed and validated with real-life experiments for the purpose of optimization of stabilization and control process. Two types of controlling algorithms have been implemented: linear quadratic regulator and proportional derivative method for driving the mechanism. Based on numerical simulations of the mechanical model being controlled by the mentioned driver, it was possible to define membership functions. After the process of defuzzification, the controller predicts quality of stabilization under defined environmental working conditions.

Findings – An autonomous energy saving system has been created that can be implemented in many applications, where environmental conditions may change significantly.

Practical implications – To test the proposed fuzzy controller, OTD has been chosen as an example object of application. It is a mechanical platform which houses the optical observation system. It is designed to provide the best working conditions during flight.

Originality/value – That kind of decision-making unit has never been implemented before during observations which were carried out during flying of an object. That innovative controller should bring significant energy consumption savings.

Keywords Fuzzy logic, Stabilization, Line of sight, Observation and tracking device

Paper type Research paper

Introduction

Imaging system is a fast growing field of science and engineering. Its main scope and origin comes from the demand of bringing detailed information about observed objects. There are many methods of increasing the amount of extracted information from captured material. Some of them are implemented by software tools (e.g. image processing). The other ones use hardware solutions – e.g. stabilizing units that ensure good observation environment. Proposed fuzzy controller, that is a subject of this article, is the unit predicting quality of stabilization provided by stabilizing platform which carries the observing system. It does not only turn on/off the observation process (in case when noises are too high) but also gives information to the platform control unit which method of stabilization to choose. In this way, an automatic decision-making unit is realized that minimizes energy consumption of active damping. Nowadays, researches focus on improving stabilizing algorithm according to working conditions. Proposed estimator is coming out from the safe-energy consumption point of view. To test the proposed fuzzy controller, observation-tracking device (OTD) has been chosen as an example object of application. It is a mechanical platform which houses the optical observation system. It is designed to provide the best working conditions during flight. To provide a stabilizing process, the OTD is equipped with an active dumping system.

As a first step of the mentioned research, mathematical model of stabilizing mechanism was created and validated by numerical model designed in SimMechanics. After that, the theoretical model was linearized, and then by using the matrix

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Aircraft Engineering and Aerospace Technology: An International Journal
88/6 (2016) 697–706

[DOI 10.1108/AEAT-09-2015-0206]

Received 11 September 2015
Revised 18 November 2015
Accepted 27 November 2015

Aircraft Engineering and Aerospace Technology: An International Journal
Volume 88 · Number 6 · 2016 · 697–706

of state and control, an optimal control scheme is proposed. In that case, two methods of control have bene implemented:

1 linear quadratic regulator (LQR); and
2 proportional derivative (PD) controller.

From numerical simulations of a mathematical model being driven by proposed controllers, it was possible to get a fuzzy rule base of boundary conditions (parameters of the unit and noises) and a fuzzy base of experiences (quality of stabilization). Based on that information, fuzzy logic rules were defined. That unit, according to environmental conditions, will automatically switch observing process into three modes: driving with LQR, driving with PD or terminating observation.

That kind of decision-making unit has never before been implemented during observations which were carried out during flying of an object. That innovative controller should bring significant energy consumption savings.

Fuzzy logic controller – design and application

Below sections will describe step-by-step methodology of defining fuzzy logic controller. It is essential to mention that stabilized platforms (as an example mechanism of described research) have been used on every type of moving vehicle, from satellites to submarines, and are even used on some handheld and ground-mounted devices described for example in Hilkert (2008) or Debruin (2008). Its application is quite abroad, and it becomes an investigative hotspot in most countries all the time. From the control point of view, line of sight (LOS) algorithms have also been already widely developed and described in the literature. Mostly conventional methods of control synthesis have been reported for such applications. For conventional design methods, well-known techniques such as Bode plots, etc., are applied. Modern synthesis tools such as LQR or linear quadratic Gaussian with loop transfer recovery and H_∞ control methodologies have also been used in some applications. Also in recent years, the fuzzy control technology has been developed successfully. It improves the system control performance and has the good adaptability for the system with nonlinear mathematical model and uncertain factors. Some of mentioned methods can be found in Moorty *et al.* (2004), Ji *et al.* (2011) and Hong (2003). However, as described in literature, controlling methods are assuming constant processes of observing, forcing hardware system (in that case stabilizing platform) to reduce disturbance effects even in case of highly demanding working conditions. Proposed estimator not only is advising stabilizing controller which method of stabilization to use but also can terminate observation.

Observation – tracking device – example mechanism

For the purpose of presenting functionality of proposed fuzzy controller, that driver will be implemented in stabilizing platform, which was prototyped in Polish Research Space Centre in Poland and is described by Grygorczuk *et al.* (2010) (Figure 1).

This mechanism is based on a double cardan joint structure (Figure 2).

The stabilizing platform includes:

Figure 1 Stabilization platform prototyped in Polish Research Space Centre

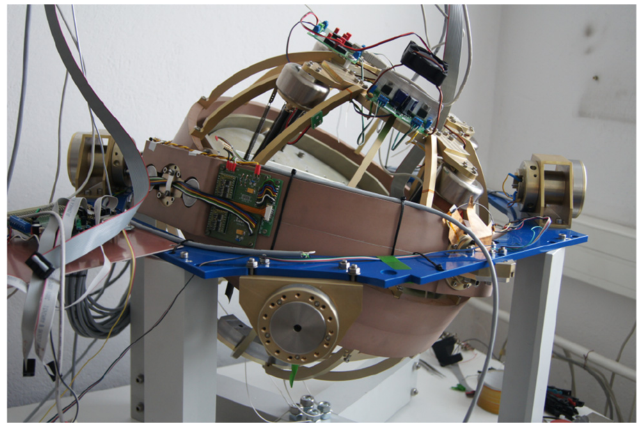
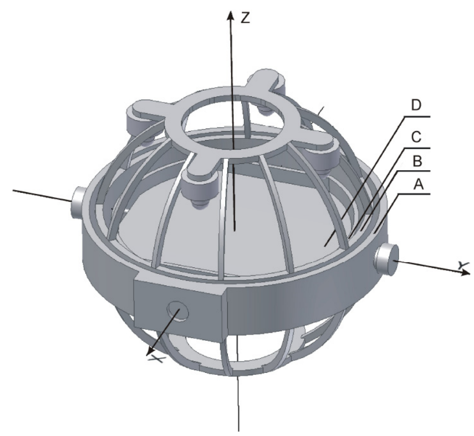


Figure 2 Double cardan joint



- exterior cardan joint (frames A and B); and
- interior cardan joint (frames C and D).

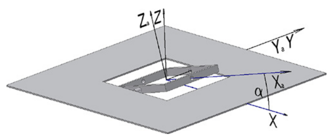
It is very often suggested and implemented in many other hardware solutions (Masten, 2008) that stabilizing platform includes a two-joint cardan.

Mathematical model

To fully understand the influence of moving parts on stabilizing effect and to adjust optimal control algorithm, the mathematical model of that device must be defined. In the first phase, moments of inertia for each moving assembly have been calculated. After that, vectors relating to each frame have to be transited into fixed coordinate system (board of the flying object). That coordinate system OXYZ is a stable system in relation to which two cardan joints are rotating. Frames A and B belong to exterior joint, frames C and D to interior cardan. Frames A and D are rotating around axle OY, frames B and C are rotating around axle OX. For each frame, separate coordinate system has to be assigned. Below, you can see examples of how transitions matrixes are being defined (Figure 3).

So the transition matrix for this example equals to:

Figure 3 Double cardan joint



$$M_\alpha = \begin{vmatrix} \cos\alpha_g & 0 & \sin\alpha_g \\ 0 & 1 & 0 \\ -\sin\alpha_g & 0 & \cos\alpha_g \end{vmatrix} \quad (1)$$

Angular velocity of each frame in particular coordinate system equals to:

$$\begin{aligned} \begin{vmatrix} \omega_{gxa} \\ \omega_{gya} \\ \omega_{gza} \end{vmatrix} &= M_\alpha \cdot \begin{vmatrix} p_p \\ q_p \\ r_p \end{vmatrix} + \begin{vmatrix} \alpha'_{gxa} \\ \alpha'_{gya} \\ \alpha'_{gza} \end{vmatrix} \\ &= \begin{vmatrix} p_p\cos\alpha_g - r_p\sin\alpha_g \\ q_p \\ p_p\sin\alpha_g + r_p\cos\alpha_g \end{vmatrix} + \begin{vmatrix} 0 \\ \alpha'_g \\ 0 \end{vmatrix} \\ &= \begin{vmatrix} p_p\cos\alpha_g - r_p\sin\alpha_g \\ q_p + \alpha'_g \\ p_p\sin\alpha_g + r_p\cos\alpha_g \end{vmatrix} \end{aligned} \quad (2)$$

where:

- α_g = equals to the angle between frame A and a stable board;
- ω_{gxa} = is the angular velocity of frame A around x-axis (the same for frames B, C and D);
- ω_{gya} = is the angular velocity of frame A around y-axis (the same for frames B, C and D); and
- ω_{gza} = is the angular velocity of frame A around z-axis (the same for frames B, C and D).

P_p, q_p and r_p are angular velocities of the flying object (later assumed to equals to zero).

The second Lagrange method helped to define positions (angle α_g, β_g, γ_g, ϕ_g) and angular velocities. Detail description of that methodology can be found in Koruba and Krzysztofik (2013), Krzysztofik (2012) and Sobolewski and Koruba (2012). For example, for angle α_g that equation looks like:

$$\frac{d}{dt}\left(\frac{dE_k}{d\dot{\alpha}_g}\right) - \frac{dE_k}{d\alpha_g} = Q_{i\alpha_g} \quad (3)$$

where:

- E_k = is the total kinetic energy; and
- $Q_{i\alpha g}$ = is the generalized force applied to drive frame A.

To estimate functions defining values of angles, it was assumed that:

- centres of masses for each moving joints are in that same place, as the point that is a geometrical result of intersection of rotation axles;
- local axles (belonging to each frame) are main and central axles; and
- linear velocity of a board equals to zero.

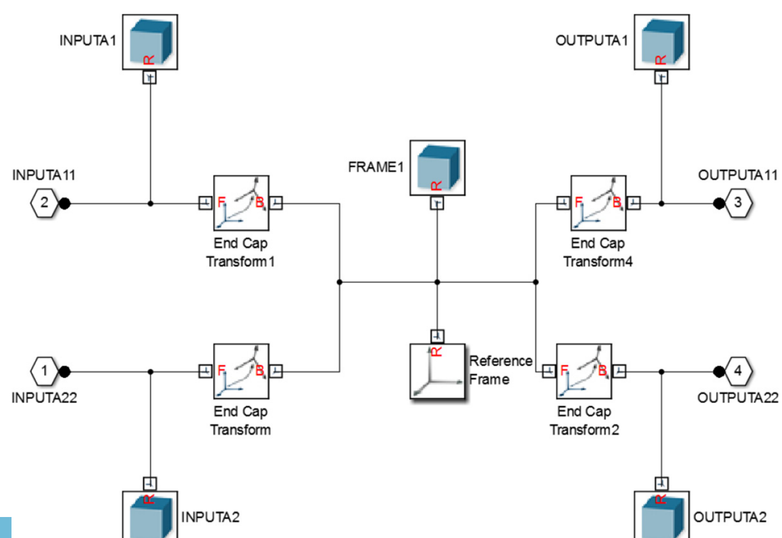
Because of the fact that there is no linear velocity for the centre of mass, and there is no distance between centre of rotation and centre of mass, total kinetic energy is only a sum of angular kinetic energy:

$$\begin{aligned} E_k = {} & \frac{1}{2}(I_{xa}\varpi_{gxa}^2 + I_{ya}\varpi_{gya}^2 + I_{za}\varpi_{gza}^2) \\ & + \frac{1}{2}(I_{xb}\varpi_{gxb}^2 + I_{yb}\varpi_{gyb}^2 + I_{zb}\varpi_{gzb}^2) \\ & + \frac{1}{2}(I_{xc}\varpi_{gxc}^2 + I_{yc}\varpi_{gyc}^2 + I_{zc}\varpi_{gzc}^2) \\ & + \frac{1}{2}(I_{xd}\varpi_{gxd}^2 + I_{yd}\varpi_{gyd}^2 + I_{zd}\varpi_{gzd}^2) \end{aligned} \quad (4)$$

where:

- I_{xa} = is a moment of inertia of frame A around X axis (the same for frames B, C and D);
- I_{ya} = is a moment of inertia of frame A around Y axis (the same for frames B, C and D); and

Figure 4 Double cardan joint stabilizing platform frame definition – SimMechanics



Aircraft Engineering and Aerospace Technology: An International Journal
Volume 88 · Number 6 · 2016 · 697–706

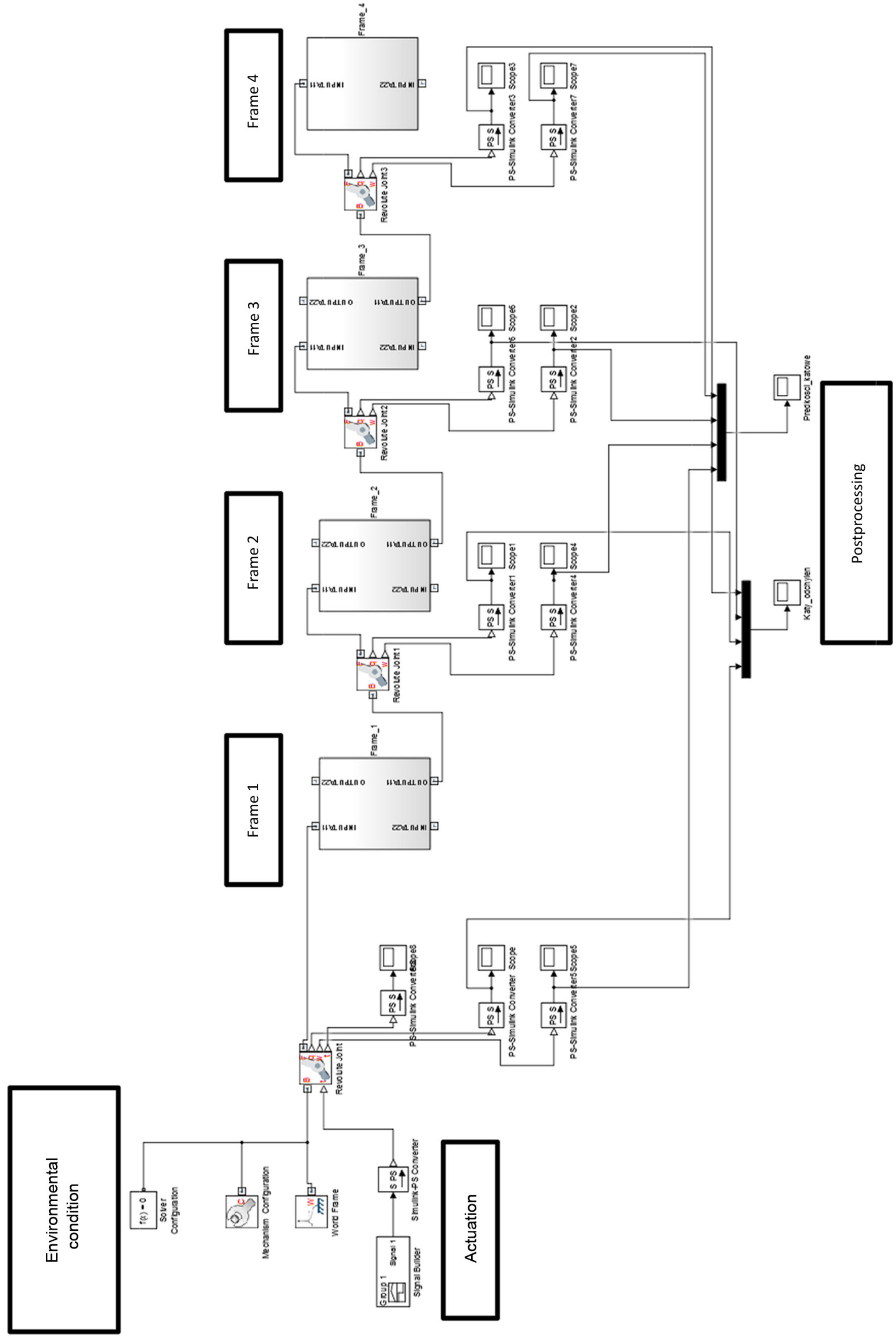


Figure 5 Stabilizing platform and working environment – SimMechanics

Figure 6 Rotation angles estimated by mathematical model and obtained in SimMechanics tool

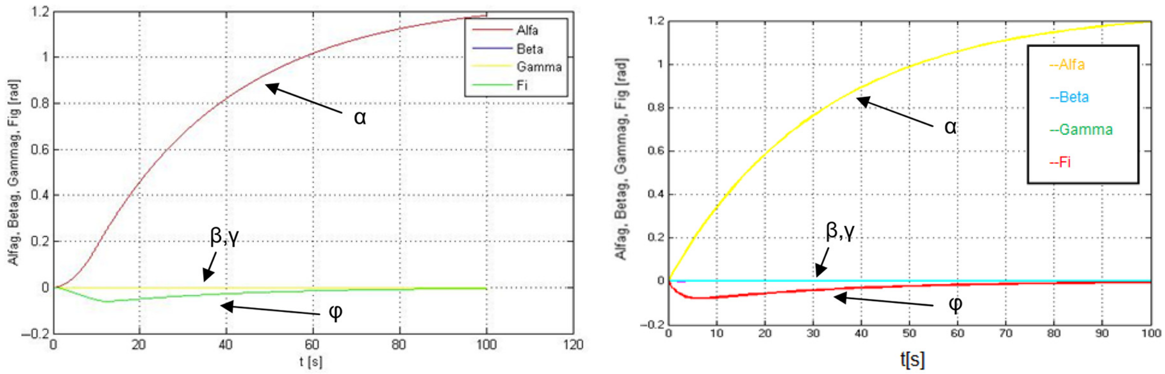
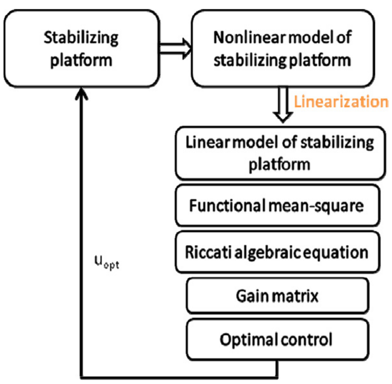


Figure 7 Block scheme of the control algorithm for the OTD



I_{za} = is a moment of inertia of frame A around Z axis (the same for frames B, C and D).

After differentiation of kinetic energy functions, four angular accelerations have been estimated. To calculate values of angular velocities and positions for each frame (in a domain of time), classic Euler method of integration is used. The linearized values of angular accelerations are presented in equations (5-9).

Model validation

To validate estimated equations, a theoretical model was designed in SimMechanics software – reference can be found in Venkataraman (2002). This kind of tool helps to simulate behaviour of the unit and is a very good method of validating long hand calculations carried out by classic methods. It gives a very clear understanding of behaviour of considered mechanics and helps to indicate possible errors. To define stabilizing platform geometry, it was assumed that each frame is a combination of zero mass ring plus cylindrical joint (Figures 4 and 5).

Each frame is connected with next frame by cylindrical joints working in defined environment. For validation purpose, impulse moment on the first joint was applied. Figures presenting angles estimated by designed mathematical model should be the same, as these were obtained by SimMechanics tool. Identity of results proves proper design of a mathematical model (Figure 6).

Linear quadratic regulator method

In Figure 7, there is an illustrated scheme of finding gain matrix to control stabilizing platform, which can be found also in Awrejcewicz and Koruba (2012). In the first step, the nonlinear functions of frame angles α_g, β_g, γ_g and Φ_g were linearized.

For the purpose of linearization, we assumed that:

- $\cos \alpha_i \approx 1$ and $\sin \alpha_i \approx \alpha_i$ for small α_i; and
- product of multiplication of small values equals to zero.

Linearized values of angular accelerations are presented below:

$$\ddot{\alpha}_g = \frac{M_\alpha - M_\phi - \dot{\alpha}_g \cdot \varepsilon_\alpha + \dot{\phi}_g \cdot \varepsilon_\phi}{I_{ya} + I_{yb} + I_{yc}} \tag{5}$$

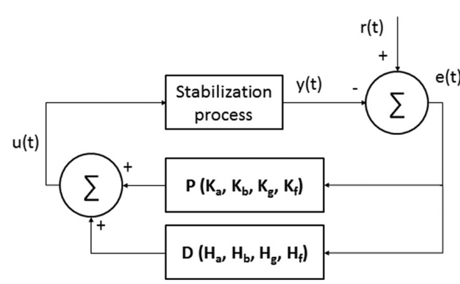
$$\ddot{\beta}_g = \frac{M_\gamma + M_\beta - \dot{\beta}_g \cdot \varepsilon_\beta + \dot{\gamma}_g \cdot \varepsilon_\gamma}{I_{xb}} \tag{6}$$

$$\ddot{\gamma}_g = \frac{M_\gamma - M_\beta + \dot{\beta}_g \cdot \varepsilon_\beta - \dot{\gamma}_g \cdot \varepsilon_\gamma + \dfrac{I_{xb} \cdot (M_\gamma - \dot{\gamma}_g \cdot \varepsilon_\gamma)}{I_{xc} + I_{xd}}}{I_{xb}} \tag{7}$$

$$\ddot{\phi}_g = \frac{M_\phi - \dot{\phi}_g \cdot \varepsilon_\phi}{I_{yd}} - \ddot{\alpha}_g \tag{8}$$

After that, linearized equations of mechanism movements were presented in the matrix of states.

Figure 8 PD controller used in stabilizing process – schematic view



Aircraft Engineering and Aerospace Technology: An International Journal
Volume 88 · Number 6 · 2016 · 697–706

Table I Noises description and stabilizing error values

Exterior noises		Interior noises			
fz – frequency (Hz × 1,000)	Az – amplitude (rad/s)	fw – frequency (Hz × 1,000)	Aw – amplitude (rad/s)	Stabilizing error (LQR) (rad/s)	Stabilizing error (PD) (rad/s)
0.005	5	0	0	81.4955	80.7230
0.005	10	0	0	304.77	264.0790
0.005	15	0	0	661.23	539.3816
0.01	5	0	0	301.14	261.0679
0.1	5	0	0	4.28e + 03	4.0815e + 03
0.3	20	0	0	8.54e + 03	Inf.
0	0	0	0	5.39	16.2065
0	0	0.005	0.1	99	101.5547
0	0	0.005	0.4	380	364.1693
0	0	0.005	0.7	661	627.6240
0	0	0.01	0.1	191	187.9189
0	0	0.1	0.1	890	801.4889
0	0	0.3	1	8.33e + 04	7.9231e + 03
0.0005	5	0	0	8.7513	16.8001
0.0005	10	0	0	8.9777	18.7075
0	0	0.0005	0.3	10.2211	41.3302
0	0	0.0005	0.6	11.8851	67.1225

Table II Membership functions definition

	Exterior noise		Interior noise	
Fuzzy classes	Fz – frequency (Hz × 1,000)	Az – amplitude (rad/s)	fw – frequency (Hz × 1,000)	Aw – amplitude (rad/s)
bm	–	–	0–0.0005–0.005	–
m	0.0005–0.005–0.01	0–5–10	0.0005–0.005–0.01	0–0.1–0.4
s	0.005–0.01–0.1	5–10–15	0.005–0.01–0.1	0.1–0.4–0.7
d	0.01–0.1–0.3	10–15–20	0.01–0.1–0.3	0.4–0.7–1

$$\dot{x} = Ax + Bu \tag{9}$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -a_{11} & 0 & 0 & 0 & 0 & 0 & a_{14} \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -a_{22} & 0 & a_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & a_{32} & 0 & -a_{33} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & -a_{41} & 0 & 0 & 0 & 0 & 0 & -a_{44} \end{bmatrix} \tag{10}$$

$$a_{11} = \frac{\varepsilon_\alpha}{I_{ya} + I_{yb} + I_{yc}} \quad a_{14} = \frac{\varepsilon_\phi}{I_{ya} + I_{yb} + I_{yc}} \quad a_{32} = \frac{\varepsilon_\beta}{I_{xb}} a_{22} = \frac{\varepsilon_\beta}{I_{xb}} \quad a_{23} = \frac{\varepsilon_\gamma}{I_{xb}} \quad a_{33} = \frac{\varepsilon_\gamma (I_{xb} + I_{xc} + I_{xd})}{I_{xb}(I_{xc} + I_{xd})}$$

$$a_{44} = \frac{\varepsilon_\phi (I_{ya} + I_{yb} + I_{yc} + I_{yd})}{I_{yd}(I_{ya} + I_{yb} + I_{yc})}$$

$$\mathbf{x}^T = \left| \alpha \quad \dot{\alpha} \quad \beta \quad \dot{\beta} \quad \gamma \quad \dot{\gamma} \quad \phi \quad \dot{\phi} \right| \tag{11}$$

$$\mathbf{u}^T = \left| M_\alpha \quad M_\beta \quad M_\gamma \quad M_\phi \right| \tag{12}$$

Table III Linguistic terms and ranges of membership

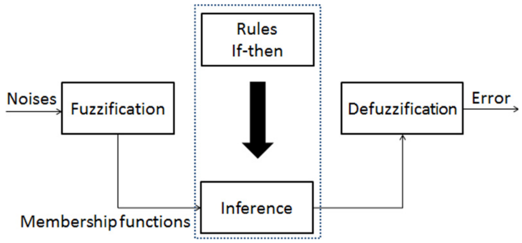
Fuzzy classes	Stabilizing error (rad/s)
bm	0–0–200–400
m	200–400–600
s	400–600–800
d	600–800–1,000
bd	800–1,000–10,000

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ b_{\alpha_1} & 0 & 0 & b_{\phi_1} \\ 0 & 0 & 0 & 0 \\ 0 & b_{\beta_1} & b_{\gamma_1} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & b_{\beta_2} & b_{\gamma_2} & 0 \\ 0 & 0 & 0 & 0 \\ b_{\alpha_2} & 0 & 0 & b_{\phi_2} \end{bmatrix} \tag{13}$$

$$b_{\alpha 1} = \frac{1}{I_{ya} + I_{yb} + I_{yc}} \; b_{\phi 1} = \frac{-1}{I_{ya} + I_{yb} + I_{yc}};$$
$$b_{\gamma 1} = \frac{1}{I_{xb}} \; b_{\beta 1} = \frac{1}{I_{xb}} \; b_{\beta 2} = \frac{-1}{I_{xb}} b_{\gamma 2} = \frac{I_{xb} + I_{xc} + I_{xd}}{I_{xb}(I_{xc} + I_{xd})}$$

$$b_{\alpha 2} = \frac{-1}{I_{ya} + I_{yb} + I_{yc}}; \; b_{\phi 2} = \frac{1}{I_{yd}} + \frac{1}{I_{ya} + I_{yb} + I_{yc}}$$

Figure 9 Fuzzy logic regulator – schematic view



To estimate the gain matrix, Riccati equation was solved – described also in Wang *et al.* (2009). In that step, the weighting factors R and Q have to be specified and verified with specified design goals. That search starts from values:

$$q_{ii} = \frac{1}{2x_{i_{\max}}} \quad (14)$$

$$r_{ii} = \frac{1}{2u_{i_{\max}}} \quad (15)$$

for

$$(i = 1, 2, \ldots 8)$$

$x_{i_{max}}$ = maximum range of deviation of i-state value; and
$u_{i_{max}}$ = maximum range of deviation of i-control value.

Afterwards, the user adjusts the weighting factors to get a controller more in line with the specified design goals (in our case, it is fast stabilization of the platform).

Proportional derivative controller

This well-known and widely used in control loop feedback system method calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable (Figure 8).

where:

k_a = is the proportional gain for first frame (the same for b, g, f);
h_a = is the derivative gain for the first frame (the same for b, g, f); and
Values of k_i and h_i = are influencing on resulting stabilization (precision and time).

Numerical simulations of observation tracking device and definition of stabilizing quality

There are many causes of stabilizing error which appear during observing process, which are very briefly described in Hilkert (2008). To estimate and present the behaviour of controlled system in different kind of situations, following disturbances have been added to the controlled unit:

- exterior noises (which physically can be interpreted as vibrations on board of flying object) with parameter of frequency f_z and amplitude A_z; and
- interior noises (which physically can be interpreted as noises of sensors and actuators in the active damping system) with parameter of frequency f_w and amplitude A_w.

To define quality of stabilization, there will be a used parameter which is described in analogue signals as:

Figure 10 Defuzzification interface view

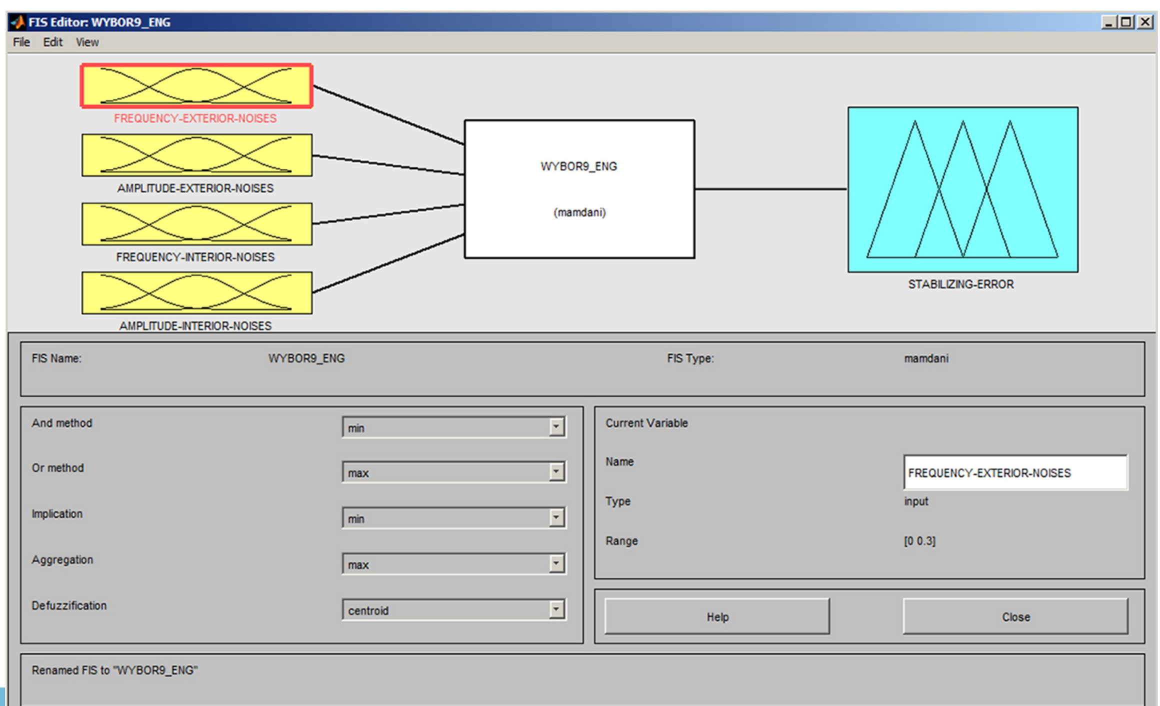


Figure 11 Input-output surface – exterior noises

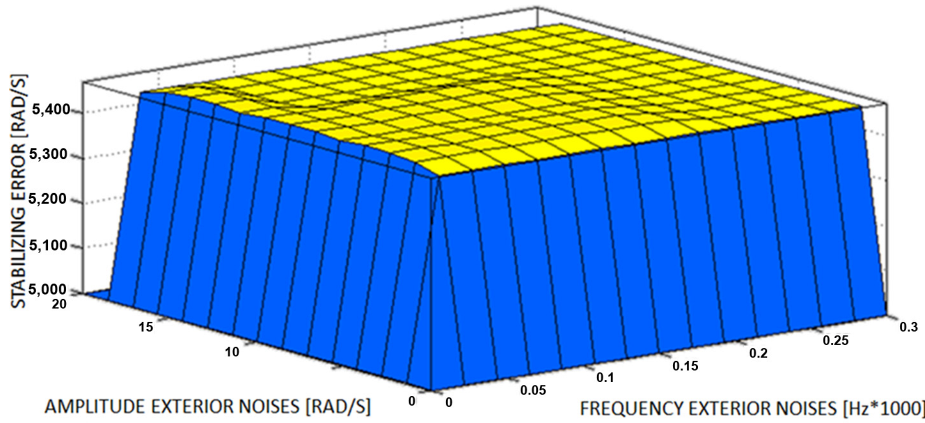
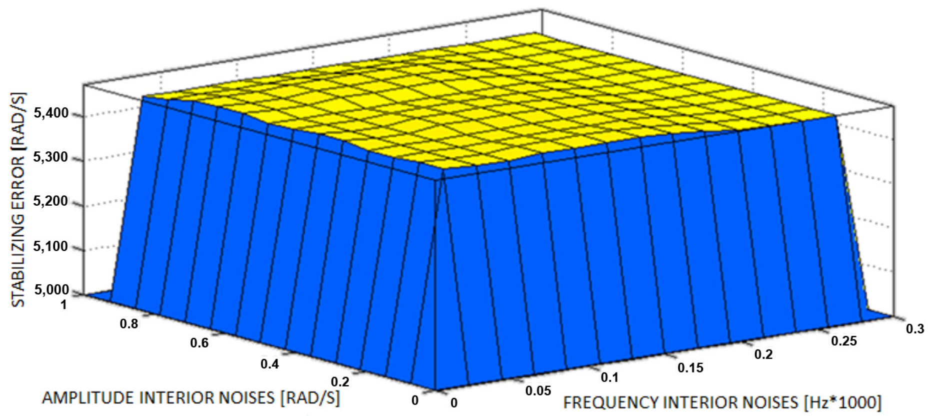


Figure 12 Input-output surface – interior noises



$$\mathcal{J}(u(t)) = \int_{t_0}^{t_k} e^2 dt \tag{16}$$

which in numerical simulations will be presented as:

$$\mathcal{J}_n = |x_z - x_r| \tag{17}$$

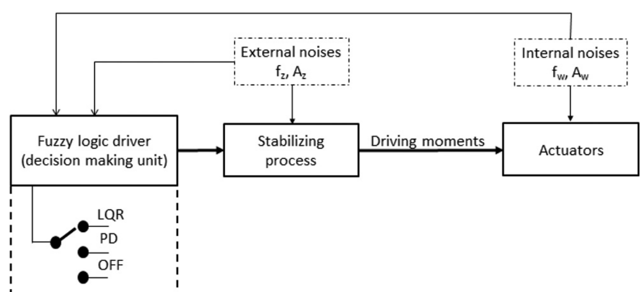
where:

x_z = is the requested value; and
x_r = is the real value.

More descriptions about stabilizing error quality can be found in Idziaszek and Grzesik (2014) and Tomaszek *et al.* (2011). According to the above mathematical definitions, stabilizing error will be a sum of differences between the desire and the real value of angle. To compare total process of stabilization for all four angles, we used a sum as described below:

$$\mathcal{J}_{nt} = \sum_{i=\alpha}^{i=\varphi} |x_z^i - x_r^i| \tag{18}$$

Figure 13 Reasoning process



That kind of parameter will describe process of stabilization in terms of accuracy and time dependency, and it will be called in that paper as a stabilizing error.

Results of numerical simulation – fuzzification and defuzzification

Simulations based on the described mathematical model with LQR and PD control methods have been performed. To understand the influence of interior and exterior noises, the following results are presented below (Table I).

According to the above results, only in case when noise frequencies are very low, it is more beneficial to drive stabilization platform by LQR method. Interior noises are

Table IV Random parameters of noise – driver checking

Exterior noises		Interior noises				
f_z – frequency (Hz × 1,000)	A_z – amplitude (rad/s)	f_w – frequency (Hz × 1,000)	A_w – amplitude (rad/s)	Stabilizing error–numerical simulation (rad/s)	Stabilizing error–fuzzy estimator (rad/s)	Difference (%)
0.002	2	0.01	0.01	162	150	7
0.002	2	0.01	0.2	220	210	5
0.005	2	0.01	0.2	375	323	14
0.006	2	0.005	0.1	310	329	6
0.006	2	0.006	0.2	225	238	6
0.006	3	0.006	0.2	230	264	15
0.006	5	0.006	0.1	149	173	16
0.006	5	0.006	0.3	316	335	6
0.006	5	0.006	0.4	430	445	3
0.006	5	0.006	0.4	430	445	3
0.006	20	0.006	1	1.5e + 03	4.92e + 03	228

more problematic for PD controller when frequencies are very low. In any other cases (greater values of noise frequencies), PD control should be implemented. It is important to mention that this comparison is based on certain values of driving constant parameters (Q, R driving matrixes and PD settings).

At this point, we defined the linguistic fuzzy logic terms and their ranges:

bm = very small
m = small
s = average
d = big
bd = very big

The membership functions are in a shape of triangle as described below. More information about defining fuzzy logic classes and rules can be found in Żurek and Grzesik (2014), Zadeh (1965) and Adamski and Rajchel (2013). Because of the fact that the interior noise is very problematic for PD control when frequencies are very low, there was a defined bm membership function for that parameter. It is assumed that fuzzy estimator will automatically switch to LQR driving method in conditions of low frequencies of internal noises (Table II).

The classes defining quality of stabilization are described by triangular and trapezoid membership functions (Table III).

The possible combinations of each states give 108 variants defined as:

If (f_z is [m, s, d]) and (A_z is [m, s, d]) and (f_w is [m, s, d]) and (A_w is [m, s, d]), then (Stabilizing error is [bm, m, s, d, bd]).

Synthesis and validation of fuzzy logic regulator

After defining classes and their borders, fuzzy logic regulator is defined as described below. Detail description can be also found in Tewari (2002) (Figure 9).

Defuzzification tool designed in Matlab is presented below (Figure 10).

For inference operation, there is applied Mamdani reasoning method. As a result, we get input-output surfaces as presented below (Figures 11 and 12).

The schematic view of how the integrated unit will work is presented below (Figure 13).

To check proper behaviour of designed controller, different parameters of noise have been applied (Table IV).

Above results prove proper behaviour of designed controller. Increasing the parameters of noises (frequencies, amplitudes) increases the stabilizing error. Proposed membership functions and borders of fuzzy classes seem appropriate for a highly demanding system in terms of environmental conditions. In case of low values of amplitudes and frequencies, fuzzy controller estimates stabilizing error is very similar to reference (maximum 16 per cent of difference). When the phenomenon of noise is increased, then the controller more conservatively indicates high stabilizing error.

Conclusions

As a result of the performed analysis and the research, we achieved effective autonomous decision-making unit which predicts failure of observation and saves energy for stabilization tracking unit. Moreover, that kind of controller does not only turn on/off stabilizing process but also advises which stabilization algorithm to apply. For instance, instead of filtering noise (cutting the signal values), it is better to control unit by another method which is not sensitive for low frequencies. Now it is up to the user and sensitivity of optical system to determine which class of stabilization will be acceptable in terms of observing. If the imaging system is not very demanding, user can accept "big" stabilizing error as the limit value of switching on condition. In case of very sensitive optical unit, the level of "medium" stabilizing error can be the selected observing condition, which always leads to energy consumption reduction.

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Further reading

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Corresponding author

Michal Sobolewski can be contacted at: michalsobolewski86@gmail.com