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Comparative Analysis of Computed Torque Control and Adaptive Computed Torque Control for a 2 Planar Manipulator under Sudden Payload Variation

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Abstract: This paper explores the performance of Computed Torque Control (CTC) and Adaptive Computed Torque Control (ACTC) for a 2R planar robotic manipulator performing precise joint movements. While CTC relies on a fixed model of the manipulator, ACTC adapts in real time to handle unexpected changes in the system's dynamics. The manipulator follows a smooth sinusoidal trajectory, and during the operation, a sudden external load is applied to test the robustness of the controllers. Simulation results, including joint positions, tracking errors, control torques, and end-effector motion, indicate that ACTC successfully maintains accurate tracking and stability, whereas CTC experiences noticeable deviations when the load is introduced. A corresponding animation visually highlights the manipulator's motion, clearly showing the moment when the load affects the system. The study demonstrates that ACTC provides a robust and adaptive solution, making it better suited for real-world scenarios where manipulator parameters can change unexpectedly.
Index Terms: Computed Torque Control, Adaptive Computed Torque Control, 2R Planar Manipulator, Trajectory Tracking, Adaptive Control.

I. INTRODUCTION

Robotic manipulators are the ones mainly used in the sectors of industry, healthcare, and research, where the accurate tracking of motion is a must. Conventional control methods, like Computed Torque Control (CTC), are able to perform joint trajectories very precisely but only under perfect conditions. Still, their application completely depends on how right the system parameters, such as link masses and lengths, are. In operations done in real-life scenarios, for instance, if there is a sudden change in payload or any unmodeled, dynamic variation, such a situation would impair performance, and thus, tracking errors or instability might occur as a consequence.

In order to check the limitation imposed by the above-stated cases, a sudden payload of 5kg is applied to the manipulator at t = 5 seconds during its movement. This mimics a realistic case where the manipulator gets subjected to an unanticipated load. The traditional CTC, which takes for granted that perfect knowledge of the manipulator parameters exists, has a hard time tracking accurately in this scenario.

Adaptive Computed Torque Control (ACTC) overcomes this difficulty by incorporating real-time parameter estimation into the control law. This allows the manipulator to get accustomed to unknown or variable dynamics, thereby, being able to keep tracking the changed trajectory accurately even after the sudden payload is applied.

The plan of the current research is that a 2R planar manipulator is moving along a smooth sinusoidal trajectory while the sudden payload is applied. The performance of CTC and ACTC is assessed in terms of joint tracking, tracking error, control torques, and endeffector motion. Moreover, to make it easier to comprehend the man's response, the instant when the external load acts is clearly marked using animations. The outcomes prove the excellent robustness and adaptability of ACTC, thus, pointing out its applicability in the real world where changes in the parameters of the manipulator can happen unexpectedly.

II. MANIPULATOR DYNAMICS

The dynamic behavior of the 2R planar manipulator can be described by the nonlinear second-order differential equation:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau}$$

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where:
$\mathbf{q} = [q_1, q_2]^T$ are the joint angles,
$\tau = [\tau_1, \tau_2]^T$ are the joint torques applied,
$\mathbf{M}(\mathbf{q})$ is the 2 × 2 positive-definite inertia matrix,
$\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is the Coriolis and centripetal matrix,
$\mathbf{g}(\mathbf{q})$ is the gravity torque vector.

Every term is dependent on the physical parameters and joint states of the manipulator. Their matrices are as follows:

$$\mathbf{M}(\mathbf{q}) = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

with

$$a_{11} = I_1 + I_2 + m_1 \left(\frac{l_1}{2}\right)^2 + m_2 \left(l_1^2 + \frac{l_2^2}{4} + l_1 l_2 \cos q_2\right)$$

$$a_{22} = I_2 + m_2 \frac{l_2^2}{4}$$

$$m_2 \left(\frac{l_2^2}{4} + \frac{l_1 l_2}{2} \cos q_2\right)$$

$$\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

with

$$h_{11} = -m_2 \frac{l_1 l_2}{2} \sin q_2 \, \dot{q}_2, \quad h_{12} = -m_2 \frac{l_1 l_2}{2} \sin q_2 \, (\dot{q}_1 + \dot{q}_2)$$

$$h_{21} = m_2 \frac{l_1 l_2}{2} \sin q_2 \, \dot{q}_1, \quad h_{22} = 0$$

Here:

$$\mathbf{g}(\mathbf{q}) = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix} = -g \begin{bmatrix} \left(m_1 \frac{l_1}{2} + m_2 l_1\right) \cos q_1 + m_2 \frac{l_2}{2} \cos(q_1 + q_2) \\ m_2 \frac{l_2}{2} \cos(q_1 + q_2) \end{bmatrix}$$

m_i = mass of link i, li = length of the ith link, • Ii = moment of inertia of i, • g = acceleration due to gravity.

III. COMPUTED TORQUE CONTROL (CTC)

Computed Torque Control is a nonlinear control technique that uses the manipulator's model to cancel nonlinear dynamics and achieve linear error dynamics for trajectory tracking.
Given the desired joint trajectory $\mathbf{q}_d(t)$, define the tracking error and its derivative:

$$\mathbf{e} = \mathbf{q}_d - \mathbf{q}, \quad \dot{\mathbf{e}} = \dot{\mathbf{q}}_d - \dot{\mathbf{q}}$$

The reference acceleration command is designed as:

$$\ddot{\mathbf{q}}_r = \ddot{\mathbf{q}}_d + K_d \dot{\mathbf{e}} + K_p \mathbf{e}$$

where K_p and K_d are positive definite gain matrices controlling the error convergence.

The computed torque control law is:

$$\boldsymbol{\tau} = \mathbf{M}(\mathbf{q}) \ddot{\mathbf{q}}_r + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}} + \mathbf{g}(\mathbf{q})$$

Substituting this control input into the robot dynamics, the error dynamics simplify to a linear second-order system:

$$\ddot{\mathbf{e}} + K_d \dot{\mathbf{e}} + K_p \mathbf{e} = \mathbf{0}$$

Since K_p and K_d are positive definite, this system guarantees asymptotic stability and convergence of the tracking error to zero.

IV. ADAPTIVE COMPUTED TORQUE CONTROL (ACTC)

Adaptive Computed Torque Control enhances the classical computed torque control by incorporating online estimation of uncertain or time-varying dynamic parameters, increasing robustness against modeling errors and external disturbances.

The manipulator dynamics can be linearly parameterized as:

$$\mathbf{M}(\mathbf{q}) \ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = Y(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}) \boldsymbol{\theta}$$

where:
$Y(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})$ is the known regressor matrix,
θ is the vector of unknown parameters.

Define the tracking error and filtered error signal:

$$\mathbf{e} = \mathbf{q}_d - \mathbf{q}, \quad \mathbf{s} = \dot{\mathbf{e}} + \Lambda \mathbf{e}$$

where Λ is a positive definite matrix.

The control input torque is computed as:

$$\boldsymbol{\tau} = Y(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}_r)\hat{\boldsymbol{\theta}}$$

where $\hat{\theta}$ are the online estimates of parameters and

The parameter estimates are updated according to the adaptive law:

$$\ddot{\mathbf{q}}_r = \ddot{\mathbf{q}}_d + K_d \dot{\mathbf{e}} + K_p \mathbf{e}$$

$$\dot{\hat{\boldsymbol{\theta}}} = -\Gamma Y^T(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}_r)\mathbf{s}$$

where Γ is a positive definite adaptation gain matrix.

A Lyapunov-based stability analysis with the candidate function:

$$V = \frac{1}{2}\mathbf{s}^T \mathbf{M}(\mathbf{q})\mathbf{s} + \frac{1}{2}\tilde{\boldsymbol{\theta}}^T \Gamma^{-1} \tilde{\boldsymbol{\theta}}$$

with $\tilde{\theta} = \hat{\theta} - \theta$, shows that:

$$\dot{V} = -\mathbf{s}^T K_d \mathbf{s} \leq 0$$

which guarantees the boundedness of the errors and convergence of the system to the desired trajectory under persistent excitation.

V. SIMULATION SETUP AND METHODOLOGY

The simulation evaluates the Computed Torque Control (CTC) performance for a 2R planar manipulator subject to a sudden payload variation.

A. Manipulator Parameters and Trajectory

The manipulator consists of two links with equal parameters: link masses $m_1 = m_2 = 1kg$ and lengths $l_1 = l_2 = 1m$. The gravitational acceleration is set to $g = 9.81 m/s^2$.

The desired joint trajectory is a smooth sinusoidal function:

$$q_d(t) = \begin{bmatrix} \sin(0.5t) \\ \cos(0.5t) \end{bmatrix}$$

with corresponding velocities and accelerations:

$$\dot{q}_d(t) = \begin{bmatrix} 0.5\cos(0.5t) \\ -0.5\sin(0.5t) \end{bmatrix}, \quad \ddot{q}_d(t) = \begin{bmatrix} -0.25\sin(0.5t) \\ -0.25\cos(0.5t) \end{bmatrix}$$

B. Payload Disturbance

At time t = 5s, a sudden payload of 5kg is applied at the end-effector, simulating unexpected load variation. Before this, the payload is zero.

C. Controller and Simulation Details

CTC employs nominal manipulator parameters (assuming no payload) to compute the control torque as

$\tau = M_{nom}(\ddot{q}_d + K_d\dot{e} + K_p e) + C\dot{q} + G_{nom}$ (2)

where $e = q_d - q$, $\dot{e} = \dot{q}_d - \dot{q}$.

The system dynamics with actual payload are integrated using: $\ddot{q} = M^{-1}(\tau - C\dot{q} - G)$.

The simulation uses a time step of 0.001 s over a 10second period. The joint positions and errors are recorded and analyzed.

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D. Visualization

The simulation also includes an animation of the manipulator's motion contrasting desired and actual trajectories, highlighting the time of payload application with a visual mark.

VI. RESULTS AND DISCUSSION

A. Joint 1 Tracking Performance

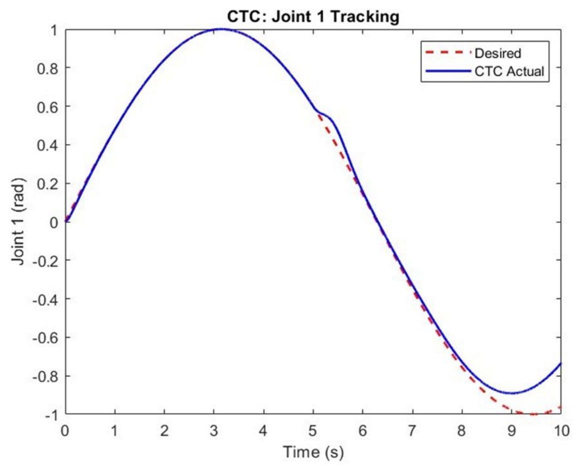

Fig. 1.1: Joint 1 tracking performance comparison: CTC

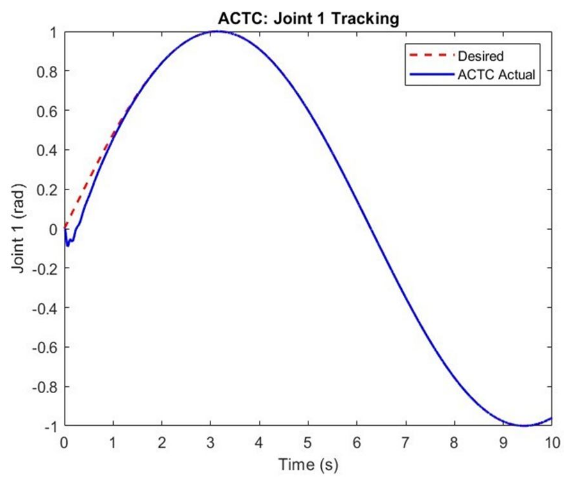

Fig. 1.2: Joint 1 tracking performance comparison: ACTC.

Figure 1 compares the tracking performance of Joint 1 under Computed Torque Control (CTC) and Adaptive Computed Torque Control (ACTC).

In the first diagram (CTC), the robot accurately follows the targeted sinusoidal path during the initial period. But when a sudden weight is added at t = 5s, the forces acting on the system change instantly, and the controller—operating on a fixed model—cannot several compensating actions. So there is a significant delay and a slower response of the actual joint trajectory.

On the other hand, the lower sketch (ACTC) reveals the adaptive controller keeping close tracking even after the addition of the payload. The adaptation process constantly refreshes internal system parameter estimates, thus effectively counteracting the unexpected load variation. As a result, the ACTC line is nearly superimposed on the desired trajectory for the entire simulation, showing less overshoot and quicker error recovery. This comparison vividly points out the increased robustness and flexibility of ACTC in managing the errors in modeling and varying payloads compared to the traditional CTC method.

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B. Joint 2 Tracking Performance

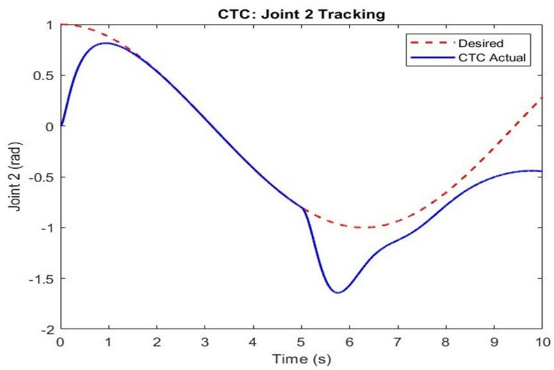

Fig. 2.1: Joint 2 tracking performance comparison: CTC

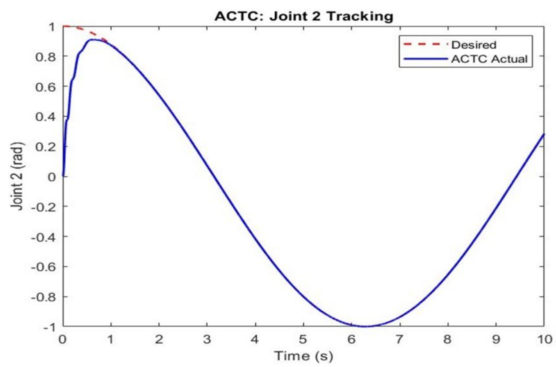

Fig. 2.2: Joint 2 tracking performance comparison: ACTC.

The intended and the measured paths of Joint 2 are shown in Figure 2, which is applicable to both strategies. In the CTC response (top), the manipulator initially very accurately traces the desired path for a few seconds, but then at t = 5s when the payload starts to act, the model mismatch brings about oscillations and delays in the response. The larger tracking error points out that the CTC controller is rather sensitive to both parameter uncertainties and external disturbances.

Conversely, the ACTC response (bottom) displays a robustness that is significantly higher than before. Upon applying the load, the adaptive mechanism instantaneously modifies the system parameters such that they now reflect a heavier system because of the added mass. This results in the actual trajectory being almost indistinguishable from the desired path, which is evident from the smooth convergence and stable motion all through.In conclusion, the performance results indicate that ACTC not only holds its ground against the traditional CTC in tracking accuracy but also surpasses it in disturbance recovery and robustness..

C. Error Tracking Performance

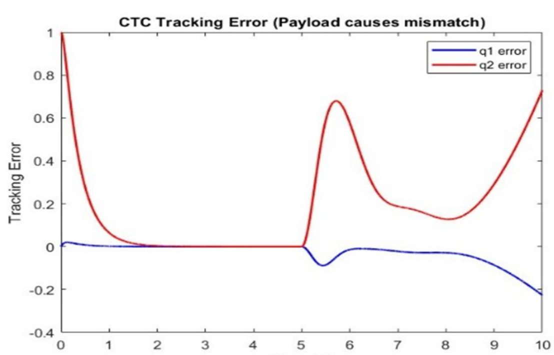

Fig. 3.1: Error Tracking performance comparison: CTC

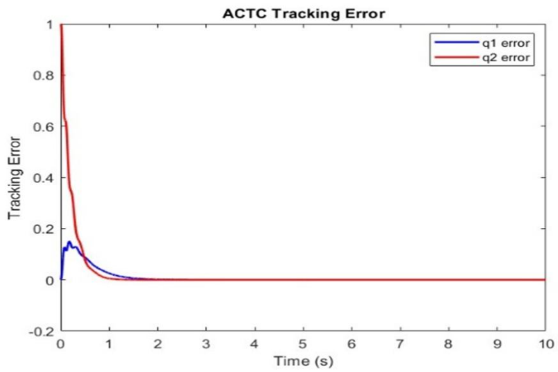

Fig. 3.2: Error Tracking performance comparison: ACTC

At first, both the revolute joints in the CTC figure traced the desired path perfectly, but a sudden distortion of load at about 5 seconds caused a steep increase in the error of the tracking, especially for the second Joint. The algorithm then required more time to settle down, which indicated that CTC was having a tough time handling the changing parameters because it depended on the fixed dynamics of the model. In contrast, the ACTC plot presents a very smooth and stable error convergence. The errors of both q_1 and q_2 are reduced very quickly close to zero and remain unaffected by the disturbance of the payload. This kind of performance proves the ACTC's capability to adjust to varying system parameters in real-time and to provide accurate control and stability.

In conclusion, ACTC has got the smaller peak errors, quicker settling time, and more robustness, while CTC has shown the error drift very clearly in a moving condition. The outcomes have backed up that ACTC offers the best tracking performance when the robot arm is working with uncertain or changing loads.

D. Animations

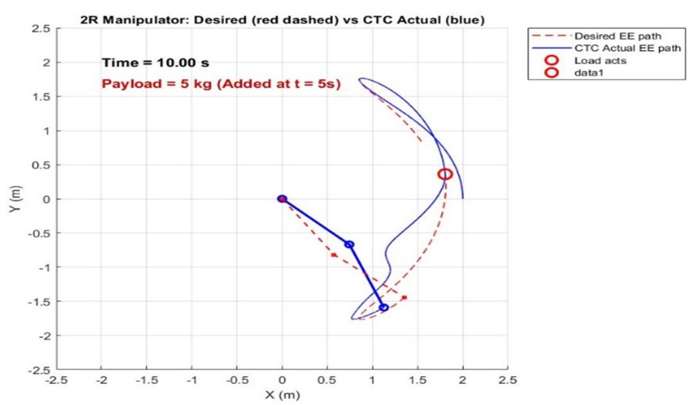

Fig. 4.1: Animation of: CTC

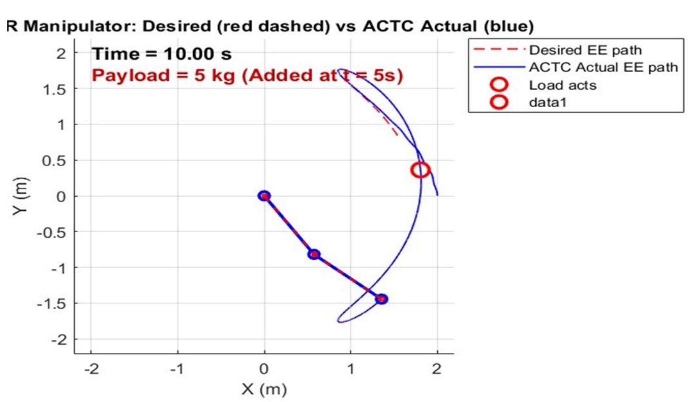

Fig. 4.1: Animation of: ACTC

Initially, in the animation, the CTC's path follows exactly the desired path but when a weight of 5 kg is applied it goes off the desired path steeply. Likewise, it shows clearly oscillations and overshoot which are signs of instability. Conversely, the ACTC path lies closer to the desired trajectory even after the load change is applied. It quickly compensates for the additional weight with less motion and quicker convergence.

The CTC's end-effector is continuously behind the desired path while ACTC is equally tracking ahead.

ACTC succeeds in adapting to the varying conditions thereby reducing both the transient and steady-state errors.

CTC cannot handle sudden disturbances because it relies on fixed model parameters. Ultimately, ACTC proves to be superior to CTC in trajectory tracking with regard to accuracy and stability.

VII. CONCLUSION

The outcome of our comparative study is a conclusive instruction for real-world robotics: Computed-Torque Control (CTC) and its adaptive version Adaptive Computed-Torque Control (ACTC) both yield good performance in ideal and predictable scenarios for a basic 2R arm, but ACTC is the outright winner for the unexpected changes of the real world.The pivotal event leading to this conclusion was the experiment with a sudden unknown change of the weight being lifted. The CTC control (inert, non-adaptive), which was based on a fixed model of the system, broke down instantly and clearly and continually made errors in tracking the desired motion which exposed its basic dependence on the correctness of its internal dynamic model and its fragility when that was not the case. At the other end of the spectrum, the ACTC control exhibited the intelligence of a real system. It very quickly employed its internal estimation mechanism to figure out the new dynamics, applied the necessary compensatory torques, and performed a spectacular recovery in real time. This excellent peddling of error and real-time recovery resulted in a non-negotiable quality of robots working in dynamic environments that is very much today expected of robots; hence it is ACTC that becomes the closer, better option for high precision and at the same time adaptable systems. The straggling simulation results must be moved to the forefront and turned into field performance through experimental verification and advanced enhancements. The very next step is to put the controllers into practice on hardware capable of supporting the testing and enduring the complexities of the real world such as sensor noise, joint friction, and unmodeled dynamics. Moreover, the analysis should be extended to cover more complicated industrial systems such as 3R or 6R arms which will confirm not only the ability of ACTC to cope with the challenges posed by the high number of degrees of freedom (DOF) and tightly coupled systems but also its computational feasibility. Lastly, for the sake of industry uptake, future developments need to include stronger and wiser control strategies (e.g., adaptive sliding mode or projection operators) alongside systematic assessments of the robustness of non-ideal conditions on control performance.

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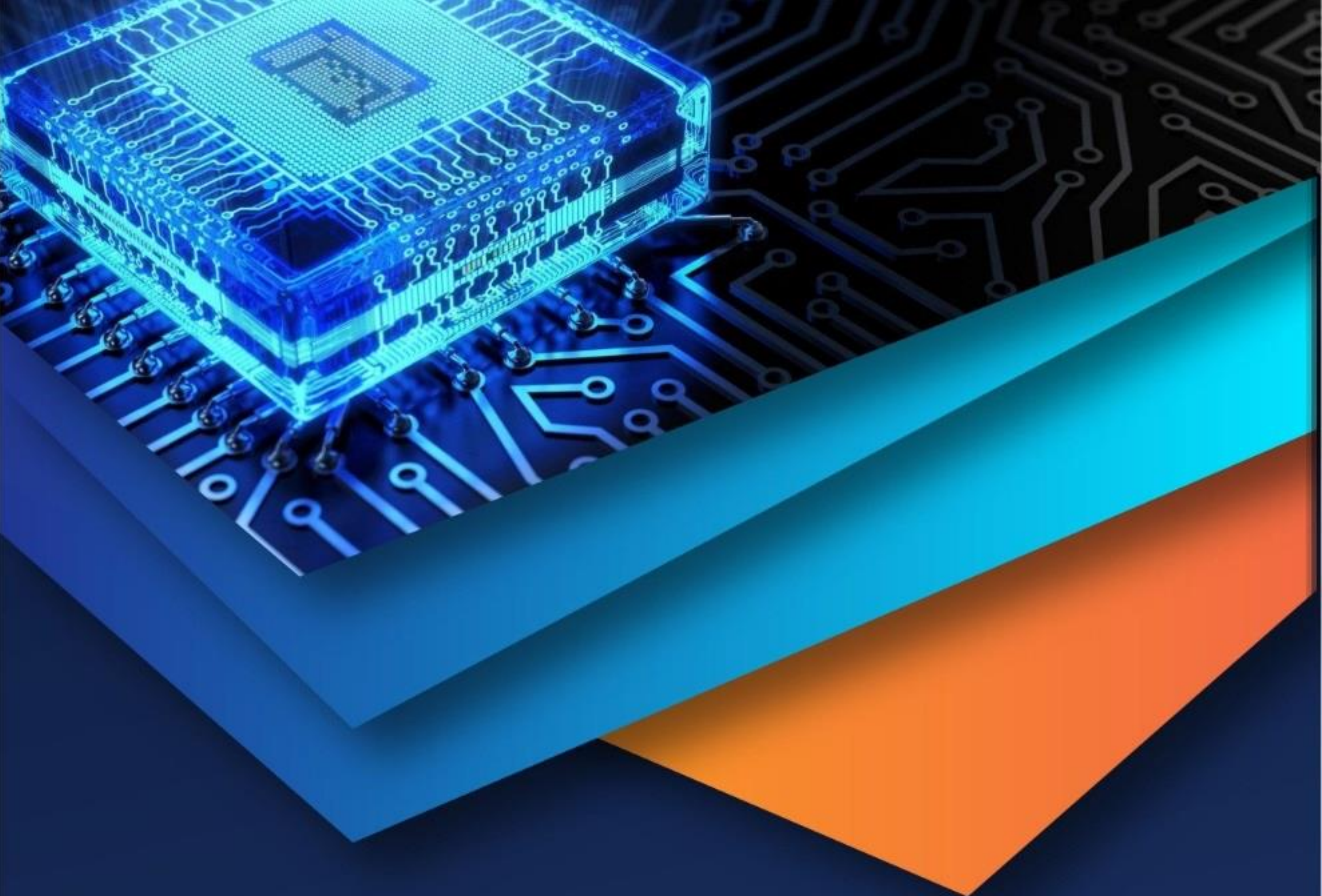

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