Fuzzy Tuned PID Controller for Vibration Control of Agricultural Manipulator

1st Satyam Paul
Department of Engineering Design and Mathematics
University of the West of England
Bristol, United Kingdom
satyam.paul@uwe.ac.uk

2nd Ajay Arunachalam
Centre for Applied Autonomous Sensor Systems (AASS)
Örebro University
Örebro, Sweden
ajay.arunachalam@oru.se

3rd Davood Khodadad
Department of Applied Physics and Electronics
Umeå University
Umeå, Sweden
davood.khodadad@umu.se

4th Olena Rubanenko
Regional Innovational Center for Electrical Engineering
Faculty of Electrical Engineering
University of West Bohemia
Pilsen, Czech Republic
rubanenk@rice.zcu.cz

***Abstract*—Image-based phenotyping systems have evolved over the years, and become an integral part of crop and plant science research. Phenotyping systems provide great potential to deliver critical insights, than the conventional destructive field m ethods. S table i mage a cquisition a nd p rocessing i s very important to accurately determine the characteristics in general, which further becomes very challenging and non-trivial when mounted over an motor mechanised arm. To address the near associated problems, we investigate on the possibility of applying the Proportional–Integral–Derivative (PID) control algorithm to the present manual setup with an aim to reduce vibration. This study focused towards investigating the active control and stabilization of the external camera shake, that may be induced by the driving motor. Nonetheless, very few researchers have focused on application of control algorithms for agriculture related practices. We validate the active control, and justify the need for the same.Type-2 fuzzy logic is combined with the PID control for better effectiveness. The non-linearity associated with the system is compensated by the type-2 fuzzy logic. The results shows that the active control has been achieved, and the vibration is minimized.**

***Index Terms*—fault detection, fuzzy logic, stability**

I. Introduction

Plant Phenotyping, often refers to the use of non-invasive & digital technologies to interpret observable physical properties of the plants. For e.g. appearance, development, interaction behavior with the environment, etc. Image-based plant phenotyping methods have evolved over the years, gaining wide acceptance [1] [2]. Autonomous agricultural robots have been the modern day practices used to automate the tedious manual operations in agriculture ranging from harvesting, picking, mowing, pruning, seeding, sorting and packing, phenotyping, field monitoring, pest spraying, disease detection, etc [3]. The robot arm have links and joints, that can move through greater angles, and can also have up or down motion, while compared to a human who can only bend their elbow in one direction (upward) with respect to the straight arm position. One such example of an articulated robot can be found in [4].

Cameras mounted over such articulated robot arm setup is more vulnerable making the image unsuitable prominently by camera shake, and poor focus during the exposure time as a result of camera motion. Camera shake induced by the running of the motors incurs serious concerns in such image acquisition pipeline. [5] investigate the blur induced by camera shake. They utilized the spectral statistics of camera shaken images to predict perceptual blur from such images. If the external camera block mounted on any motion-based setup incurs lot of shaking/jittering it will result in poor degraded quality pictures. Such, vulnerable situation can be handled in two ways - Offline/Online [6]. In the past, researchers have focused a lot on the former one, that requires application of complex algorithms to carry out different steps offline for image correction, noise removal, camera calibration, etc. On the other hand, the latter one suits well for the real-time application scenarios. Previous works for online process were focused on using complex algorithms online, that makes it further complex, and computationally overloaded. As our aim moving ahead is to mechanise the current setup inplace, this urged us to investigate it from the hardware point of view (motor), where the control algorithms can be applied to cancel out the vibrations incurred by the motor.Industrial manipulators also commonly known as robot arm, have been widely used in the past.

Control and stabilization of such manipulators is an continuous ongoing research problem. In the past, several adaptive control strategies were introduced. The robustness of PID controllers against noise and parameter variations, makes it feasible for real control problems. [7] present their study on the motion of a 6-DoF robot mechanism regardless of the forces and torque that cause it. Control algorithms being popular are widely used in many industrial applications, i.e., e.g: in context to structural vibration control. [8] suggest that with the use of implementable mechanical damping device an uniform exponential stability can be gained. But, then the active control becomes a non-trivial task, when it is non-linear in nature [9]. In the article [10], the authors proposed to use an adapted vibratory drive for a vibrating mixer [11] and vibration grinding [12]. But this developed system of generation and control of mechanical oscillations can also perform the function of a mechanical damping system. However, it should be noted that this system should be used when the oscillation parameters do not change significantly over time. Etxebarria et al. [13] proposed a scheme that uses sliding-mode controller, for flexible link robotic manipulators, aimed to alleviate the uncertainty and disturbances with introduction of smooth function rather than using the sign function. In the work by Paul et al. [14], PD/ PID controllers is utilized to control the unwanted vibration involved in bidirectional structure and the stability of the controllers is validated. A discrete time sliding mode controller in combination with type-2 fuzzy logic system is implemented for the vibration control of milling chatter [15].

The robustness and simplicity of a system can be maintained by implementing the concept of fuzzy logic, which has gained extreme research popularity due to its ability to conduct non-linear mapping. Being robust in mapping non-linear nature effectively, fuzzy logic has been widely used. A type-2 fuzzy logic with embedded additional DOF termed as footprint of uncertainty outperforms the type-1 fuzzy logic system [16] [17]. The main concept with technical content related to the type-2 fuzzy was illustrated by Liang and Mendel [18]. One of the efficient way to compensate uncertainties is the utilization of type-2 fuzzy logic as it has superior performance capacity than type-1 fuzzy logic [19]. In the work of Paul et al. [20], it was demonstrated that the type-2 fuzzy PD/PID controller performed better than the classical fuzzy PD/PID controller in the control of vibration of the structure. An innovative concept involving type-1 and type-2 fuzzy logic systems were proposed for pitch angle controlled wind energy systems as an application for the performance investigation. The results show that the type-2 fuzzy logic system offers better performance in comparison to type-1 fuzzy logic systems [21]. A comparison between type-1 fuzzy and type-2 fuzzy logic controllers implemented in laser tracking systems was carried out by Bai et al. [22].

Although many control strategies have been utilized to control the vibration in manipulator associated to various applications, no control strategy have been provided to control the vibration in such envisioned agricultural manipulator with simple low-cost hardware devices. Also, the combination of PID control with Type-2 fuzzy logic (T2-F-PID) is an innovative way, and first of its kind for this application for vibration control. These are the main motivations of this paper. Also, the vibration attenuation results with T2-F-PID is compared with conventional PID controller and the stability of the combined controller is validated using Lyapunov stability analysis.

II. Fuzzy Modeling of Manipulator

The polar moment of inertia of a DC motor is given by:

$$P_t = m_m r_m^2 \tag{1}$$

where, m_m signifies motor mass and r_m signifies motor radius.The mathematical model of the manipulator having rotational motion due to the motor is:

$$P_t\ddot{\theta} + D_\theta\dot{\theta} + S\theta = f_e \tag{2}$$

where θ is the angular position, P_t is the polar moment of inertia, D is the damping force, S is the stiffness force vector, and $\mathbf{f}_e$ is the external force on the manipulator. The manipulator with motor arrangements is shown in Fig. 1.

Fig. 1. Manipulator with motor arrangement.

Now let u_θ be the control force require to attenuate the torsional vibration. For minimization of vibration along theta direction, a torsion actuator (TA), is positioned at the physical center of the motor box arrangement, see Fig. 2. The TA is a rotating disc like structure combined with a DC motor. .

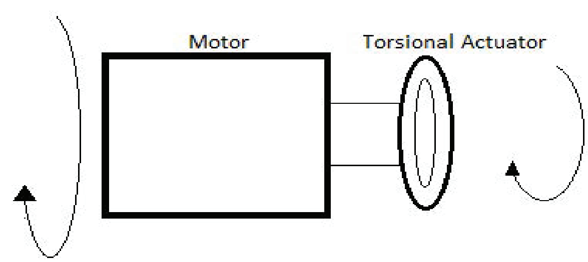

Fig. 2. The placement of TA.

The modeling equation of the manipulator (2) with the control force u_θ is:

$$P_t\ddot{\theta} + D_\theta\dot{\theta} + S\theta = f_e + u_\theta - F_{ta} \tag{3}$$

where F_{ta} is the damping and friction force vector associated with the torsional actuator. The torque T_τ generated by the torsional actuator is [23]:

$$T_\tau - F_{ta} = P_{ta}(\ddot{\theta}_{ta} + \ddot{\theta})$$

where P_{ta} is the polar moment of inertia of the TA, $\ddot{\theta}_{ta}$ is the angular acceleration of the TA . The friction in the torsional actuator is:

$$F_{ta} = C\dot{\theta} + (F_c + F_{cs} \sec h(H\dot{\theta})) \tanh(B\dot{\theta})$$

where C and F_c represents torsional viscous friction coefficient and Coulomb friction torque respectively, F_{cs} is the Striebeck effect component. Also, H and B are the dependent variables associated to F_{cs} and F_c respectively. The closed loop system (3) becomes

$$P_t\ddot{\theta}+D_\theta\dot{\theta}+S\theta+C\dot{\theta}+(F_c+F_{cs} \sec h(H\dot{\theta})) \tanh(B\dot{\theta})-f_e = u_\theta \quad (4)$$

Now in eqn. (4), u_θ is the control force to be fed to the torsional actuator for the vibration control which is equivalent to the torque force $P_{ta}(\ddot{\theta}_{ta} + \ddot{\theta})$.

The term $C\dot{\theta}+(F_c+F_{cs} \sec h(H\dot{\theta})) \tanh(B\dot{\theta})-f_e$ involves nonlinearity and has to be dealt in an effective manner. Now the nonlinear term can be expressed as follows:

$$f_\theta = C\dot{\theta} + (F_c + F_{cs} \sec h(H\dot{\theta})) \tanh(B\dot{\theta}) - f_e \quad (5)$$

So the eqn. (4) is:

$$m_m r_m^2 \ddot{\theta} + D_\theta\dot{\theta} + S\theta + f_\theta = u_\theta \quad (6)$$

For handling the nonlinearities, Type-2 fuzzy logic system is implemented.The type-2 fuzzy sets can model uncertainties with less fuzzy rules and with greater ease.The type-2 fuzzy sets has advantages over type-1 fuzzy sets as type-2 fuzzy involves less fuzzy rules in dealing uncertainities effectively. The output associated with the fuzzy technique $\hat{f}_\theta$ can be expressed as: [24]:

$$\begin{gathered} \hat{f}_\theta = \tfrac{y_{right}+y_{left}}{2} \\ \hat{f}_\theta = \tfrac{1}{2}\left[\phi_r^T(z_\theta)w_r(z_\theta) + \phi_l^T(z_\theta)w_l(z_\theta)\right] \end{gathered} \quad (7)$$

where $z = \begin{bmatrix}\theta & \dot{\theta}\end{bmatrix}^T$.

III. Type-2 Fuzzy Control of Manipulator

PID controllers utilizes the methodology of feedback strategy which has three incorporated actions:

P : To increase the speed of response;

D : For damping purposes;

I: To obtain a desired steady-state response. When type-2 fuzzy technique is combined with the PID controller then the outcome is:

$$u_\theta = -K_p\theta - K_i\int_0^t \theta d\tau - K_d\dot{\theta} - \frac{1}{2}\phi_r^T(z_\theta)w_r(z_\theta) - \frac{1}{2}\phi_l^T(z_\theta)w_l(z_\theta) \quad (8)$$

The closed loop equation can be extracted from (6) and (8):

$$m_m r_m^2\ddot{\theta} + D_\theta\dot{\theta} + S\theta + f_\theta = -K_p\theta - K_i\int_0^t \theta d\tau$$

$-K_d\dot{\theta} - \frac{1}{2}\phi_r^T(z_\theta)w_r(z_\theta) - \frac{1}{2}\phi_l^T(z_\theta)w_l(z_\theta)$(9)

Let, $K_i\int_0^t \theta d\tau = I_\theta$, then

$$\dot{I}_\theta = K_i\theta$$

$$\begin{aligned} \tfrac{d}{dt}(\theta) = -\left(m_m r_m^2\right)^{-1}[&D_\theta\dot{\theta} + S\theta + f_\theta + K_p\theta + K_d\theta + I_\theta \\ &+\tfrac{1}{2}\phi_r^T(z_\theta)w_r(z_\theta) + \tfrac{1}{2}\phi_l^T(z_\theta)w_l(z_\theta)] \end{aligned} \quad (10)$$

where I_θ is the auxiliary variable. In matrix form, (10) is

$$\frac{d}{dt}\begin{bmatrix} I_\theta \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} K_{ix}\theta \\ \dot{\theta} \\ -\left(m_m r_m^2\right)^{-1}[D_\theta\dot{\theta} + S\theta + f_\theta + u_\theta] \end{bmatrix} \quad (11)$$

From (9) it is justified that the origin is not at the equilibrium and is in the format $\begin{bmatrix}\theta & \dot{\theta} & I_\theta\end{bmatrix} = \begin{bmatrix}\theta & \dot{\theta} & I_\theta^*\end{bmatrix}$ .Since at equilibrium point $\theta = 0, \dot{\theta} = 0$, then the equilibrium is

$$[0, 0, \lambda_\theta(0, 0)]$$

where $I_\theta^* = I_\theta - \lambda_\theta(0, 0)$. Using Stone-Weierstrass theorem, f_θ can be estimated as:

$$f_\theta = \frac{1}{2}\phi_r^T(z_\theta)w_r^*(z_\theta) + \frac{1}{2}\phi_l^T(z_\theta)w_l^*(z_\theta) + \lambda_\theta \quad (12)$$

where the model error is represented by λ_θ and

$$\begin{gathered} \tilde{w}_r(z_\theta) = -\left[w_r(z_\theta) + w_r^*(z_\theta)\right] \\ \tilde{w}_l(z_\theta) = -\left[w_l(z_\theta) + w_l^*(z_\theta)\right] \end{gathered} \quad (13)$$

Using(9) and (12):

$$\begin{gathered} m_m r_m^2\ddot{\theta} + D_\theta\dot{\theta} + S\theta + \tfrac{1}{2}\phi_r^T(z_\theta)w_r^*(z_\theta) + \tfrac{1}{2}\phi_l^T(z_\theta)w_l^*(z_\theta) + \lambda_\theta = \\ -K_p\theta - I_\theta + I_{eq}(0, 0) - K_d\dot{\theta} - \tfrac{1}{2}\phi_r^T(z_\theta)w_r(z_\theta) - \tfrac{1}{2}\phi_l^T(z_\theta)w_l(z_\theta) \end{gathered} \quad (14)$$

The lower bound of λ_θ which is nonlinear in nature is illustrated as:

$$\int_0^t \lambda_\theta d\theta = \int_0^t F_{\theta ta} d\theta - \int_0^t f_{\theta e} d\theta$$

$-\frac{1}{2}\int_0^t \phi_r^T(z_\theta)w_r(z_\theta)d\theta + \frac{1}{2}\int_0^t \phi_l^T(z_\theta)w_l(z_\theta)d\theta$ (15)

The lower bounds are $\int_0^t F_{\theta ta} d\theta = -\bar{F}_{\theta ta}$ and $\int_0^t f_{\theta e} d\theta = -\bar{f}_{\theta e}$. Also, the Gaussian functions are represented by $\phi_r^T(z_\theta)$ and $\phi_l^T(z_\theta)$. Now the modeling error λ_θ is Lipschitz over a, b such that:

$$\|\lambda_\theta(a) - \lambda_\theta(b)\| \le L_\theta \|a - b\| \quad (16)$$

where L_θ is the Lipschitz constant. So using (15) and (16):

$$L_\theta = -\bar{F}_{\theta ta} - \bar{f}_{\theta e} - \frac{\sqrt{\pi}}{4}\operatorname{erf}(z_\theta)\left[w_r(z_\theta) + w_l(z_\theta)\right]$$

Also to prove the stability of the T2-F-PID control, the property of Eigen value should be considered and stated as:

$$0 < \lambda_m(m_m r_m^2) \le r_m^2\|m_m\| \le \lambda_M(m_m r_m^2) \le r_m^2\bar{m} \quad (17)$$

where the min and max eigenvalues of the matrix m_m are represented by $\lambda_m(m_m)$ and $\lambda_M(m_m)$ respectively, also $r_m^2 \bar{m} > 0$ is the upper bound.

The following theorem gives the stability analysis of T2-F-PID controller (8).

Theorem: If the T2-F-PID controller (8) is use to control a closed loop manipulator system (3), then the asymptotic stabilty of the system is assured when the fuzzy laws are

$$\begin{aligned} \frac{d}{d\theta}\tilde{w}_r(z_\theta) &= -\frac{\eta_1 r_m^2}{t_1}\left[(\dot{\theta}+\rho_\theta\theta)^T\phi_r^T(z_\theta)\right]^T \\ \frac{d}{d\theta}\tilde{w}_l(z_\theta) &= -\frac{\eta_2 r_m^2}{t_2}\left[(\dot{\theta}+\rho_\theta\theta)^T\phi_l^T(z_\theta)\right]^T \end{aligned} \tag{18}$$

and the PID control gains are within the range as

$$\begin{aligned} &\lambda_m(K_p) \geq \frac{2}{\rho_\theta}\lambda_M(K_i) + \lambda_M(D_\theta) + L_\theta + \frac{2}{\rho_\theta}\Gamma_M \\ &\lambda_M(K_i) \leq \frac{\sqrt{\lambda_m(K_p)^3}\sqrt{\lambda_m(m_m)}}{10.4(\lambda_M(m_m))} \\ &\lambda_m(K_d) \geq \frac{\rho_\theta}{2}\lambda_M(m_m) - \Gamma_M - \frac{\rho_\theta}{2}\lambda_M(D_\theta) - \lambda_m(D_\theta) \end{aligned} \tag{19}$$

where $\lambda_m$and λ_M are the minimum and maximum eigenvalues of the matrices.

IV. Numerical Analysis

In order to verify the capability of the proposed fuzzy PID controller, the parameters of manipulator are extracted from [25], [26]. These parameters are used to simulate the manipulator process and to achieve the motion with vibration control.

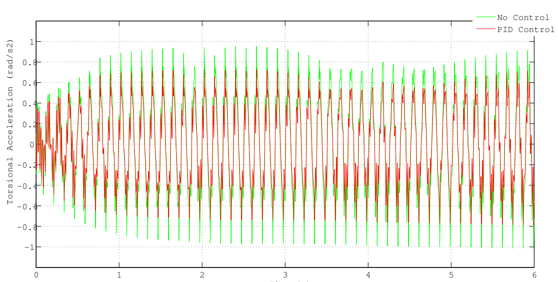

Fig. 3. Manipulator vibration control using PID controller.

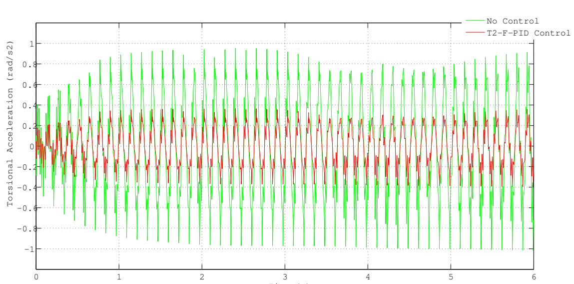

Fig. 4. Manipulator vibration control using T2-F-PID controller.

For the simulation purpose, the input nonlinearity is the Coulomb friction associated with the torsional movement of the manipulator. The Coulomb friction [27] is of the form which is nonlinear in nature:

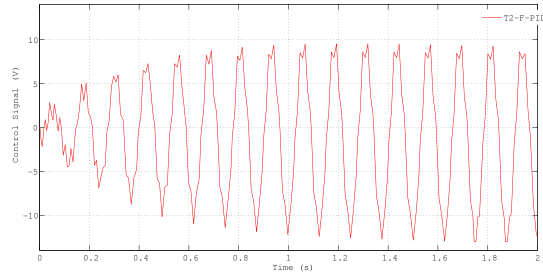

Fig. 5. T2-F-PID control signal.

$$FC_{sim} = \alpha_0 sgn(\dot{\theta}) + \alpha_1(\exp)^{-\alpha_2|\dot{\theta}|}sgn(\dot{\theta}) \tag{20}$$

where $\alpha_0, \alpha_1, \alpha_2$ are the friction constants and $\dot{\theta}$ is the velocity of the manipulator. The platform *Matlab/Simulink* is utilized to carry out the simulation of the manipulator. The simulink software is used to generate various simulations to prove that by using T2-F-PID controller sufficient vibration attenuation of the agriculture manipulator can be achieved. In order to verify the effectiveness of the T2-F-PID controller, the vibration attenuation capabilities of the stated controller is compared with conventional PID controller. The inputs: position error and velocity error, are considered to be Gaussian membership functions. Four membership functions are allocated for position error whereas three membership functions are allocated for velocity error. Normalization are set as $[\mathbf{-1}, \mathbf{1}]$.The type-2 fuzzy system is defuzzified using Karnik-Mendel technique [18]. For type-2 fuzzy system, six IF-THEN rules are sufficient to maintain the regulation error. Ten IF-THEN rules suffices the maintaining of minimal regulation error in case of type-1 fuzzy system. The technique of Gaussian functions is introduced for type-1 fuzzy logic. Both type-1/type-2 fuzzy system are based on IF-THEN rules illustrated by:

$$\begin{array}{lll} \text{IF} & \theta & \text{is} \quad \Psi_1 \\ \text{AND} & \dot{\theta} & \text{is} \quad \Psi_2 \\ \text{THEN} & u_\theta & \text{is} \quad \Psi_3 \end{array} \tag{21}$$

where θ is the position error, $\dot{\theta}$ is the velocity error, and u_θ is the required control force. Ψ_1, Ψ_2 ,and Ψ_3 are the fuzzy sets. The design parameters are, $\frac{\eta_1}{t_1} = \frac{\eta_2}{t_2} = 8$. The required criteria for the minimum proportional gain, minimum derivative gain and maximum integral gain are extracted from the theorem. Now, utilizing the ranges from theorem 1:

$$\lambda_m(K_p) \geq 219, \lambda_m(K_d) \geq 69, \lambda_M(K_i) \leq 2500 \tag{22}$$

After attempting several trials with the gains based on eqn. (22), it is observed that for PD, PID, T1-F-PID and T2-F-PID controller the most suited gains for efficient vibration attenuation as well as stability are:

$$\lambda_{\min}(K_p) = 273, \lambda_m(K_d) = 81, \lambda_M(K_i) = 1690 \tag{23}$$

From Fig. 3 and Fig. 4, it is validated that T2-F-PID has the superior vibration attenuation capabilities. The Fig. 5 depicts the control signal plot of T2-F-PID controller.

V. Conclusions

Image-based phenotyping plays a critical role, provided the quality of the data is good. Camera-shake in particular leads to distortion of the image, which requires too much calibrations to be done offline. In this paper, we verify & validate the control, and stabilization of the non-linear uncertainty associated with the mechanical manipulator arm, when envisioned to be automated in the current configuration as desired for the agriculture applications. The camera setup, when mounted with such motorized arm, will incur tremendous vibrations. This sort of vibration experienced hinders the quality of the acquired data. The vibration control of such envisioned manipulator in an effective manner is the main motivation of this paper. To achieve this we used a conventional PID controller in combination with the type-2 fuzzy logic (T2-F-PID). The main control action is generated by the PID controller, whereas the non-linear compensation is dealt using the type-2 fuzzy logic. The action of torsion actuator (TA) is simulated for active vibration control. The simulation results of T2-F-PID with TA is compared with simple PID controller. The analysis result validates that T2-F-PID is the best among all the controllers in achieving suitable vibration attenuation.

References

[1] L. Li, Q. Zhang and D.Huang,"A Review of Imaging Techniques for Plant Phenotyping", Sensors 14, pp.20078 - 20111, 2014.

[2] S. Sakurai, H. Uchiyama, A. Shimada, D. Arita, and R. Rin-ichiro Taniguchi, "Two-step Transfer Learning for Semantic Plant Segmentation", ICPRAM, 2018.

[3] R. R. Shamshiri, C. Weltzien, I. A. Hameed, I. J. Yule, T. E. Grift, S. K. Balasundram, et al., "Research and development in agricultural robotics: A perspective of digital farming", Int J Agric Biol Eng, Vol. 11, No. 4, pp. 1–14, 2018.

[4] "ROBOTICS-INTRODUCTION"
Available: http://www.site.uottawa.ca/ petriu/CEG4392-IntroRobotics-Arms.pdf

[5] T. Oh, J. Park, K. Seshadrinathan, S. Lee, and A. C. Bovik, "No-Reference Sharpness Assessment of Camera-Shaken Images by Analysis of Spectral Structure," in IEEE Transactions on Image Processing, vol. 23, no. 12, pp. 5428-5439, 2014.

[6] S. Varde, M. S., and Panse, "Offline Stereo Camera Calibration of Raspberry Pi Compute Module," International Journal of Latest Technology in Engineering, Management Applied Science, Vol. 6, No. 9, 2017.

[7] M. T. Nguyen, C. Yuan, J. H. and Huang, "Kinematic Analysis of A 6-DOF Robotic Arm". Advances in Mechanism and Machine Science, vol. 73, 2019.

[8] G. Leugering, "Control and stabilization of a flexible robot arm", Dynamics and Stability of Systems, Vol. 5, No. 1, pp. 37-46, 1990.

[9] S. N. Singh, "Control and stabilization of nonlinear uncertain elastic robotic arm," IEEE Transactions on Aerospace and Electronic Systems, vol. 24, No. 2, pp. 148-155, 1988.

[10] V. Yanovych , T. Honcharuk , I. Honcharuk , K. Kovalova, Design of the system to control a vibratory machine for mixing loose materials, Eastern-European Journal of Enterprise Technologies, Vol. 6, PP. 4-13, 2017.

[11] V. Yanovych , T. Honcharuk , I. Honcharuk , K. Kovalova, Engineering management of vibrating machines for targeted mechanical activation of premix components, INMATEH - Agricultural Engineering,Vol. 8, pp.25-32, 2018.

[12] V. Yanovich, I. Kupchuk, Determination of rational Operating parameters for a vibrating dysk-type grinder used in ethanol industry, INMATEH - Agricultural Engineering, Vol. 52, pp. 143-148, 2017.

[13] V. Etxebarria, S. Arantza, and L. Ibone, "Control of a Lightweight Flexible Robotic Arm Using Sliding Modes", International Journal of Advanced Robotic Systems, Vol. 2, NO. 2, pp. 103 - 110, 2005.

[14] S. Paul, and W. Yu, "A method for bidirectional active control of structures", Journal of Vibration and Control, Vol. 24, No. 15, pp. 3400–3417, 2018.

[15] S. Paul, and R. Morales-Menendez, "Chatter Mitigation in Milling Process Using Discrete Time Sliding Mode Control with Type 2-Fuzzy Logic System", Appl. Sci., Vol.9, 2019.

[16] R.I John, P.R Innocent, and M.R Barnes,Neuro-fuzzy clustering of radiographic tibia image data using type 2 fuzzy sets, Information Sciences, Vol. 125, No. 1–4, pp. 65-82, 2000.

[17] J. M. Mendel, "Uncertain Rule-Based Fuzzy Logic Systems: Introduction and New Directions"; Prentice Hall PTR:Upper Saddle River, NJ, USA, 2001.

[18] Q. Liang, and J. M. Mendel, "Interval type-2 Fuzzy Logic Systems: Theory and Design", IEEE Trans. Fuzzy Syst., Vol. 8, pp. 535–550, 2002.

[19] R. Sepúlveda, O. Castillo, P. Melin, A. Rodríguez-Díaz, and O. Montiel, "Experimental Study of Intelligent Controllers Under Uncertainty using Type-1 and Type-2 Fuzzy Logic", Information Sciences, Vol. 177, No. 10, pp. 2023-2048, 2007.

[20] S. Paul, W. Yu, W, and X. Li, "Bidirectional active control of structures with type-2 fuzzy PD and PID", Int. J. Syst. Sci, Vol. 49, pp. 766–782, 2018.

[21] K. A. Naik, and C. P. Gupta, Performance comparison of type-1 and type-2 fuzzy logic systems. In Proceedingsof the 4th International Conference on Signal Processing,Computing and Control (ISPCC), Solan, India, pp. 72-76, 2017.

[22] Y. Bai, and D. Wang, "On the Comparison of type-1 and Interval type 2 Fuzzy Logic Controllers Used in a Laser Tracking System", IFAC-PapersOnLine, Vol. 51 pp. 1548–1553, 2018.

[23] C. Rolda´n, F. J. Campa, O. Altuzarra, and E. Amezua, "Automatic identification of the inertia and friction of an electromechanical actuator", Mechanisms and Machine Science Vol. 17, pp. 409–416, 2014.

[24] T. C. Lin, H. L. Liu, and M. J. Kuo, "Direct Adaptive Interval Type-2 Fuzzy Control of Multivariable Nonlinear Systems", Eng. Applications of Artificial Intelligence, Vol.22, No. 3, pp. 420-430, 2009.

[25] s. Yavuz, L. Malgaca, and H. Karagülle, "Vibration control of a single-link flexible composite manipulator", Composite Structures, Vol. 140, pp. 684-691, 2016.

[26] M. Hassan, R. Dubay, C. Li, and R. Wang, "Active vibration control of a flexible one-link manipulator using a multivariable predictive controller", Mechatronics, Vol. 17, No. 6, pp. 311-323, 2007.

[27] J. O. Jang, and G. J. Jeon, "A parallel neuro-controller for DC motors containing nonlinear friction, Neurocomputing", Vol. 30, No. 1-4, pp. 233-248, 2000.