Volume 4, Issue 5, 2020 ISSN: 2617-4537
DOI: https://doi.org/10.31058/j.data.2020.45003

Approach to Effective Stability Consideration for CNC Machine-Tool Positional Control System

Win Myat Mon[1*]

[1] Department of Electronic Engineering, Technological University (Taunggyi), Aye Thar Yar, Myanmar

Email Address

ecdepartment.ytu@gmail.com (Win Myat Mon)
*Correspondence: ecdepartment.ytu@gmail.com

Received: 1 August 2020**; Accepted:** 20 September 2020**; Published:** 12 October 2020

Abstract:

The paper presents the approaching to effective stability consideration for CNC machine-tool positional control system in Industrial automation with flexible manufacturing system. The problem in this study is stability condition in positional control design for CNC machines. The solution to resolve that research problem is to design the effective controller design for automation system in reality. There has been numerical analysis for stability checks based on the ultimate concepts in the control problem formulation. The experimental data are from the specification of the standard parameters for practical application. The experimental results and simulation results confirm that the developed controller design for specific control system met the high performance condition for the automation system design.

Keywords:

Stability Test, CNC machine, Machine-Tool System, Positional Control System, Numerical Analysis

1. Introduction

The industrial automation is a vital role to enhance the modern technology for industrial engineering. The flexible manufacturing system is one of the solutions for many challenging issues for stability analysis on dynamical system in modern industries. Many systems operate under computer control, and Figure 1 shows a target model of a CNC machine-tool control system [1,2,3]. Information relating to the shape of the work-piece and hence the motion of the machine table is stored in a computer program. This is relayed in digital format, in a sequential form to the controller and is compared with a digital feedback signal from the shaft encoder to generate a digital error signal. This is converted to an analogue control signal which, when amplified, drives a DC servomotor. Connected to the output shaft of the servomotor (in some cases through a gearbox) is a lead-screw to which is attached the machine table, the shaft encoder and a tachogenerator [4,5,6,7]. The purpose of this latter device, which produces an analogue signal proportional to velocity, is to form an inner, or minor control loop in order to dampen, or stabilize the response of the

Volume 4, Issue 5, 2020 ISSN: 2617-4537
DOI: https://doi.org/10.31058/j.data.2020.45003

system. The block diagram for the CNC machine-tool control system is shown in Figure 2.

The physical configuration and block diagram representation of CNC machine-tool is shown in Figure 1 and Figure 2. The fundamental control problem here is that, by design, the lead-screw (by the use of re-circulating ball-bearings) is friction-free. This means that the positional control system will have no damping, and will oscillate continuously at the undamped natural frequency of the closed-loop system [8,9,10,11,12,13]. Therefore we have to follow the ultimate concepts for solving the stability problems for dynamical systems in the modern industries. In this study, we will have to design the effective controller design for automation system in reality.

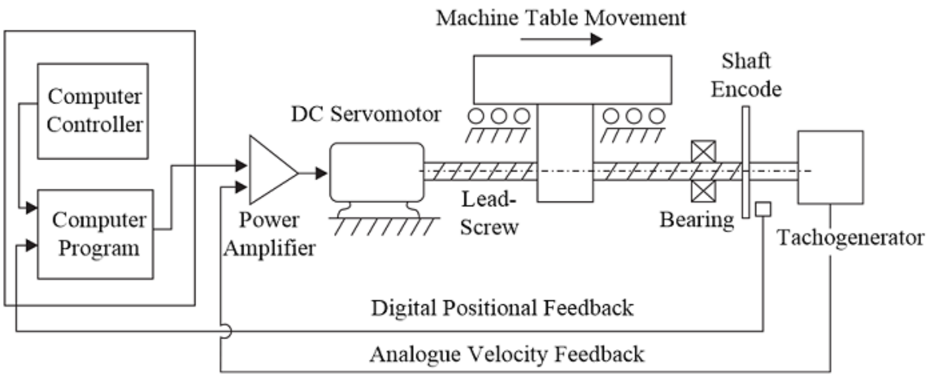

Figure 1. *Computer Numerically Controlled Machine-tool.*

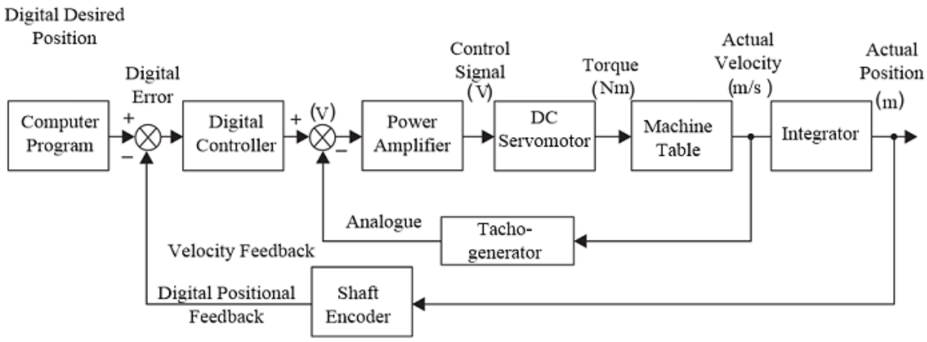

Figure 2. *Block Diagram of CNC Machine-tool Control System.*

The rest of the paper is organized as follows. Section II presents the background theory of the CNC machine-tool system. Section III mentions the Numerical Design Implementation. Section IV points out the results and discussions. Finally, the conclusion section is offered in the last section.

2. Background Theory

Damping can be introduced a number of ways:

(a) A dashpot attached to the lead-screw: This is wasteful on energy and defeats the objective of a friction-free system.

(b) Velocity feedback: A signal from a sensor that us the first derivative of the output (i.e. velocity) will produce as damping term in the closed-loop transfer function.

(c) PD control: A PD controller will also provide a damping term. However, the practical realization will require an additional filter to remove unwanted high frequency noise.

Most machine-tool manufacturing employ velocity feedback to obtain the necessary damping. Since overshoot in a cutting operation usually cannot be tolerated, the damping coefficient for the system must be unity, or greater.

For this study, the machine-tool configuration will be essentially the same as shown in Figure, with the exception that:

(i) A gearbox will be placed between the servo-motor and the lead-screw to provide additional torque.

(ii) The machine table movement will be measured by a linear displacement transducer attached to the table. This has the advantage of bringing the table 'within the control-loop' and hence providing more accurate control.

System element dynamic equations: With references to Figure 1 and Figure 3.

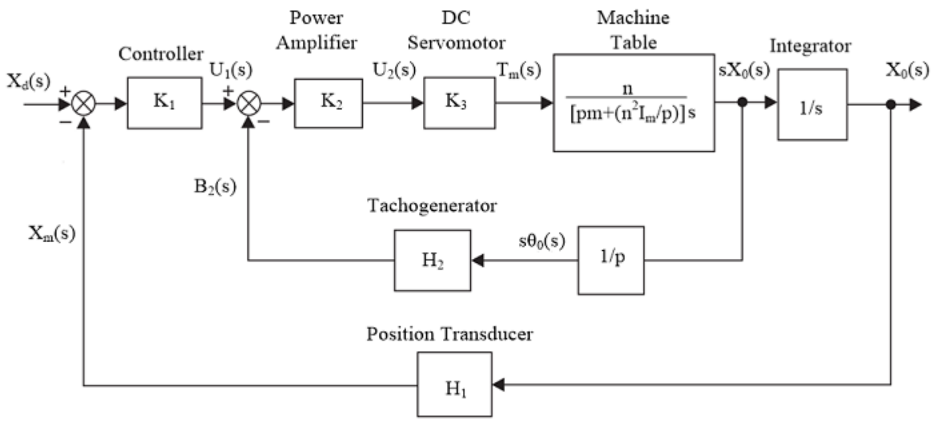

Figure 3. *Block Diagram of CNC Machine-tool Control System.*

The Controller could be identified as:

Proportional control gain K_1(V/m)

Control Signal $U_1(s)=K_1(X_d(s)-X_m(s))$

The Power Amplifier could be modelled as:

Gain K_2(V/V)

Control signal $U_2(s)=K_2(U_1(s)-B_2(s))$

The DC servo motor could be analyzed as: Field controlled, with transfer function as shown in Figure 3. It will be assumed that the field time constant L_f/R_f is small compared with the dynamics of the machine table, and therefore can be ignored. Hence, DC servo-motor gain K_3(Nm/V).

The Gearbox, lead-screw and machine-table could be designed as: With reference to Figure 4. (free-body diagram of a gearbox), the motor-shaft will have zero viscous friction Cm, hence equation (2.22), using Laplace notation, becomes

The free-body diagrams for the motor shaft and output shaft are shown in Figure 4.

Equations of Motion are

For Motor shaft,

$$\sum M = I_m \frac{d^2\theta_m}{dt^2}$$

$$T_m(t) - C_m \frac{d\theta_m}{dt} - aX(t) = I_m \frac{d^2\theta_m}{dt^2}$$

Re-arranging the above equation,

$$X(t) = \frac{1}{a}\left(T_m(t) - I_m \frac{d^2\theta_m}{dt^2} - C_m \frac{d\theta_m}{dt} \right)$$

$$X(s)=1/a[T_m(s)-I_m s^2\theta_m(s)]$$

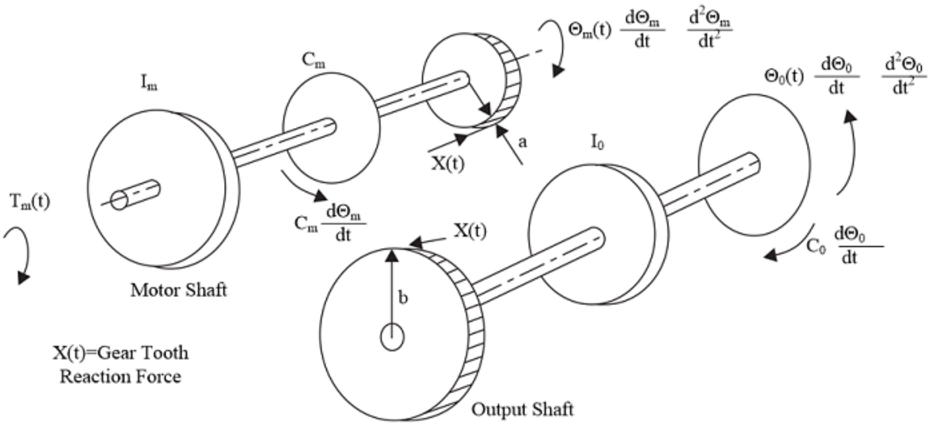

Figure 4. *Free-body Diagrams for Reduction Gerabox.*

The output shaft in this case is the lead-screw, which is assumed to have zero moment of inertia IO and viscous friction CO. The free-body diagram of the machine-table and lead-screw are shown in Figure 5.

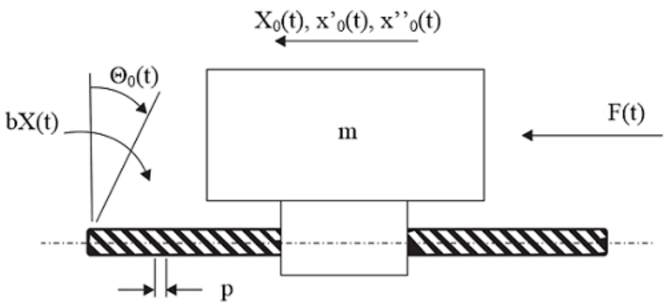

Figure 5. *Free-body Diagrams of Lead-screw and Machine Table.*

3. Numerical Design Implementation

For lead-screw,

Work in =Work out

$bX(t)\theta_O(t)=F(t)x_O(t)$

or

$F(t)=bX(t)[\theta_O(t)/x_O(t)]$

Now the pitch p of the lead-screw is

$p= x_O(t)/\theta_O(t)$

by substituting

$F(t)=bX(t)/p$

The equation of motion for the machine-table is

$F(t)=mx_O$

By equating

$X(t)=1/b[pmx_O]$

Taking Laplace transforms

$X(s)=1/b[pms^2X_O(s)]$

By equating

$[pms^2X_O(s)]=b/a[T_m(s)-I_ms^2\theta_m(s)]$

Now

b/a=gear ratio n

$\theta_m(s)=n\theta_O(s)$

By substituting

$[pms^2X_O(s)]=nT_m(s)-nI_m(n/p)\ s^2X_O(s)]$

Or

$nT_m(s)=[pm+(n^2I_m/p)]\ s^2X_O(s)$

Giving the transfer function for the gearbox, lead-screw and machine-table as

$$\frac{X_O(s)}{T_m}=\frac{n}{(pm+n^2I_m/p)s^2}$$

Where the term n^2I_m/p may be considered equivalent mass of I_m referred to the machine-table

The Tachogenerator could be developed as:

Gain H_2(Vs/rad)

Feedback signal $B_2(s)=H_2s\theta_O(s)$

Or, from above equation

$B_2(s)=(H_2/p)s\ X_O(s)$

The Position transducer could be specified as:

Gain H_1(V/m)

Feedback signal $X_m(s)=H_1X_O(s)$

The system element dynamic equations can now be combined in the block diagram shown in Figure 3. By using the closed-loop standard transfer function equation of $\frac{C}{R}(s)=\frac{G(s)}{1+G(s)H(s)}$, the inner-loop transfer function is

$$G(s)=\frac{K_2K_3np}{\left(p^2m+n^2I_m\right)s+K_2K_3nH_2}$$

Again, using the closed-loop transfer function standard equation of $\frac{C}{R}(s)=\frac{G(s)}{1+G(s)H(s)}$, the overall closed-loop transfer function becomes

$$\frac{X_O}{X_d}(s)=\frac{K_1K_2K_3np}{\left(p^2m+n^2I_m\right)s^2+K_2K_3nH_2s+K_1K_2K_3npH_1}$$

Which can be written in standard from

$$\frac{X_O}{X_d}(s)=\frac{\frac{1}{H_1}}{\left(\frac{p^2m+n^2I_m}{K_1K_2K_3npH_1}\right)s^2+\left(\frac{H_2}{K_1pH_1}\right)s+1}$$

Specification: The CNC machine-table control system is to be critically damped with a settling time of 0.1 seconds.

The Control Problem could be proposed based on the selection of the controller gain K_1 to achieve the settling time and tachogenerator constant to provide critical damping. Table 1 gives the system parameters for the design analysis.

Table 1. *System Parameters.*

Variable	Value
K_2	2 V/V
N	10:1
M	50 kg
H_1	60 V/m
K_3	4 Nm/V
p	5×10^{-3} m
I_m	10×10^{-6} kgm^2

By calculating of K_1, in general, the settling time of a system with critical damping is equal to the periodic time of the undamped system, as can be seen in Figure 6.

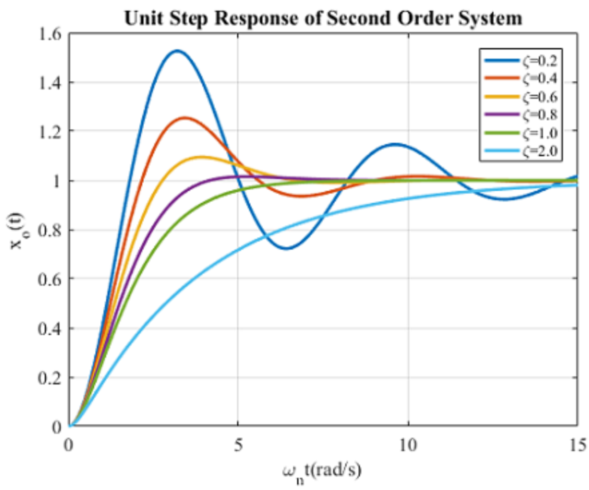

Figure 6. *Unit Step Response of Second Order System.*

This can be demonstrated using unit step response for critical damping

$$x_O(t)=\left[1-e^{-\omega_o t}\left(1+\omega_o t\right)\right]$$

When

$$t = \frac{2\pi}{\omega_n}$$

$$x_O(t) = \left[1 - e^{-2\pi}\left(1 + 2\pi\right)\right] = 0.986$$

Thus, for a settling time of 0.1 seconds for a system that is critically damped, the undamped natural frequency is

$$\omega_n = \frac{2\pi}{0.1} = 62.84 \, {rad}/{s}$$

Comparing the closed-loop transfer function given in above equation with the standard form

$$\omega_n^2 = \frac{K_1 K_2 K_3 npH_1}{p^2 m + n^2 I_m}$$

Hence

$$K_1 = \frac{\omega_n^2\left(p^2 m + n^2 I_m\right)}{K_2 K_3 npH_1}$$

$$K_1 = \left[\frac{\left\{\left(5\times10^{-3}\right)^2 \times 50\right\} + \left(10^2 \times 10 \times 10^{-6}\right)}{\left(2\times4\times10\times5\times10^{-3}\times60\right)}\right] \times 62.84^2 = 0.365 \, {V}/{V}$$

Again, comparing with the standard from

$$\frac{2\zeta}{\omega_n} = \frac{H_2}{K_1 pH_1}$$

$$H_2 = \frac{2\zeta K_1 pH_1}{\omega_n} = \frac{2\times1\times0.365\times5\times10^{-3}\times60}{62.84} = 3.485\times10^{-3} \, {Vs}/{rad}$$

4. Results and Discussions

Figure 7 shows the Bode Plot for CNC Machine-tool Position Control System. According to the bode plot for the closed-loop transfer function, the magnitude plots and phase responses are seen to be met with the standard condition of the stability response for the unknown system. The gain margin and phase margin values are also fitted with the high performance response of the system in control system design. Figure 8 demonstrates the Nyquist Plot for CNC Machine-tool Position Control System.

There is no encirclement and enclosed loop for the system performance and this responses say the performance stability checks of the system is met with the stability standard.

Figure 9 illustrates the Root Locus Plot for CNC Machine-tool Position Control System. This system could not find the roots in the right hand side of the s-plane and these responses say that the stability performances are met with the standard values.

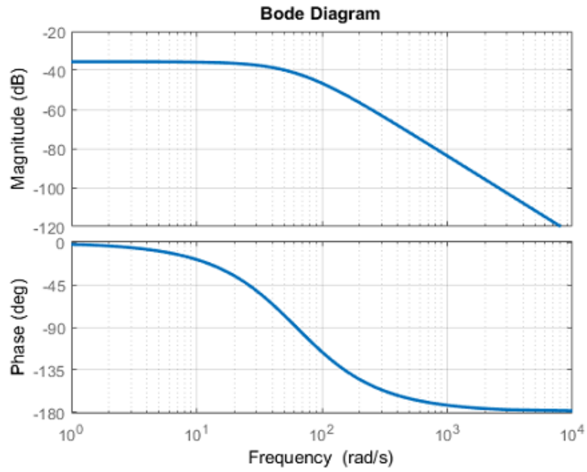

Figure 7. *Bode Plot for CNC Machine-tool Position Control System.*

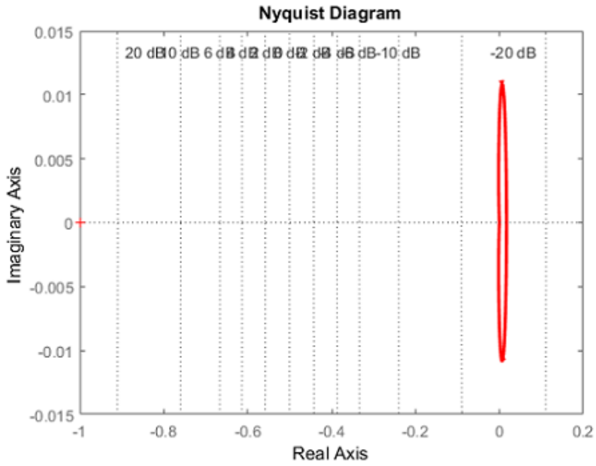

Figure 8. *Nyquist Plot for CNC Machine-tool Position Control System.*

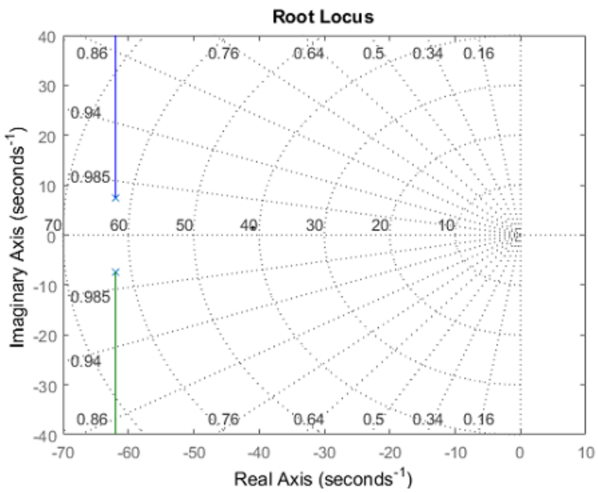

Figure 9. *Root Locus Plot for CNC Machine-tool Position Control System.*

Figure 10 mentions the Closed-loop Stability Response for CNC Machine-tool Position Control System. According to the closed-loop stability response of the CNC Machine-tool positional control system, there is no overshoot in this response. The response is nearly met with critical damped and the settling time is only 0.1 second for the stability condition. This results confirmed that the developed numerical implementation for stability analyses for CNC Machine-tool positional control system was met the high performance stability condition in reality.

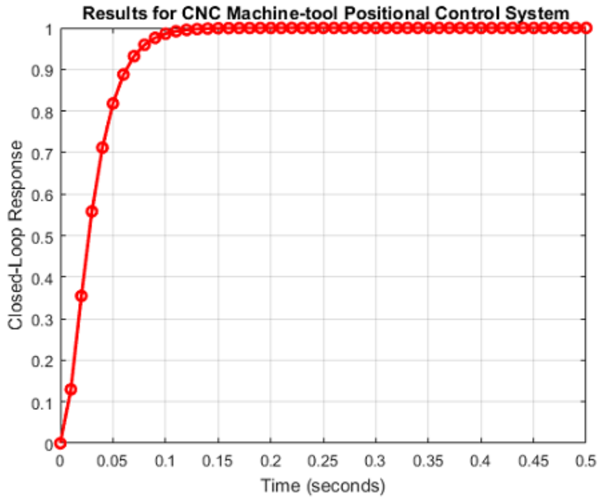

Figure 10. *Closed-loop Stability Response for CNC Machine-tool Position Control System.*

5. Conclusion

The paper was proved the stability condition in positional control design for CNC machines in the real control system. The first analysis was performed based on the numerical consideration for respective gain and other parameters. After that, the stability check for the closed-loop stability response of the CNC Machine-tool positional control system was completed. Based on the various stability tests with Bode, Nyquist, Root Locus and closed-loop analyses, the responses say that the analyzed and implemented control system was met the high performance control system design for real world applications.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Author Contributions

The author has solved the main problem in this study is stability condition in positional control design for CNC machines. The solution which the author has proved is to design the effective controller design for automation system in reality. The author mainly correspondingly emphasized this implementation based on the ultimate concepts on designing the control system for automation industries. The developed numerical computation could be utilized to experimental studies in the classroom lectures for undergraduate studies.

Funding

This work is partially supported by Government Research Funds Grant No of GB/D(4)/2019/1.

Acknowledgement

The author would like to acknowledge my research advisor from the Department of Electronic Engineering of Yangon Technological University for his kind guidance and supports this work without difficulties.

References

[1] Dale, E.S.; Thomas, F.E.; Duncan, A.M. Process Dynamics and Control. 2007; pp. 318, Second Edition, Wiley.

[2] Coughanowr, D.R.; Koppel, L.B. Process Systems Analysis and control. McGraw-Hill, New York, 1965.

[3] Astrom, K.J.; Hagglund, H. PID controllers: Theory, design and tuning (2nd ed.)". ResearcTriangle Park, NC: Instrument Society of America, 1995.

[4] Grassi, E.; Tsakalis, K.; Dash, S.; Gaikwad, S.V.; Macarthur, W.; Stein, G. Integrated system identification and PID controller tuning by frequency loop-shaping. *IEEE Transactions on Control Systems Technology*, 2001, 9(2), 285-294.

[5] Ho, W.K.; Gan, O.P.; Tay, E.B.; Ang, E.L. Performance and gain and phase margins of well-known PID tuning formulas. *IEEE Transactions on Control Systems Technology*, 1996, 4(4), 473-477.

[6] Liu, T.K.; Chen, Y.P.; Chou, J.H. Solving Distributed and Flexible Job-Shop Scheduling Problems for a Real-World Fastener Manufacturer. *IEEE Access*, 2014, 2, 1598-1606.

[7] Zhang, X.G.; Li, Y.L.; Ran, Y.; Zhang, G.B. A Hybrid Multilevel FTA-FMEA Method for a Flexible Manufacturing Cell Based on Meta-Action and TOPSIS. *IEEE Access*, 2019, 7, 110306-110315.

[8] Liu, G.Y.; Zhang, L.C.; Liu, Y.T.; Chen, Y.F.; Li, Z.W.; Wu, N.Q. Robust Deadlock Control for Automated Manufacturing Systems Based on the Max-Controllability of Siphons. *IEEE Access*, 2019, 7, 88579-88591.

[9] Flores, A.; de Oca, A.M.; Flores, G. A simple controller for the transition maneuver of a tail-sitter drone. In *2018 IEEE Conference on Decision and Control (CDC)*, Dec 2018, pp. 4277-4281.

[10] Stastny, T.; Siegwart, R. Nonlinear model predictive guidance for fixed-wing uavs using identified control augmented dynamics. In *2018 International Conference on Unmanned Aircraft Systems (ICUAS)*, June 2018, pp. 432-442.

[11] Chen, Y.; Liang, J.; Wang, C.; Zhang, Y. Combined of lyapunovstable and active disturbance rejection control for the path following of a small unmanned aerial vehicle. *International Journal of Advanced Robotic Systems*, 2017, 14(2), 1-10.

[12] Zhou, B.H.; Xi, L.F.; Cat, J.G. Knowledge-based decision support system for tool management in flexible manufacturing system. *Journal of Systems Engineering and Electronics*, 2004, 15(4), 537-541.

[13] Liu, T.K.; Chen, Y.P.; Chou, J.H. Solving Distributed and Flexible Job-Shop Scheduling Problems for a Real-World Fastener Manufacturer. IEEE Access, 2014, 2, 1598-1606.