Journal of Robotics and Control (JRC)
Volume 6, Issue 1, 2025
ISSN: 2715-5072, DOI: 10.18196/jrc.v6i1.25207

Design of Adaptive Synergetic Controller for One Degree of Freedom Robotic ARM Under External Disturbance

Ahmed Khalaf Hamoudi [1], Suha S. Husain [2*]
[1] Control and System Engineering Department, University of Technology-Iraq, Baghdad, Iraq
[2] Construction and Projects Department, University of Technology-Iraq, Baghdad, Iraq
Email: [1] 60155@uotechnology.edu.iq, [2] suha.s.hussein@uotechnology.edu.iq
*Corresponding Author

***Abstract*—In order to manage a one-link robot arm, this research proposes a unique control architecture based on the Synergetic Control (SC) principle. The synergetic control design is initially developed using known system parameters and subjected to external disturbances. However, in practical robotic systems, uncertainties are inherent in the system parameters. As a result, an algorithm known as Adaptive Synergetic Control (ASC) is presented and developed for a robot arm that encounters parameters uncertainty. To estimate disturbances and guarantee the asymptotic stability of the monitored system, adaptive synergetic laws are developed. The adaptive laws and control of the ASC were established to ensure the stability of the controlled robotic arm. The recommended controller addresses the tracking problem of a single-degree-of-freedom (SDOF) robot arm, and disturbance control scenario was conducted and simulated. Additionally, the paper compares the ASC method with the adaptive backstepping control technique to evaluate the effectiveness of ASC, this comparison demonstrated the efficiency of the recommended strategy in terms of maximum tracking error and maximum control effort. The performance of both SC, ASC is demonstrated through computer simulations, showing that the adaptive controller can handle uncertainties as well as disturbance and maintain system stability**.

Keywords—Synergetic Control; Adaptive Synergetic Control; Robotic ARM; Stability Analysis.

I. INTRODUCTION

Robotic arm control systems are a critical aspect of new robotics, enabling precise and efficient motion in a variety of applications across industries, including manufacturing, healthcare, aerospace, and time-saving everyday life applications. As robotic applications increase, the demand for more sophisticated control systems is increasing, increasing the need for advanced solutions and robust control strategy design [1][2]. Additionally, nonlinear systems with unpredictable dynamic features are found in robotics [3][4].

Therefore, it is essential to force the robot arm track the desired path with the least possible tracking error through the design of controller [5][6].

Consequently, durable and high-performance controllers are required. many controllers are designed to control robot arm, these include classical, intelligent and robust controllers' schemes. PID control for a robotic manipulator arm is designed by numerous researchers [6][7]. Okubanjo, A. A. et al. [8] A suggested PID control scheme to control a 2-degree-of-freedom (2-DOF) robotic arm. Scaff et al. [9] introduced an optimal PID controller for position control in a single-link robot driven by McKibben Pneumatic Artificial Muscles (PAM). The optimization of the PID controller gains was achieved through a Simulated Optimization Algorithm. K. Bai and colleagues [10] introduced an adaptive backstepping control method based on fuzzy approximation for the dual arms of a humanoid robot Sure! Here's a rephrased version of the sentence in English:

"Moreover, Y. Pan et al. [11] proposed an adaptive command-filtered backstepping control strategy for a robotic arm equipped with compliant actuators. Additionally, M. Junaid R and L. Beebi M [12] developed an Adaptive Backstepping Controller (ABC) for regulating the position of a robotic arm. P. Neto et al. [13] applied an Artificial Neural Network (ANN) with a back-propagation algorithm for controlling robots. A model predictive control method was implemented by A. Carron et al. [14] to manage an industrial robot. Furthermore, K. Liu et al. [15] introduced a posture synergy-based approach to design the kinematic transmission method of a multi-joint upper-limb exoskeletal rehabilitation robot with two actuators. In [16], Al-Jodah and Khames evaluated the performance of first- and second-order sliding mode control (SMC) to for angular position tracking of a 1-DOF robotic arm powered by Pneumatic Artificial Muscles. Additionally, in [17], Lilly and Yang applied SMC for angle tracking of planar PAM-actuated manipulators arranged in an agonist/antagonist configuration under load conditions. Moreover, several other control strategies for robotic systems have been proposed [18]-[23]. These studies contribute to the evolving field of control methods for robotic arms, with each having its own limitations in specific areas. Similar to systems that are subjected to external disturbances, a robotic arm requires a robust control technique capable of managing both external factors and model uncertainties. While some classical controllers can handle tracking, they are not effective at resisting external disturbances on the robot arm. Therefore, a robust control mechanism is necessary for this system to address uncertainties in parameters and external influences [24]-[25]. Robust control techniques, such as Sliding Mode Control (SMC), have been utilized in the literature due to their ability to withstand disturbances. However, these methods suffer from the chattering problem, which necessitates the use of approximations to mitigate this issue [26]-[32]. Most of the strategies proposed in the literature review consider the system transactions to be certain and not uncertain, which is far from the reality of practical applications.

Furthermore, the strategy of an Adaptive Backstepping Controller was proposed by [12], as this strategy succeeded in overcoming the external disturbance, but the tracking error is somewhat large and can be reduced, as well as the control effort.

In this study, both classical and Adaptive Synergetic Control (SC and ASC) strategies were introduced to regulate the robot arm. These strategies were selected because of their capability to drive the system's states towards manifold, which is designed according to the required control specifications, while accounting for parametric uncertainties and external disturbances [33][34]. Furthermore, the SC strategy avoids the chattering issue [35][36], while the ASC guarantees stability even in the presence of parameters uncertainty [37]. In adaptive control performances, the parameters of a plant in real time are regulated in order to preserve a desired level of dynamic performance when the system is exposed to varying and unknown parameters [38]–[39]. The adaptive form of control based on the synergetic approach is dedicated to solving the problem of parameter uncertainties in the robotic arm parameters due to the effect of external disturbance by modifying the controller value to reduce the tracking error. The stability of the controlled robotic arm was proven and examined on the basis of Lyapunov theory.

The main contributions of this work can be summarized as follows:

- An ASC is developed and compared with the SC law for a robotic arm.
- To prove the asymptotic stability of robot arm controlled by classical and adaptive synergetic control, such that all errors lastly converge to their consequent zero equilibrium points based on Lyapunov stability.
- The performance of the ASC is compared with that of the ABC technique.
- Control effort and tracking error are minimized.
- The chattering problem is mitigated.

The structure of the paper is as follows: Section two describes the robot arm model, while section three elaborates on the control strategy, which combines classical synergetic control with an adaptive scheme. Section four showcases the computer simulation results, which are used to evaluate the effectiveness of the proposed control approach. Lastly, section five presents the conclusions and suggests directions for future research.

II. Modeling of the Robotic Arm

Equation (1), as in [12], provides the modeling equation for the robotic arm seen in Fig. 1.

$$\ddot{\theta} = -\frac{g}{l}\sin\theta - \frac{v}{ml^2}\,\dot{\theta} + \frac{1}{ml^2}u \tag{1}$$

The applied voltage is represented by v, the pendulum mass is denoted by m, u stands for the control input, g is the gravitational acceleration, l refers to the length of the robotic arm, and θ indicates the angle of the rod from the vertical position.

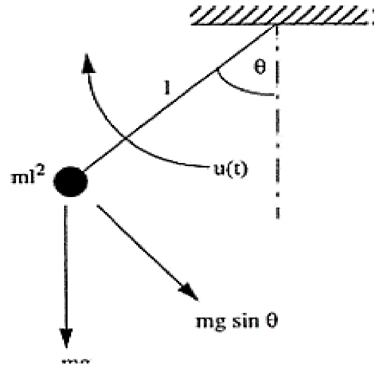

Fig. 1. Robotic arm [12]

Let $\boldsymbol{x_1 = \theta}$ and $\boldsymbol{x_2 = \dot{\theta}}$. Then equation (1) is expressed as below:

$$\begin{aligned}\dot{x}_1 &= x_2\\ \dot{x}_2 &= -\frac{v}{m\,l^2}\,x_2 - \frac{g}{l}\,\sin(x_1) + \frac{1}{m\,l^2}\,u\end{aligned} \tag{2}$$

By introducing additional external disturbances $d(t)$ to the equation above, $d(t)$ results from the external load, which leads to the disruption of the system's parameters, resulting a model uncertainty [14]. the robot arm's mathematical model will be represented by the equation below:

$$\begin{aligned}\dot{x}_1 &= x_2\\ \dot{x}_2 &= -\frac{v}{m\,l^2}\,x_2 - \frac{g}{l}\,\sin(x_1) + \frac{1}{m\,l^2}\,u + d(t)\end{aligned} \tag{3}$$

Two control strategies will be applied in the next section to control rod angle for robotic arm. The robot arm is a tracking system so the controller is designed based on the error between the actual rod angle and the desired rod angle as shown in Fig. 2.

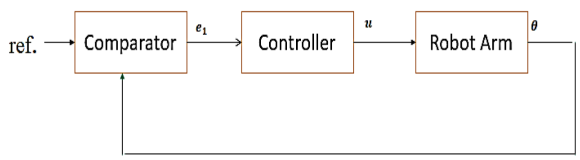

Fig. 2. Control scheme

III. Control Strategy Design

The tracking control problem is addressed by suggesting two control strategies of the rod angle in a robotic arm. The first approach is based on conventual SC, while the second involves ASC which is a control technique that can be applied to several dynamical models, primarily nonlinear dynamical models, serves in the second to attain a stable control system [40]–[41]. Furthermore, these strategies were able to drive the system's states towards manifold, which is designed according to the required control specifications, while accounting for perturbations.

A. Synergetic Control Strategy

To design SC must define error between actual x_1 and desired x_d rod angle and error derivative as follows [42]-[43];

$$e_1 = x_1 - x_d$$
$$\dot{e}_1 = x_2 - \dot{x}_d$$
$$\ddot{e}_1 = \dot{x}_2 - \ddot{x}_d = -\frac{v}{m\,l^2}\,x_2 - \frac{g}{l}\,\sin(x_1) + \frac{1}{m\,l^2}\,u + d(t) - \ddot{x}_d \tag{4}$$

Firstly, define the equation of the Marco variable $\boldsymbol{s_m(e_1)}$ as [44];

$$s_m(e_1) = k_m e_1 + \dot{e}_1 \tag{5}$$

where, $\boldsymbol{k_m}$ is a synergetic control gain. finding the first derivative of Eq. (5) to get;

$$\dot{s}_m = k_m \dot{e}_1 + \ddot{e}_1 \tag{6}$$

The $\boldsymbol{s_m(e_1)}$ denotes the variable of manifold equation described by;

$$F_m \dot{s}_m(e_1) + s_m(e_1) = 0 \tag{7}$$

Where $\boldsymbol{F_m}$is positive, and it represents the converging ratio of $\boldsymbol{s_m(e_1)}$ to the manifold, with $\boldsymbol{s_m(e_1) = 0}$. By substituting Equation (6) into Equation (7), the result is:

$$F_m(k_m \dot{e}_1 + \ddot{e}_1) + s_m = 0 \tag{8}$$

Using $\boldsymbol{\ddot{e}_1}$ from Eq. (4), one can obtain;

$$F_m\left(k_m \dot{e}_1 - \frac{v}{m\,l^2}\,x_2 - \frac{g}{l}\,\sin(x_1) + \frac{1}{m\,l^2}\,u + d(t) - \ddot{x}_d\right) + s_m = 0 \tag{9}$$

Based on Equation (9), the synergetic control law for robotic arm can be get as;

$$u = m\,l^2\left(-k_m \dot{e}_1 + \frac{g}{l}\,\sin(x_1) + \frac{v}{m\,l^2}\,x_2 - d(t) + \ddot{x}_d - \frac{s_m}{F_m}\right) \tag{10}$$

The candidate positive definite Lyapunov function is assumed as below:

$$V = \frac{1}{2}\left(s_m(e_1)\right)^2 \tag{11}$$

Used time derivative of the above Equation:

$$\dot{V} = s_m(e_1)\dot{s}_m(e_1) \tag{12}$$

Substitute $\boldsymbol{\dot{s}_m(e_1)}$ from Eq. (7), one can obtained;

$$\dot{V} = -\frac{\left(s_m(e_1)\right)^2}{F_m} \tag{13}$$

This demonstration illustrates that the controller described above guarantees the stability of the robotic arm system. This is due to the fact that the Lyapunov function $\boldsymbol{V}$ is positive definite, and its derivative $\boldsymbol{\dot{V}}$ is negative definite, as outlined in Equations (11) and (13). This explains the observed.

B. Adaptive Synergetic Control Strategy

Use either SI (MKS) or CGS as primary units. (SI The disturbance exposure has led to uncertainty in the coefficients of the robotic arm [45]-[47], and the system can be represented as follows:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -\frac{v}{m\,l^2}\,x_2 - A\,\sin(x_1) + \frac{1}{m\,l^2}\,u + d(t) \tag{14}$$

Where $= \frac{g}{l}$. For this study, the coefficients A and v are consider uncertain [48]. This can be expressed as below:

$$\hat{A} = A + \tilde{A}$$
$$\hat{v} = v + \tilde{v} \tag{15}$$

Where $\boldsymbol{\hat{A}}$ and $\boldsymbol{\hat{v}}$ are the estimated values coefficient $\boldsymbol{A}$ and $\boldsymbol{v}$. The positive Lyapunov function defined as:

$$V = \frac{1}{2}(s_m)^2 + \frac{1}{2}y_1\tilde{A}^2 + \frac{1}{2}y_2\tilde{v}^2 \tag{16}$$

Where $\boldsymbol{y_1}$ and $\boldsymbol{y_2}$ are adaptation law. The result of time derivative of Eq. (16) as follows:

$$\dot{V} = s_m\dot{s}_m + y_1\tilde{A}\,\dot{\hat{A}} + y_2\tilde{v}\,\dot{\hat{v}} \tag{17}$$

Substituting Eq. (5) into Eq. (17), can be obtain;

$$\dot{v} = s_m(k_m\dot{e}_1 + \ddot{e}_1) + y_1\tilde{A}\,\dot{\hat{A}} + y_2\tilde{v}\,\dot{\hat{v}} \tag{18}$$

Substituting $\boldsymbol{\ddot{e}_1}$ in above equation, resulting:

$$\dot{v} = s_m\left(k_m\dot{e}_1 - \frac{v}{m\,l^2}\,x_2 - A\sin(x_1) + \frac{1}{m\,l^2}\,u + d(t) - \ddot{x}_d\right) + y_1\tilde{A}\,\dot{\hat{A}} + y_2\tilde{v}\,\dot{\hat{v}} \tag{19}$$

The controller $\boldsymbol{u}$ can be designed based on Eq. (10) utilizing the selected estimated values,

$$u = m\,l^2\left(-k_m\dot{e}_1 + \hat{A}\,\sin(x_1) + \frac{\hat{v}}{m\,l^2}\,x_2 - d(t) + \ddot{x}_d - \frac{s_m}{F_m}\right) \tag{20}$$

Utilizing the intended control law which offered in Eq. (20) then Eq. (19), $\boldsymbol{\dot{v}}$ become;

$$\dot{v} = s_m\left(-\frac{v}{m\,l^2}\,x_2 + \frac{\hat{v}}{m\,l^2}\,x_2 - A\sin(x_1) + \hat{A}\,\sin(x_1) - \frac{s_m}{F_m}\right) + y_1\tilde{A}\,\dot{\hat{A}} + y_2\tilde{v}\,\dot{\hat{v}}$$
$$\dot{v} = -\frac{{s_m}^2}{F_m} + y_1\tilde{A}\,\dot{\hat{A}} + s_m\tilde{A}\sin(x_1) + s_m\frac{\tilde{v}}{m\,l^2}\,x_2 + y_2\tilde{v}\,\dot{\hat{v}} \tag{21}$$
$$\dot{v} = -\frac{{s_m}^2}{F_m} + \tilde{A}\left(s_m\sin(x_1) + y_1\,\dot{\hat{A}}\right) + \tilde{v}\left(\frac{s_m}{m\,l^2}\,x_2 + y_2\dot{\hat{v}}\right)$$

To guarantee $\boldsymbol{\dot{v} < 0}$ The last two terms must be solved to be zeros; that is,

$$s_m\sin(x_1) + y_1\,\dot{\hat{A}} = 0 \tag{22}$$
$$\frac{s_m}{m\,l^2}\,x_2 + y_2\dot{\hat{v}} = 0 \tag{23}$$

Based on equations (22) and (23), the adaptive synergetic laws of the robot arm are designed as follows:

$$\dot{\hat{A}} = -\frac{s_m \sin(x_1)}{y_1} \quad (24)$$

$$\dot{\hat{v}} = -\frac{s_m}{m\, l^2 y_2} x_2 \quad (25)$$

The adaptive law in equations (24) and (25) ensures that $\dot{\boldsymbol{v}}$ is negative definite, thereby guaranteeing the asymptotic stability of the robotic arm under both external disturbances and parameters uncertainty, which is controlled by the ASC.

IV. Simulation Result

In this section, two scenarios are presented; the first scenario is to conduct a comparative performance analysis to validate the efficiency of both SC and ASC. The aim was to show which controller is more effective in mitigating external disturbances. The second scenario is to conduct a comparative study between ASC and the adaptive backward controller (ABC), which was designed in a previous study [12], to demonstration the effectiveness of the recommended controller. The numerical simulations were performed in the MATLAB/SIMULINK environment utilizing the "ODE45" solver with a variable in step time, and a maximum step size of 10^{-3}. Table I provides a catalog of the numerical values for the system and controller parameters.

TABLE I. The System and Controller Parameter [12]

Parameter	value
$\boldsymbol{l}$	$1m$
$\boldsymbol{m}$	$2\ kg$
v	$6\ {}^{\text{kg m}^2}/_{s}$
$\boldsymbol{F_m}$	0.001
$\boldsymbol{k_m}$	1
$\boldsymbol{y_1}$	0.2
$\boldsymbol{y_2}$	0.1

In this study, the external disturbance $\boldsymbol{d(t)}$ is considered to be bounded and the upper bound is known. $\boldsymbol{d(t)}$ is selected **as** $\boldsymbol{(0.1\ \sin t)}$. External disturbance in which the system is exposed and tracking performance of robotic arm when using SC and ASC when sinusoidal input is applied as illustrated in Fig. 3 and Fig. 4, respectively.

The tracking error and control action of the robot arm, controlled by SC and ASC, are displayed in Fig. 5 and Fig. 6, respectively.

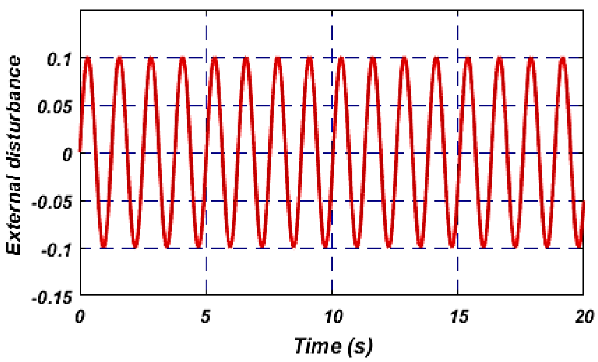

Fig. 3. External disturbance

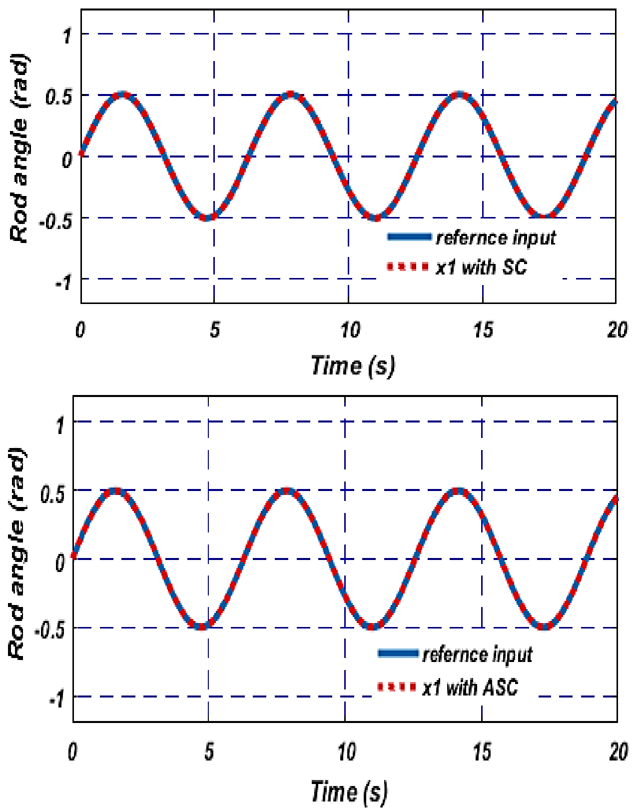

Fig. 4. Rod angle with SC and ASC respectvly

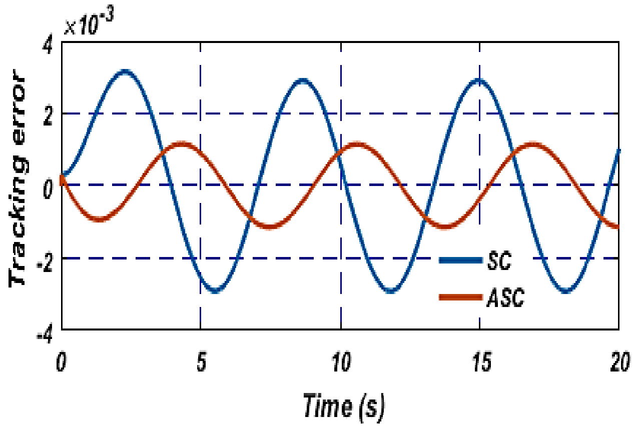

Fig. 5. Tracking error of the robot arm when controlled by SC and ASC separately

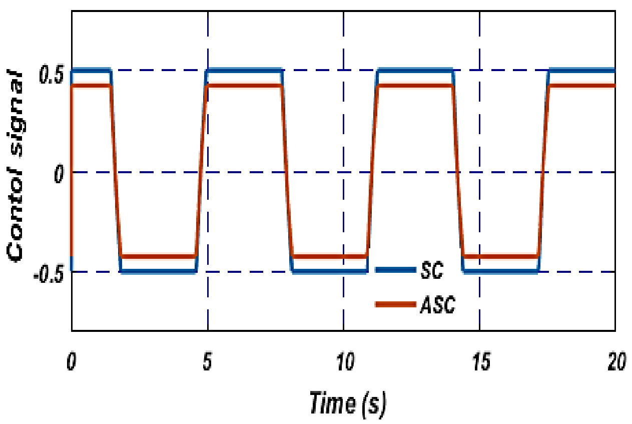

Fig. 6. Control efforts of a robotic arm governed by SC and ASC, respectively

The results above indicate that ASC has a lower error compared to SC, with SC exhibiting the highest error value of (3×10^ (-3)), while ASC's highest error value is (1×10^ (-3)). In terms of the control signal, the highest value of the control signal resulting from SC to control the robot arm is (0.5) while the highest control signal given by ASC is (0.44).

Fig. 7 and Fig. 8 depict the performance of the uncertainty model observed produced by utilizing the adaptive laws for both coefficients of the robot arm.

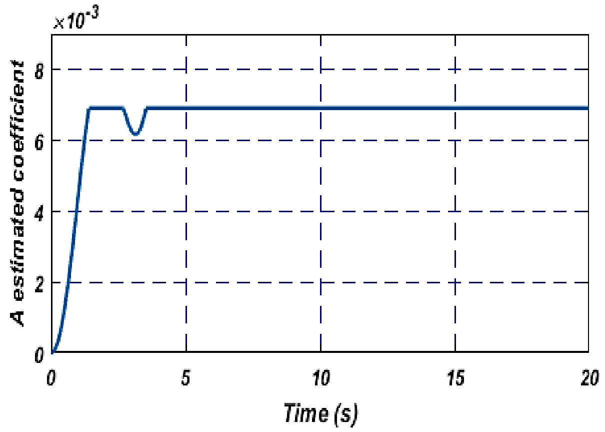

Fig. 7. The estimated value of parameter *A*

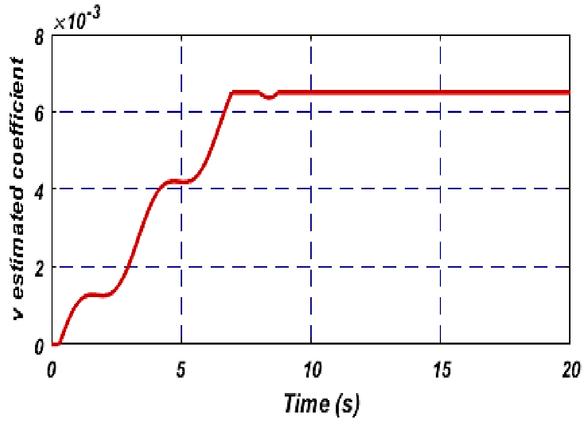

Fig. 8. The approximate value of the v parameter

From the observation of Fig. 7 and Fig. 8, parameter $\widetilde{\boldsymbol{A}}$ ranges between 0 and 7 and parameter $\widetilde{\boldsymbol{v}}$ is between 0 and 6.2 for $0 \leq t \leq 20s$. Therefore, it is concluded that ASC can effectively limited these parameters within limited values over the simulation time, and thus the adaptive controller can prevent the instability problem that may increases due to the uncertainty deviation in the system parameters. Without such bounds, the estimated coefficients could increase indefinitely, potentially causing instability in the adaptive control system.

A comparative study has been managed between the ASC and the Adaptive Backstepping Controller (ABC), which was designed in a previous study [12], to showcase the effectiveness of the proposed controller.

This comparison was made after introducing an external disturbance to the control law from a previous study [12]. The control law design from the previous study is as follows:

$$u = \frac{1}{\varphi_3}\left(-k\,\emptyset + \ddot{x}_d + k_1\dot{e}_1 + \varphi_1 \sin(x_1) + \varphi_2 x_2 - d(t)\right) \tag{26}$$

Where $\boldsymbol{\varphi}$ represent the error variable, and defined as;

$$\emptyset = x_2 - x_{2d} \tag{27}$$

$$x_{2d} = -k_1 e_1 + \dot{x}_d \tag{28}$$

And the parameter update laws known by;

$$\varphi_1 = -r_1 \emptyset \sin(x_1) \tag{29}$$

$$\varphi_2 = -r_2 \emptyset x_2 \tag{30}$$

$$\varphi_3 = r_3 \emptyset u \tag{31}$$

Where $\boldsymbol{r_1}, \boldsymbol{r_2}$ and $\boldsymbol{r_3}$ are adaptation gain constants. For more information see [12]. The design parameters of ABC ($\boldsymbol{k = 4, k_1 = 6, r_1 = 2, r_2 = 3}$ and $\boldsymbol{r_3 = 3}$) Table II demonstration the compression between ASC and ABC.

TABLE II. THE COMPRESSION BETWEEN ASC AND ABC

Parameter	ASC	ABC [12]
Max. tracking error (radian)	0.001	0.02
Max. control effort (N. m)	0.5	0.72

As shown in Table II, ASC gains ranges from (0.001) to (0.2) while control gain of ABC ranges from (3) to (6), therefore the controller ASC needs less gain compared to the ABC controller. Furthermore, the above result show that ASC is better than ABC in term of tracking error and control effort.

V. CONCLUSSION

This work introduces the design of an adaptive control system derived from synergetic theory to mitigate the impact of external disturbances on a robot arm. The stability analysis was performed using Lyapunov's method to improve the control algorithm, thereby guaranteeing the stability of the controlled robotic arm system. Furthermore, a performance comparison was made between the ASC and SC schemes, this comparison showed the effectiveness of ASC in terms of tracking error and control procedures. This comparison was also followed by another comparison between SC and ABC. The results of the last comparison showed the efficiency of the suggested controller in terms of gains, tracking error and control action. Additionally, the design of the ASC led to control and adaptive laws that resulted in bounded coefficient estimates.

Future work will focus on the implementation and actual verification of the proposed control strategy. The proposed controller [49]-[53] can be compared with different control strategies that do not require prior knowledge of external disturbance, do not cause chatter phenomenon, or observer structures to estimate the perturbation in the system parameters [54]-[56] and optimization methods can be proposed to determine the best gain values [57]-[60].

REFERENCES

[1] E. Oumaymah, O. Abdellah, B. Omar, and E. B. Lhoussain, "Backstepping Design Control Applied to the Wind PMSG Generator and Grid Connection Using A Multilevel Inverter," in *2021 8th International Conference on Electrical and Electronics Engineering*

(ICEEE), pp. 136–141, 2021, doi: 10.1109/ICEEE52452.2021.9415945.

[2] P. Badoniya, "Two Link Planar Robot Manipulator Mechanism Analysis with MATLAB," *Int. J. Res. Appl. Sci. Eng. Technol.*, vol. 6, no. 7, pp. 778–788, Jul. 2018, doi: 10.22214/ijraset.2018.7132.

[3] B. Mahboub and D. Stephen, "A Two-Link Robot Manipulator: Simulation and Control Design," *Int. J. Robot. Eng.*, vol. 5, no. 2, Dec. 2020, doi: 10.35840/2631-5106/4128.

[4] M. T. Vo *et al.*, "Back-stepping control for rotary inverted pendulum," *J. Tech. Educ. Sci.*, vol. 15, no. 4, pp. 93–101, 2020.

[5] H. Al-Khazraji, R. M. Naji, and M. K. Khashan, "Optimization of Sliding Mode and Back-Stepping Controllers for AMB Systems Using Gorilla Troops Algorithm," *J. Eur. des Systèmes Autom.*, vol. 57, no. 2, pp. 417–424, Apr. 2024, doi: 10.18280/jesa.570211.

[6] N. A. Elkhateeb and R. I. Badr, "Novel PID Tracking Controller for 2DOF Robotic Manipulator System Based on Artificial Bee Colony Algorithm," *Electr. Control Commun. Eng.*, vol. 13, no. 1, pp. 55–62, Dec. 2017, doi: 10.1515/ecce-2017-0008.

[7] P. Chotikunnan and R. Chotikunnan, "Dual design PID controller for robotic manipulator application," *Journal of Robotics and Control (JRC)*, vol. 4, no. 1, pp. 23-34, 2023.

[8] A. A. Okubanjo, O. K. Oyetola, M. O. Osifeko, O. O. Olaluwoye, and P. O. Alao, "Modeling of 2-DOF robot arm and control," *Futo J Ser.*, vol. 3, no. 2, pp. 80–92, 2017.

[9] W. Scaff, O. Horikawa, and M. de S. Guerra Tsuzuki, "Pneumatic Artificial Muscle Optimal Control with Simulated Annealing," *IFAC-PapersOnLine*, vol. 51, no. 27, pp. 333–338, 2018, doi: 10.1016/j.ifacol.2018.11.618.

[10] K. Bai, G. Jiang, G. Jiang, and Z. Liu, "Based on fuzzy-approximation adaptive backstepping control method for dual-arm of humanoid robot with trajectory tracking," *Int. J. Adv. Robot. Syst.*, vol. 16, no. 3, May 2019, doi: 10.1177/1729881419831904.

[11] Y. Pan, H. Wang, X. Li, and H. Yu, "Adaptive Command-Filtered Backstepping Control of Robot Arms With Compliant Actuators," *IEEE Trans. Control Syst. Technol.*, vol. 26, no. 3, pp. 1149–1156, May 2018, doi: 10.1109/TCST.2017.2695600.

[12] M. R. Junaid, L. M. Beebi, and C. R. Ashima, "Backstepping and adaptive backstepping control on robotic ARM," in *2015 International Conference on Control Communication & Computing India (ICCC)*, IEEE, Nov. 2015, pp. 1–6. doi: 10.1109/ICCC.2015.7432860.

[13] P. Neto, J. N. Pires, and A. P. Moreira, "Accelerometer-based control of an industrial robotic arm," in *RO-MAN 2009 - The 18th IEEE International Symposium on Robot and Human Interactive Communication*, IEEE, Sep. 2009, pp. 1192–1197. doi: 10.1109/ROMAN.2009.5326285.

[14] A. Carron, E. Arcari, M. Wermelinger, L. Hewing, M. Hutter, and M. N. Zeilinger, "Data-Driven Model Predictive Control for Trajectory Tracking With a Robotic Arm," *IEEE Robot. Autom. Lett.*, vol. 4, no. 4, pp. 3758–3765, Oct. 2019, doi: 10.1109/LRA.2019.2929987.

[15] K. Liu, C.-H. Xiong, L. He, W.-B. Chen, and X.-L. Huang, "Postural synergy based design of exoskeleton robot replicating human arm reaching movements," *Rob. Auton. Syst.*, vol. 99, no. 4, pp. 84–96, Jan. 2018, doi: 10.1016/j.robot.2017.10.003.

[16] L. Khames and A. Al-Jodah, "Second order sliding mode controller design for pneumatic artificial muscle," *J. Eng.*, vol. 24, no. 1, pp. 159–172, 2018.

[17] J. H. Lilly and Liang Yang, "Sliding mode tracking for pneumatic muscle actuators in opposing pair configuration," *IEEE Trans. Control Syst. Technol.*, vol. 13, no. 4, pp. 550–558, Jul. 2005, doi: 10.1109/TCST.2005.847333.

[18] J. Rubio, "Sliding mode control of robotic arms with deadzone," *IET Control Theory Appl.*, vol. 11, no. 8, pp. 1214–1221, May 2017, doi: 10.1049/iet-cta.2016.0306.

[19] S. Xu, M. Zhang, and C. Lu, "Research on Intelligent Multimodal Gesture-Guided Control of Robotic Arms," *Research Square*, 2024, doi: 10.21203/rs.3.rs-4538013/v1.

[20] K. Chenchireddy, R. Dora, G. B. Mulla, V. Jegathesan, and S. A. Sydu, "Development of robotic arm control using Arduino controller," *IAES Int. J. Robot. Autom.*, vol. 13, no. 3, pp. 264-271, Sep. 2024.

[21] A. Al-Naib, "Design an Industrial Robot Arm Controller Based on PLC," *Przegląd Elektrotechniczny*, vol. 1, no. 7, pp. 107–111, Jul. 2022, doi: 10.15199/48.2022.07.18.

[22] H. I. Abdulameer and M. J. Mohamed, "Fractional Order Fuzzy PID Controller Design for 2-Link Rigid Robot Manipulator.," *Int. J. Intell. Eng. Syst.*, vol. 15, no. 3, 2022.

[23] H. I. Abdulameer and Mohamed J. Mohamed, "Fractional Order Fuzzy Like PID Controller Design for Three Links Rigid Robot Manipulator," *Iraqi J. Comput. Commun. Control Syst. Eng.*, pp. 80–98, Dec. 2022, doi: 10.33103/uot.ijccce.22.4.7.

[24] S. S. Husain and T. MohammadRidha, "Integral Sliding Mode Control for Seismic Effect Regulation on Buildings Using ATMD and MRD," *J. Eur. des Systèmes Autom.*, vol. 55, no. 4, pp. 541–548, Aug. 2022, doi: 10.18280/jesa.550414.

[25] V. Utkin, A. Poznyak, Y. V Orlov, and A. Polyakov, *Road map for sliding mode control design*. Springer, 2020.

[26] V. Utkin, A. Poznyak, Y. Orlov, and A. Polyakov, "Conventional and high order sliding mode control," *J. Franklin Inst.*, vol. 357, no. 15, pp. 10244–10261, Oct. 2020, doi: 10.1016/j.jfranklin.2020.06.018.

[27] S. S. Husain and T. MohammadRidha, "Integral Sliding Mode Controlled ATMD for Buildings under Seismic Effect," *Int. J. Saf. Secur. Eng.*, vol. 12, no. 4, pp. 413–420, Aug. 2022, doi: 10.18280/ijsse.120401.

[28] Z. Li, F. Wang, D. Ke, J. Li, and W. Zhang, "Robust Continuous Model Predictive Speed and Current Control for PMSM With Adaptive Integral Sliding-Mode Approach," *IEEE Trans. Power Electron.*, vol. 36, no. 12, pp. 14398–14408, Dec. 2021, doi: 10.1109/TPEL.2021.3086636.

[29] D. Al-hadithy and A. Hammoudi, "Two-Link Robot Through Strong and Stable Adaptive Sliding Mode Controller," in *2020 13th International Conference on Developments in eSystems Engineering (DeSE)*, IEEE, Dec. 2020, pp. 121–127. doi: 10.1109/DeSE51703.2020.9450762.

[30] A. M. Hameed and A. K. Hamoudi, "A 2-Link Robot with Adaptive Sliding Mode Controlled by Barrier Function," *J. Eur. des Systèmes Autom.*, vol. 56, no. 6, pp. 1105–1113, Dec. 2023, doi: 10.18280/jesa.560620.

[31] A. F. Abd and S. A. Al-Samarraie, "Integral Sliding Mode Control Based on Barrier Function for Servo Actuator with Friction," *Eng. Technol. J.*, vol. 39, no. 2A, pp. 248–259, Feb. 2021, doi: 10.30684/etj.v39i2A.1826.

[32] M. R. Hassan and S. A. Al-Samarraie, "Robust Nonlinear Control Design for the HVAC System Based on Adaptive Sliding Mode Control," *J. Eur. des Systèmes Autom.*, vol. 55, no. 5, pp. 593–601, Nov. 2022, doi: 10.18280/jesa.550504.

[33] K. Erenturk, A. Draou, and A. AlKassem, "Design and Comparison of Different Types of Synergetic Controllers for Islanded DC Microgrids," *Sustainability*, vol. 14, no. 14, p. 8792, Jul. 2022, doi: 10.3390/su14148792.

[34] S. M. Mahdi, N. Q. Yousif, A. A. Oglah, M. E. Sadiq, A. J. Humaidi, and A. T. Azar, "Adaptive Synergetic Motion Control for Wearable Knee-Assistive System: A Rehabilitation of Disabled Patients," *Actuators*, vol. 11, no. 7, p. 176, Jun. 2022, doi: 10.3390/act11070176.

[35] M. Nicola and C.-I. Nicola, "Improved Performance in the Control of DC-DC Three-Phase Power Electronic Converter Using Fractional-Order SMC and Synergetic Controllers and RL-TD3 Agent," *Fractal Fract.*, vol. 6, no. 12, p. 729, Dec. 2022, doi: 10.3390/fractalfract6120729.

[36] M. Nicola, C.-I. Nicola, and D. Selișteanu, "Improvement of PMSM Sensorless Control Based on Synergetic and Sliding Mode Controllers Using a Reinforcement Learning Deep Deterministic Policy Gradient Agent," *Energies*, vol. 15, no. 6, p. 2208, Mar. 2022, doi: 10.3390/en15062208.

[37] F. R. Al-Ani, O. F. Lutfy, and H. Al-Khazraji, "Optimal Synergetic and Feedback Linearization Controllers Design for Magnetic Levitation Systems: A Comparative Study," *J. Robot. Control*, vol. 6, no. 1, pp. 22–30, 2025.

[38] A. J. Humaidi and A. F. Hasan, "Particle swarm optimization–based adaptive super-twisting sliding mode control design for 2-degree-of-freedom helicopter," *Meas. Control*, vol. 52, no. 9–10, pp. 1403–1419, Nov. 2019, doi: 10.1177/0020294019866863.

[39] F. H. Ajeil, I. K. Ibraheem, A. T. Azar, and A. J. Humaidi, "Grid-Based Mobile Robot Path Planning Using Aging-Based Ant Colony Optimization Algorithm in Static and Dynamic Environments," *Sensors*, vol. 20, no. 7, p. 1880, Mar. 2020, doi: 10.3390/s20071880.

[40] Z. N. Mahmood, H. Al-Khazraji, and S. M. Mahdi, "Adaptive Control and Enhanced Algorithm for Efficient Drilling in Composite Materials," *J. Eur. des Systèmes Autom.*, vol. 56, no. 3, pp. 507–512, Jun. 2023, doi: 10.18280/jesa.560319.

[41] R. A. Kadhim, M. Q. Kadhim, H. Al-Khazraji, and A. J. Humaidi, "Bee Algorithm Based Control Design for Two-links Robot Arm Systems," *IIUM Eng. J.*, vol. 25, no. 2, pp. 367–380, Jul. 2024, doi: 10.31436/iiumej.v25i2.3188.

[42] H. AL-Khazraji, C. Cole, and W. Guo, "Analysing the impact of different classical controller strategies on the dynamics performance of production-inventory systems using state space approach," *J. Model. Manag.*, vol. 13, no. 1, pp. 211–235, Feb. 2018, doi: 10.1108/JM2-08-2016-0071.

[43] H. Al-Khazraji, K. Albadri, R. Almajeez, and A. J. Humaidi, "Synergetic control-based sea lion optimization approach for position tracking control of ball and beam system," *Int. J. Robot. Control Syst.*, vol. 4, no. 4, pp. 1547–1560, 2024.

[44] A. F. Mutlak and A. J. Humaidi, "A Comparative Study of Synergetic and Sliding Mode Controllers for Pendulum Systems," *J. Eur. des Systèmes Autom.*, vol. 56, no. 5, pp. 871–877, Oct. 2023, doi: 10.18280/jesa.560518.

[45] H. Benbouhenni, "Synergetic control theory scheme for asynchronous generator based dual-rotor wind power," *J. Electr. Eng. Electron. Control Comput. Sci.*, vol. 7, no. 3, pp. 19–28, 2021.

[46] S. Zhen, C. Meng, X. Liu, and Y. Chen, "Robust trajectory tracking control design for the robotic arm with uncertainty and experimental validation," *J. Vib. Control*, vol. 30, no. 19–20, pp. 4351–4367, Oct. 2024, doi: 10.1177/10775463231209394.

[47] A. F. Mutlak and A. J. Humaidi, "Adaptive synergetic control for electronic throttle valve system," *Int. Rev. Appl. Sci. Eng.*, vol. 15, no. 2, pp. 211–220, Jun. 2024, doi: 10.1556/1848.2023.00706.

[48] L. Cao, J. Liu, J. Zhang, C. Jiang, and D. Zhang, "Positioning Accuracy Reliability Analysis of Industrial Robots Considering Epistemic Uncertainty and Correlation," *J. Mech. Des.*, vol. 145, no. 2, Feb. 2023, doi: 10.1115/1.4055926.

[49] H. P. H. Anh and C. Van Kien, "Hybrid Fuzzy Sliding Mode Control for Uncertain PAM Robot Arm Plant Enhanced with Evolutionary Technique," *Int. J. Comput. Intell. Syst.*, vol. 14, no. 1, p. 594, 2021, doi: 10.2991/ijcis.d.210107.001.

[50] A. K. Hamoudi and L. T. Rasheed, "Design of an Adaptive Integral Sliding Mode Controller for Position Control of Electronic Throttle Valve," *J. Eur. des Systèmes Autom.*, vol. 57, no. 3, pp. 729–735, Jun. 2024, doi: 10.18280/jesa.570310.

[51] S. J. Abbas, S. S. Husain, S. Al-Wais, and A. J. Humaidi, "Adaptive Integral Sliding Mode Controller (SMC) Design for Vehicle Steer-by-Wire System," *SAE Int. J. Veh. Dyn. Stability, NVH*, vol. 8, no. 3, pp. 10-08-03–0021, Jun. 2024, doi: 10.4271/10-08-03-0021.

[52] S. S. Husain, A. Q. Al-Dujaili, A. A. Jaber, A. J. Humaidi, and R. S. Al-Azzawi, "Design of a Robust Controller Based on Barrier Function for Vehicle Steer-by-Wire Systems," *World Electr. Veh. J.*, vol. 15, no. 1, p. 17, Jan. 2024, doi: 10.3390/wevj15010017.

[53] S. Mobayen, F. Bayat, S. ud Din, and M. T. Vu, "Barrier function-based adaptive nonsingular terminal sliding mode control technique for a class of disturbed nonlinear systems," *ISA Trans.*, vol. 134, pp. 481–496, Mar. 2023, doi: 10.1016/j.isatra.2022.08.006.

[54] M. A. Mossa, H. Echeikh, and A. Ma'arif, "Dynamic Performance Analysis of a Five-Phase PMSM Drive Using Model Reference Adaptive System and Enhanced Sliding Mode Observer," *J. Robot. Control*, vol. 3, no. 3, pp. 289–308, May 2022, doi: 10.18196/jrc.v3i3.14632.

[55] Y. Fan, B. Qiu, L. Liu, and Y. Yang, "Global fixed-time trajectory tracking control of underactuated USV based on fixed-time extended state observer," *ISA Trans.*, vol. 132, pp. 267–277, Jan. 2023, doi: 10.1016/j.isatra.2022.06.011.

[56] N. Gu, D. Wang, Z. Peng, J. Wang, and Q.-L. Han, "Disturbance observers and extended state observers for marine vehicles: A survey," *Control Eng. Pract.*, vol. 123, p. 105158, Jun. 2022, doi: 10.1016/j.conengprac.2022.105158.

[57] L. Qu, W. Qiao, and L. Qu, "Active-Disturbance-Rejection-Based Sliding-Mode Current Control for Permanent-Magnet Synchronous Motors," *IEEE Trans. Power Electron.*, vol. 36, no. 1, pp. 751–760, Jan. 2021, doi: 10.1109/TPEL.2020.3003666.

[58] A. Alizadeh, F. S. Gharehchopogh, M. Masdari, and A. Jafarian, "An improved hybrid salp swarm optimization and African vulture optimization algorithm for global optimization problems and its applications in stock market prediction," *Soft Comput.*, vol. 28, no. 6, pp. 5225–5261, Mar. 2024, doi: 10.1007/s00500-023-09299-y.

[59] A. F. Hasan, N. Al-Shamaa, S. S. Husain, A. J. Humaidi, and A. Al-dujaili, "Spotted Hyena Optimizer enhances the performance of Fractional-Order PD controller for Tri-copter drone," *Int. Rev. Appl. Sci. Eng.*, vol. 15, no. 1, pp. 82–94, Jan. 2024, doi: 10.1556/1848.2023.00659.

[60] A. J. Humaidi, S. K. Kadhim, and A. S. Gataa, "Optimal Adaptive Magnetic Suspension Control of Rotary Impeller for Artificial Heart Pump," *Cybern. Syst.*, vol. 53, no. 1, pp. 141–167, Jan. 2022, doi: 10.1080/01969722.2021.2008686.

[61] Z. A. Waheed and A. J. Humaidi, "Design of Optimal Sliding Mode Control of Elbow Wearable Exoskeleton System Based on Whale Optimization Algorithm," *J. Eur. des Systèmes Autom.*, vol. 55, no. 4, pp. 459–466, Aug. 2022, doi: 10.18280/jesa.550404.