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Control Momentum Gyro's Gimbal Control Using FPGA

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Abstract*— Spacecraft's are used for a variety of purposes, including communications, earth observation, meteorology, navigation, planetary exploration and transportation of humans and cargo. A spacecraft's attitude at orbit must be stabilized and controlled by managing the orientation with respect to an inertial frame of reference or another entity (the celestial sphere, certain fields, nearby objects ,etc.) to meet the mission objectives. Controlling vehicle attitude requires sensors to measure vehicle orientation, actuators to apply the torques needed to reorient the vehicle to a desired attitude, and algorithms to command the actuators. A control momentum gyroscope (CMG) is an attitude control device generally used for spacecraft attitude control systems. CMG comprises of a momentum wheel gimbaled in one or two axes. CMG produces control torques by changing the direction of the momentum vector. The spinning rotor along with the motorized gimbals tilts the rotor's angular momentum. As the rotor tilts, the changing angular momentum causes a gyroscopic torque that reorients the spacecraft in the desired axis. The required gimbals' rate is commanded from spacecraft control system to generate the desired torque on the spacecraft's axis. In the present work the gimbal is driven using a permanent magnet synchronous motor (PMSM). The present study is aimed to arrive at the specified rate of gimballing demonstrating the efficiency and capability of control momentum gyroscope (CMG) as an actuator. The PMSM motor considered for this study is controlled using Field Oriented Control (FOC) technique to achieve the required rate of control performance. In the present study it is aimed to achieve a precision servo mechanism for control momentum gyroscope (CMG). It can be used for gimbal control of control momentum gyroscope (CMG), with minimum ripple and maximum accuracy.
***Keywords*— Attitude, CMG , FOC , FPGA ,Gimbal , PMSM.**

I. INTRODUCTION

A spacecraft can be defined as a vehicle, vessel or machine designed to fly in outer space. Spacecraft are used for a variety of purposes, including communications, earth observation, meteorology, navigation, space colonization, planetary exploration, and transportation of humans and cargo. Spacecraft attitude is briefly the angular orientation of a spacecraft body vector with respect to an external reference frame. A spacecraft attitude determination and control system typically uses several sensors and actuators and because attitude is described by three or more variables (apart from the angles, one can add the rotational speed etc.), the difference between the desired and the measured state is complicated to be evaluated, most of the time being either undetermined or over-determined. The attitude of a spacecraft is its orientation in space. The motion of a rigid spacecraft is specified by its position, velocity, attitude and attitude motion. Attitude analysis may be divided into determination, prediction, and control. This typically involves several types of sensors on each spacecraft and sophisticated data processing. Attitude control is the process of orienting the spacecraft in a specified predetermined direction. It consists of two areas – attitude stabilization which is the process of maintaining an existing orientation, and attitude maneuver control which is the process of controlling the reorientation of the spacecraft from one attitude to another.The limiting factor for attitude control is typically the performance of the maneuver hardware and the control electronics, although with autonomous control systems, it may be the accuracy of orbit or attitude information. Some form of attitude determination is required for nearly all spacecraft. Attitude control is required to avoid solar or atmospheric damage to sensitive components, to control heat dissipation, to point directional antennas and solar panels (for power generation), and to orient rockets used for orbit maneuvers. Once the proper orbit and attitude have been obtained and the hardware has been tested, the mission operations phase, in which the spacecraft carries out its basic purpose, is initiated. At this stage, attitude determination and control becomes a routine process. On complex missions, such as lunar or planetary explorations, the acquisition phase may be repeated at various intervals as new hardware or new conditions are introduced. A spacecraft's attitude must typically be stabilized and controlled for a variety of reasons. It is often needed so that the spacecraft's high gain antenna may be accurately pointed to Earth for communications, so that onboard experiments may accomplish precise pointing for accurate collection and subsequent interpretation of data. Also it is needed so that the heating and cooling effects of sunlight and shadow may be used intelligently for thermal control. There are two principal approaches to stabilizing attitude control on spacecraft, out of which one is spin stabilization. Spin-stabilization can be accomplished by setting the spacecraft spinning. 3-axis-stabilization is an alternative method of spacecraft attitude control. There are advantages and disadvantages to both spin stabilization and three-axis stabilization. Spin-stabilized craft provide a continuous sweeping motion that is desirable for fields and particles instruments, as well as some optical scanning instruments, but they may require complicated systems to de-spin antennas or optical instruments that must be pointed at targets for science observations or communications with Earth. Three-axis controlled craft can point optical instruments and antennas without having to de-spin them. If thrusters are used for routine stabilization, optical observations such as imaging must be designed knowing that the spacecraft is always slowly rocking back and forth, and not always exactly predictably. Reaction wheels (RW) provide a much steadier spacecraft from which to make observations, but they add mass to the spacecraft, they have a limited mechanical lifetime, and they require frequent momentum desaturation maneuvers, which can perturb navigation solutions because of accelerations imparted by their use of thrusters. A control momentum gyroscope (CMG) is a related but different type of attitude actuator, generally consisting of a momentum wheel mounted in a one-axis or two-axis gimbal as shown in Figure 1. These are rotors spun at constant speed, mounted on gimbals to provide attitude control. A control momentum gyroscope (CMG) is a related but different type of attitude actuator, generally consisting of a momentum wheel mounted in a one-axis or two-axis gimbal. While a CMG provides control about the two axes orthogonal to the gyro spin axis, triaxial control still requires two units. When mounted to a rigid spacecraft, applying a constant torque to the wheel using one of the gimbals motors causes the spacecraft to develop a constant angular velocity about a perpendicular axis, thus allowing control of the spacecraft's pointing direction. The maximum torque (but not the maximum angular momentum change) exerted by a CMG is greater than for a momentum wheel, making it better suited to large spacecraft. CMGs are generally able to produce larger sustained torques than RWs with less motor heating, and are preferentially used in larger and/or more-agile spacecraft, including Skylab and the International Space Station. A CMG is a bit more expensive in terms of cost and mass , since gimbals and their drive motors must be provided. The torque production capability of a CMG is directly proportional to the angular momentum of the wheel.

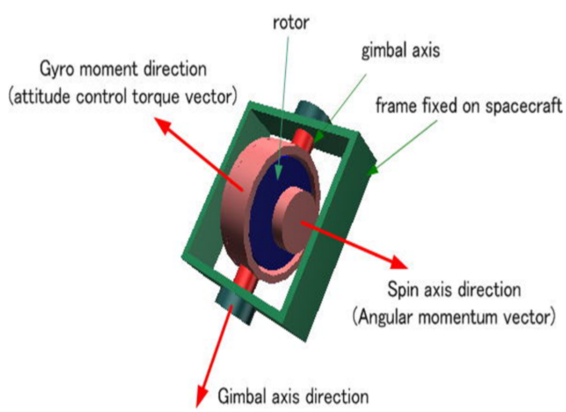

Fig. 1. Example Conceptual schematic of control momentum gyroscope

A major drawback is the additional complexity, which increases the number of failure points. For this reason, the International Space Station uses asset of four CMG to provide dual failure tolerance.

II. IMPLENENTATION

For any position of the rotor, there is an optimal direction of the net stator field, which maximizes torque; there is also a direction, which will produce no torque. If the permanent magnet rotor in the same direction as the field produces the net stator field, no torque is produced. The fields interact to produce a force, but because the force is in line with the axis of rotation of the rotor, it only serves to compress the motor bearings, not to cause rotation. On the other hand, if the stator field is orthogonal to the field produced by the rotor, the magnetic forces work to turn the rotor and torque is maximized. In order to model the fields produced by the stator windings in terms of winding current, 'current space vectors' are used. The current space vector for a given winding has the direction of the field produced by that winding and a magnitude proportional to the current through the winding. This allows us to represent the total stator field as a current space vector that is the vector sum of three current space vector components, one for each of the stator windings. An intuitive way to view the stator current space vector is as a fictitious current that would flow in a single fictitious winding that rotates so as to produce the same stator field direction and magnitude as the combination of three real currents through real stator windings. In order to efficiently produce constant smooth torque, the

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stator current space vector should ideally be constant in magnitude and should turn with the rotor so as to always be in the quadrature direction, irrespective of rotor angle and speed. While the stator current space vector may be constant in magnitude and direction if viewed from the rotating frame of reference of the rotor, from the fixed frame of the stator the current space vector describes a circle as the motor turns.

A. *Need of Field Oriented Control(FOC)*

The fundamental weakness of sinusoidal commutation is that it attempts to control motor currents that are time variant in nature. This breaks down as speeds and frequencies go up due to the limited bandwidth of P-I controllers. Field Oriented Control solves this problem by controlling the current space vector directly in the d-q reference frame of the rotor. In the ideal case, the current space vector is fixed in magnitude and direction (quadrature) with respect to the rotor, irrespective of rotation. Because the current space vector in the d-q reference frame is static, the P-I controllers operate on dc, rather than sinusoidal signals. This isolates the controllers from the time variant winding currents and voltages, and therefore eliminates the limitation of controller frequency response and phase shift on motor torque and speed. Using Field Oriented Control, the quality of current control is largely unaffected by speed of rotation of the motor.

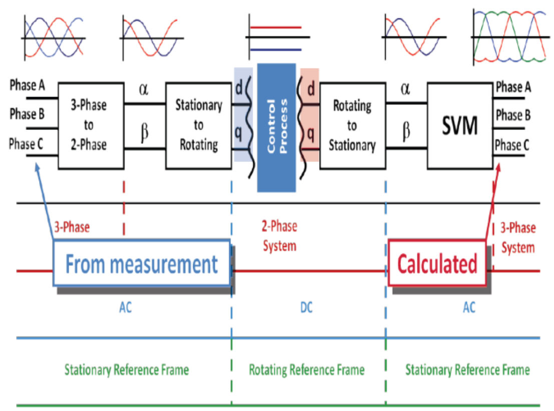

Fig. 2. Block diagram of FOC Control

The process of field oriented control involves transformation from 3-phase (a, b, c) to two phase (α, β) transformation. Since this transformation is within the stator reference frame and PI controllers can work with ease on conversion from stator to rotor reference frame.

III. TRANSFORMATIONS

The behavior of three-phase machines is usually described by their voltage and current equations. The coefficients of the differential equations that describe their behavior are time varying (except when the rotor is stationary). The mathematical modelling of such a system tends to be complex since the flux linkages, induced voltages, and currents change continuously as the electric circuit is in relative motion. For such a complex electrical machine analysis, mathematical transformations are often used to decouple variables and to solve equations involving time varying quantities by referring all variables to a common frame of reference. Among the various transformation methods available, the most appropriate are- Clarke Transformation, Park Transformation.

A. *Clarke Transformation*

The three-phase quantities are translated from the three-phase reference frame to the two-axis orthogonal stationary reference frame using Clarke transformation. The Clarke transformation is expressed by the following equations:

$$I_\alpha = \frac{2}{3} . I_a - \frac{1}{3} (I_b - I_c) \qquad (1)$$

$$I_\beta = \frac{2}{\sqrt{3}} . (I_b - I_c) \qquad (2)$$

where, Ia, Ib, and Ic are three-phase quantities, Iα and Iβ are stationary orthogonal reference frame quantities

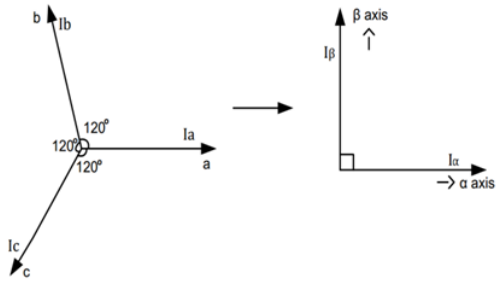

Fig. 3. Clarke Transformation

B. Inverse Clarke Transformation

The transformation from a two-axis orthogonal stationary reference frame to a three-phase stationary reference frame is accomplished using Inverse Clarke transformation as shown in Figure 4

Fig. 4. Inverse Clarke Transformation

The Inverse Clarke transformation is expressed by the following equations:

$$V_a = V\alpha \tag{3}$$

$$V_b = \frac{V_\alpha + \sqrt{3}V_\beta}{2} \tag{4}$$

$$V_c = \frac{V_\alpha - \sqrt{3}V_\beta}{2} \tag{5}$$

C. Park Transformation

The two-axis orthogonal stationary reference frame quantities are transformed into rotating reference frame quantities using Park transformation as shown in Figure 5.

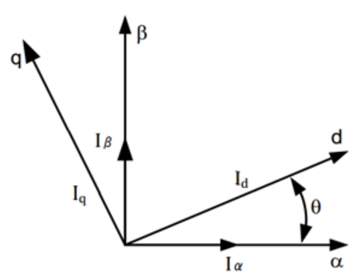

Fig. 5. Park Transformation

The Park transformation is expressed by the following equations:

$$Id = I\alpha * \cos(\theta) + I\beta * \sin(\theta) \tag{6}$$
$$Iq = I\beta * \cos(\theta) - I\alpha * \sin(\theta) \tag{7}$$

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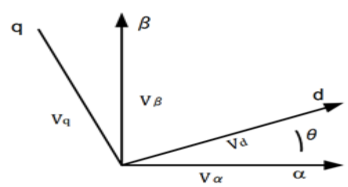
where,
Id, Iq are rotating reference frame quantities
Iα, Iβ are orthogonal stationary reference frame quantities
θ is the rotation angle.

D. Inverse Park Transformation

The quantities in rotating reference frame are transformed to two-axis orthogonal stationary reference frame using Inverse Park transformation as shown in Figure 6. The Inverse Park transformation is expressed by the following equations:

$$V\alpha = Vd * \cos(\theta) - Vq * \sin(\theta) \tag{8}$$
$$V\beta = Vq * \cos(\theta) + Vd * \sin(\theta) \tag{9}$$

where,
Vα, Vβ are orthogonal stationary reference frame quantities,
Vd , Vq are rotating reference frame quantities.



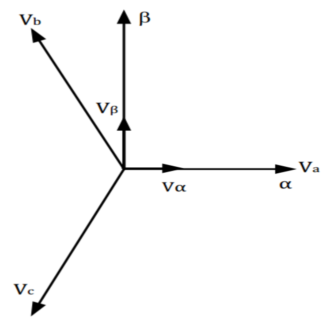


Fig. 6. Inverse Park Transformation (An Algorithm For Vector Rotation)

IV. CORDIC THEORY

The Coordinate Rotation Digital Computer (CORDIC) algorithm was developed by J. E. Volder in 1959 for the computation of trigonometric functions, which has been recognized as the best compromise between large memories needed and speed of converging to the desired precision. In 1971, Walther has generalized this algorithm to implement rotation in circular, linear and hyperbolic co-ordinate systems. Since then it has been used as an elegant method to realize elementary functions such as multiplication, division, logarithmic and exponential functions by computation of two dimensional vector rotations These transcendental functions are the core for many applications such as digital signal processing, graphics, image processing, and kinematic processing. The advances in the VLSI technology have extended the application of CORDIC algorithm recently to the field of biomedical signal processing, neural networks and wireless communications. All of the trigonometric functions can be computed or derived from functions using vector rotations, as will be discussed in the following sections. Vector rotation can also be used from polar to rectangular and rectangular to polar conversions, for vector magnitude, and as a building block in certain transforms such as DFT and DCT. The CORDIC algorithm provides an iterative method of performing vector rotations by arbitrary angles using only shifts and adds. The algorithm credited to Volder is derived from the general rotation transform-

$$x' = x \cos\varnothing - y \sin\varnothing \tag{10}$$
$$y' = y \cos\varnothing + x \sin\varnothing \tag{11}$$

which provides relationship to rotate a vector in a Cartesian plane by the angle Ø

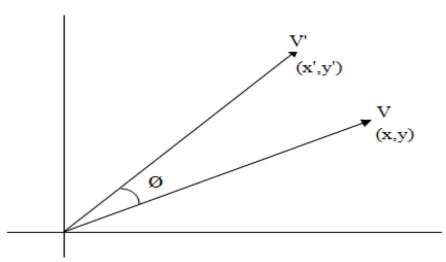


Fig. 7. Rotation of a vector V by angle ø

These can be rearranged as

$$x' = \cos\text{Ø}*(x - y\tan\text{Ø}) \quad (12$$
$$y' = \cos\text{Ø}*(y + x\tan\text{Ø}) \quad (13$$

So far nothing is simplified. However if the rotation angles are restricted so that tan(Ø)= −i ± 2, the multiplication by the tangent term is reduced to simple shift operation

V. RESULTS

The present study was carried to explore the usage of CMG in place of Reaction Wheel (RW) and its suitability for heavy spacecraft's. In the present study the primary step towards the objective has been carried. Figure 8 shows the implementatio of cordic algorithm for calculating Sin θ ,Cos θ where , θ=rotor angle. After obtaining the Sin θ ,Cos θ corresponding to rotor angle the stator's winding current (Ia,Ib.Ic) can be calculated. These stator currents are further processed for FOC control and future experiments are supposed to be carried out.

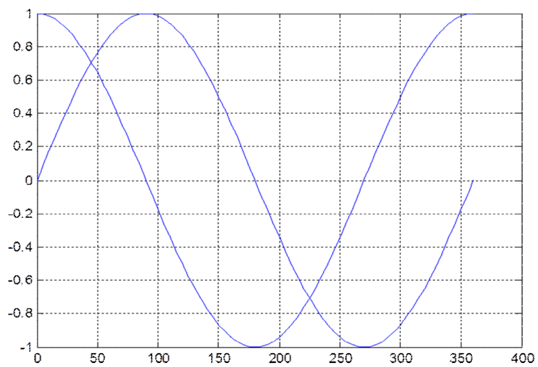


Fig. 8. Implementation of Cordic Algorithm

The proposed configuration is thus proposed to provide advantages as mentioned in Table 1.

Sin θ,
Cos θ

Angels in degree

TABLE I. COMPARISON WITH PROPOSED AND EXISTING SYSTEM

System	*Parameters for Comparison*			
	Generated Torque	Motor Type	Ripple In Generated Torque	Mass Of Satelite
Existing	0.3Nm max	BLDC based reaction wheel	10% of developed torque	Lighter Satelite
Proposed	3Nm max	PMSM based Gimbal control (CMG)	To be studied in detail	Heavier Satelite

VI. CONCLUSION

The study concludes that the replacement of BLDC motor with PMSM -coreless motor will enable to achieve much high torque than BLDC motor. Commercially available chip are µp, RAM, ROM which are placed on the single chip, are not suitable for this case, because of power constraint. Therefore a µp/ µc, external RAM, external ROM is planned to be used using FPGA. The comparison of ripples generated in this two motor class needs to be further investigated. The study will be further carried using Actel family FPGA because of the antifuse mechanism .Finally A2F500 Board will be used for the implementation, because of its long life, reprogrammable nature.

As direct result of advances in technology and control techniques and also considering the above results of the study, it can be preliminary stated that CMGs can be considered as an alternative to reaction wheels for small satellite missions. Also it is inferred that with the use of high performance control electronics, the requirements of tight mass and volume constraints demanded by small satellite missions can be met. Considering the advances in motors, bearings and lubricants more robust mechanical configurations can be adopted to meet and survive the challenging mechanical environment typically experienced by small satellites. With the completion of the all activities mentioned previously, the concept can be further worked after obtaining the in-flight performance of the CMG based attitude control system for small satellites.

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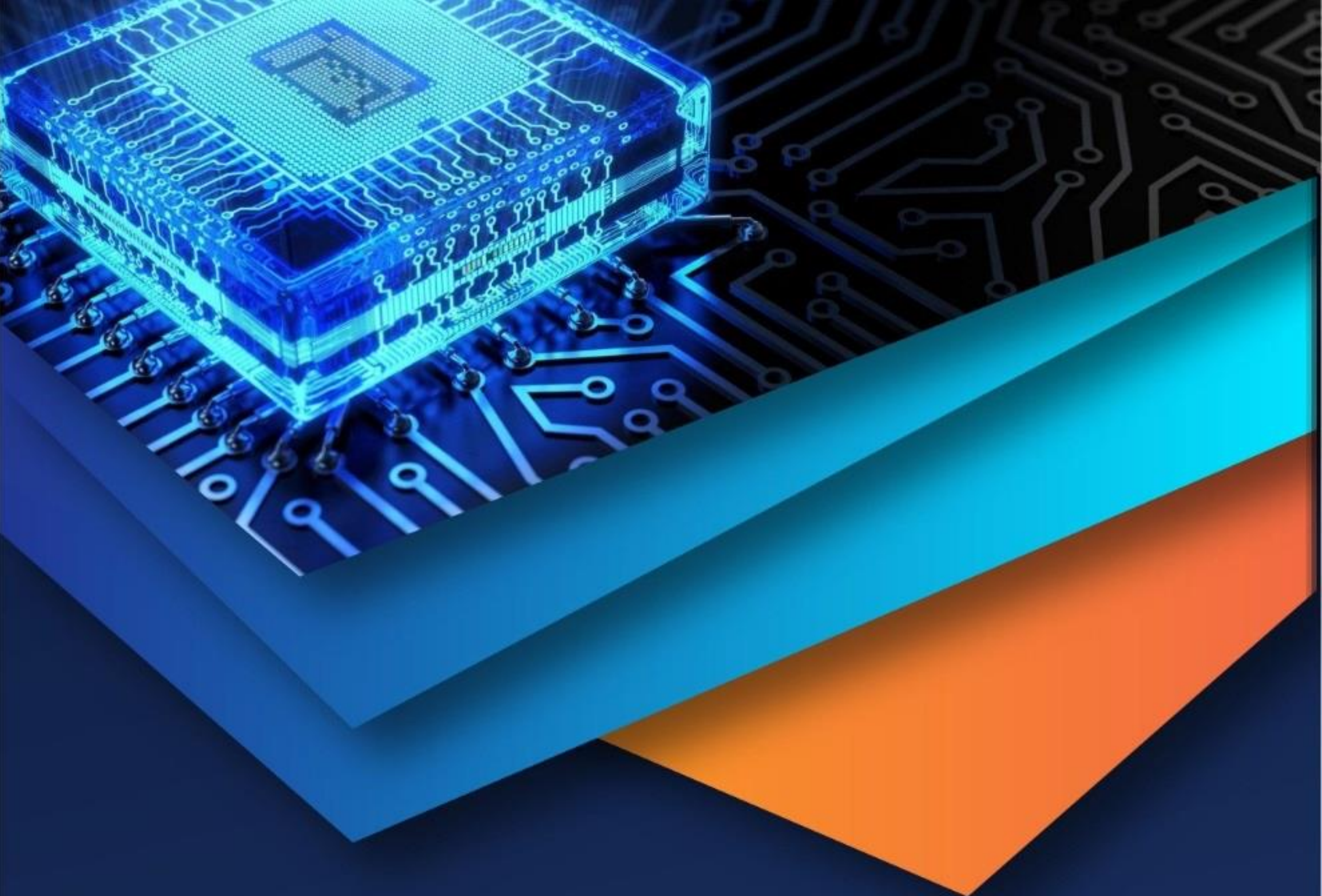

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