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Modular Autonomous Unmanned Aerial Vehicle for Agricultural Assistance

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Abstract: In the past few years, Unmanned Aerial Vehicles (UAVs) have attracted research interest with applications spanning multiple areas. This includes military surveillance, search and rescue, border patrol, climate monitoring and to study several earth sciences based phenomena. Farmers in India are faced with umpteen number of problems: Uncertainty in crop success rate, excess or under-use of pesticides leading to quality deterioration, lack of proper resources and instruction, and external factors like weather, water deficiency and pest attacks lead to crop damage. This paper aims to tackle this problem by conceptualising a Cloud Based Autonomous UAV. Inspired by Google Ara smartphone project, Modular drones empowers farmers to have custom-made UAVs, which aids in staying up-to-date with technological advancements. This allows flexibility in the functionalities of an UAV, while maintaining the strict budget constraints.
Keywords— Unmanned Aerial Vehicle (UAV), Quadrotor, Simultaneous Localisation and Mapping, State Estimation, Way-point navigation, Modularity

I. INTRODUCTION

Modular UAVs allows easy change between various configurations, thus acquiring a necessary balance between functionality, mass and cost. The extent of modularity can cover the larger components such cameras and robotic end-effectors, and can also include variably pitched propellers, allowing for a more custom-made flight. The selected configuration of the UAV is quad-motored rotor craft. A quadrotor is a Vertical Take Off and Landing(VTOL) ability. It is an under-actuated system with four inputs and six outputs. Fixed-wing UAVs though efficient, are unable to hover and Avian based UAVs requires perception of complex fluid mechanics and aero-elasticity thus, rotor based UAVs are the most suitable platform as they provide perfect balance between required manoeuvrability and efficiency. [Ratti. J and Vachtsevanos G, 2011] [1]. Moreover, it is easier to calculate motion control equations for a quadrotor. A quad rotor has 4 Degrees of Freedom and can manoeuvre in 3D Space. Two rotors revolve in clockwise direction about z axis (Figure 1) and the other two in anti-clckwise direction. The short and stubby blades of the quad rotor don't flap due to gyroscopic moments produced during yaw.

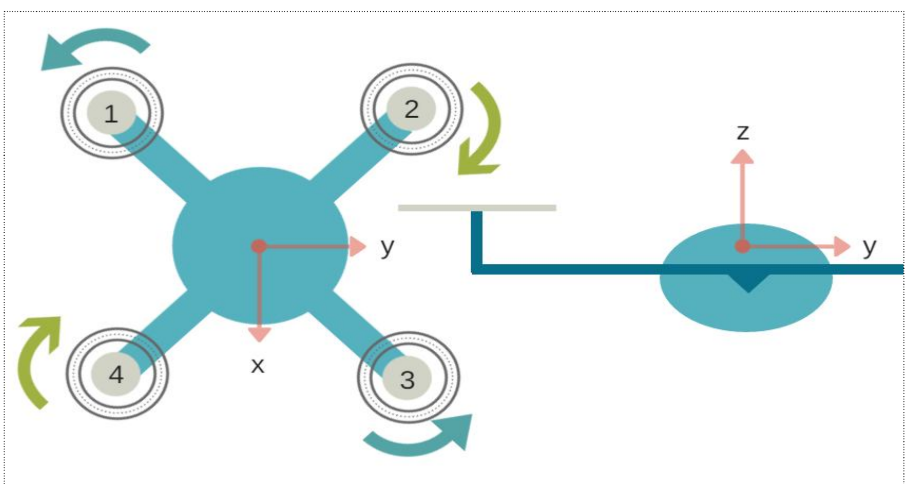

Fig 1: Layout of Quadrotor

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Fig 2. Modular Configuration Design Render. The Complete set of module designs is available on https://bmscemodularuav.weebly.com/modular-uavs.html

II. OBSTACLE EVASION

Robot has to be very agile to avoid unexpected obstacles like birds etc. therefore the goal is to maximize agility:

A. Stop quickly – decrease stopping distance (by increasing linear acceleration)

B. Turn quickly – minimize turning radius (by increasing angular acceleration).

C. To achieve this

D. For a 2d robot model: taking acceleration along vertical direction, to decrease stopping distance, thrust (T) to weight (mg) ratio should be increased and to decrease turning radius, moment (M) to moment of inertia (I_{xx}) ratio has to be increased.

Based on Froude Scaling (For low speed applications) of size of quad rotor, [Wolowicz. et al, 1979] [2], linear acceleration remains nearly constant and angular acceleration varies inversely with distance between centre of mass and axis of rotation. Hence the quad rotor has to be compact for angular agility.

III. COMPONENT SELECTION

The hover state is considered as the design state (fig 3). For the minimum thrust needed to balance the weight, the speed of the motor is known; And the corresponding 'drag moment' acting on the propeller is also plotted. The motor is chosen such that, it produces a torque able to balance the drag moment. Based this result, the thrust to weight ratio can also be adjusted. Both the drag moment and the thrust are proportional to the square of the RPM.[William Hanna, 2014] [3] Furthermore, based on the current energy density of Li-Po batteries in the market, 25% to 40% of the mass of the UAV, hence battery selection is an important design consideration. Compromises have to be made on the flight time of UAV.

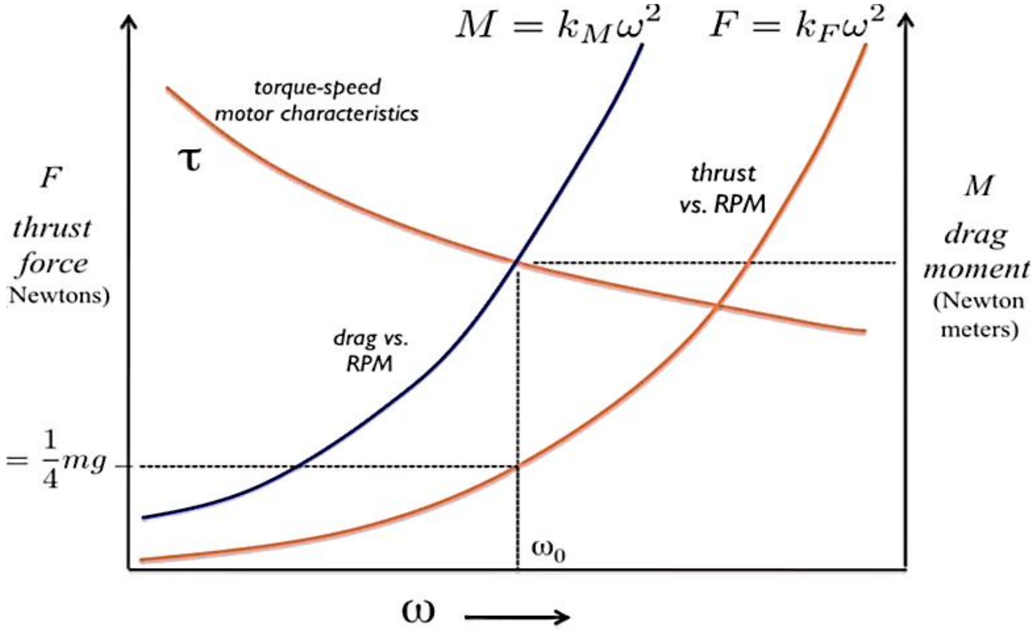

Fig 3 Motor Selection - Source(Aerial Robotics - Coursera)

IV. STATE ESTIMATION

For a sustained autonomous flight, continuous data about robot's position and orientation has be measured. This involves myriad of sensors and camera unit. Inertial Measurement Unit (IMU) comprising of gyroscope (orientation data) and accelerometer (specific force data) can be used for SLAM (Simultaneous Localization and Mapping) technique.

SLAM (Figure 4) - UAV at location 1, finds out the distance and orientation of fixed obstacles from it. Then it moves to location 2 where it finds updated distance and orientation with respect to the obstacles. With this data, UAV calculates the change in its position and orientation. With modularity, different types of cameras (Laser Focused or Beacon based or Thermal or Colour-Depth or Multi-Spectral), varying accuracy of field maps are obtained, with laser based cameras providing highest accuracy.

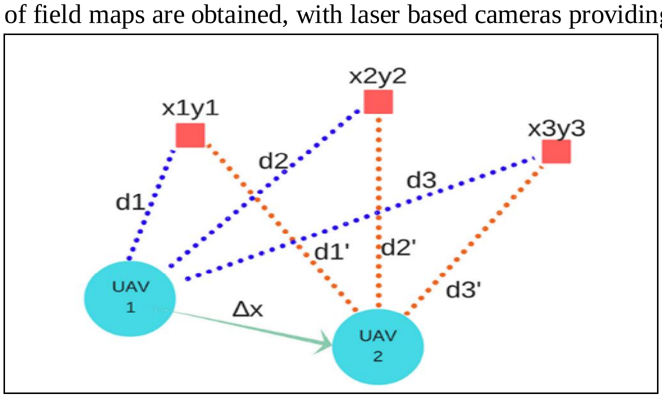

Fig4. SLAM

V. FORCE AND MOMENT EQUATIONS

input that drives the motor to the desired height, ‘u’: (Here u=acceleration required)

$$u = \frac{1}{m}\left[\sum_{i=1}^{4} k_f \omega^i + m\vec{g}\right]$$

The data received from IMU is in Body Fixed Co-ordinates of UAV. For analysis, Earth fixed Co-ordinate values are required. Co-ordinate Conversion can be achieved in following ways:

A. Rotation Matrices
B. Euler Angles
C. Axis Angle Representation
D. Quaternions
E. Exponential Co-ordinates

For Force equation, Rotation matrices(R) is multiplied

$$F = m\ddot{r} = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} + R\begin{bmatrix} 0 \\ 0 \\ F_1 + F_2 + F_3 + F_4 \end{bmatrix}$$

For moment equation, Euler angles are used in the Euler’s equation of motion [F. Šolc*, 2010] [Teppo Luukkonen] [4] [5]

$$I\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} L \times (F_2 - F_4) \\ L \times (F_3 - F_1) \\ M_1 - M_2 + M_3 - M_4 \end{bmatrix} - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times I\begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

Where p, q and r are angular velocities and L is the characteristic length of UAV.

VI. PID CONTROLLER

Any system, when it has to move from a state to another, a delay is experienced because of the transitions that are needed. So, we define an error function ‘e (t)’ which should converge exponentially to zero. A general form of the equation can be:

$$\ddot{e} + K_v\dot{e} + K_p e = 0$$

Here, $\ddot{x_{des}}(t)$ is the desired acceleration, K_v is the derivative gain and K_p is the proportional gain. Modelling the equation for the disturbances (including payload and wind), we get a third order differential equation. [5]

$$u(t) = \ddot{x_{des}}(t) + K_v e(\dot{t}) + K_p e(t) + K_i \int_0^t e(t)\, dt$$

Fine tuning the values of these constants can allow us to make the system springy or damped.
But this equation would be limited by the maximum thrust the motors can produce.

$$u_{max} = \frac{1}{m}\left[T_{max} - mg\right]$$

VII. TRAJECTORY GENERATION

The quad rotor in three dimension has 4 Degrees of freedom. So, the terms that can be explicitly be defined for desired position are

$$r_{des} = [x(t) \quad y(t) \quad z(t) \quad \varphi(t)].$$

The other two variables are dependent on these values.

$$\emptyset = pitch, \theta = roll, \varphi = yaw$$
$$and\ r = current\ position$$

A. Trajectory Tracking (Assuming a linear model such that $\emptyset$ and θ are small):

The data from IMU is sent to position controller (generates thrust) and attitude controller (generates moment for orienting), which drives the motor controller (controls motors as per output from position and attitude controller). Hence the commanded position is generated by PID Controller.

$$\ddot{r}_c = \ddot{r}_{des}(t) + K_d e_v + K_p e_p.$$

Using PID controller throughout for all three directions given i=1, 2, 3, the general form would be:

$$\ddot{r}_{i,c} = \ddot{r}_{i,des} + k_{d,i}\left(\dot{r}_{i,des} - \dot{r}_{i}\right) + k_{p,i}\left(r_{i,des} - r_i\right)$$

$u_1 = m(g + \ddot{r}_{3,c})$, is the commanded thrust sent to motor controller by position controller.

The pitch ($\emptyset$) and the roll angle (θ) are also calculated based on a linear model approximations. [5]

$$\emptyset_c = \frac{1}{g}\left[\ddot{r}_{1,c}\sin(\varphi_{des}) - \ddot{r}_{2,c}\cos(\varphi_{des})\right]$$

$$\theta_c = \frac{1}{g}\left[\ddot{r}_{1,c}\cos(\varphi_{des}) - \ddot{r}_{2,c}\sin(\varphi_{des})\right]$$

$$u_2 = \begin{bmatrix} k_{p,\emptyset}(\emptyset_c - \emptyset) + k_{d,\emptyset}(p_c - p) \\ k_{p,\theta}(\theta_c - \theta) + k_{d,\theta}(q_c - q) \\ k_{p,\varphi}(\varphi_c - \varphi) + k_{d,\varphi}(r_c - r) \end{bmatrix}$$

, is the commanded moment sent to motor controller by attitude controller.

B. Generating trajectories for an agricultural drone with smooth waypoints (Minimum Jerk Trajectory):

Using the concept of 'Calculus of Variations' to obtain the shortest distance geometry that can allow us to develop a n^{th} order trajectory. Since we have considered a minimum jerk trajectory, the system is 3^{rd} order. [Shaojie Shen, 2014] [6] [5]

$$(x^*(t)) = argmin_{x(t)} \int_0^T L\left(x^{(n)}, x^{(n-1)} \ldots, \dot{x}, x, t\right) dt$$

Where for shortest path,

$$Jerk\ Function = L = \left(x^{(n)}\right)^2 \ and \left(y^{(n)}\right)^2 and \left(z^{(n)}\right)^2$$

The above minimum functions can be solved by the Euler-Lagrange equation for x, y, z, φ explicitly:

$$\frac{\delta L}{\delta x} - \frac{d}{dx}\left(\frac{\delta L}{\delta \dot{x}}\right) + \frac{d^2}{dt^2}\left(\frac{\delta L}{\delta \ddot{x}}\right) - \ldots\ldots\ldots + (-1)^n \left[\frac{d^n}{dx^n}\left(\frac{\partial L}{\partial x^{(n)}}\right)\right] = 0$$

Solving for n=3, we get, $x^{(6)}(t) = 0$; Upon Integrating this, the solution would be:

$$x(t) = c_5 t^5 + c_4 t^4 + c_3 t^3 + c_2 t^2 + c_1 t + c_0$$

Most navigation (especially 2^{nd} order and higher systems) require smooth trajectories. And this requires that the quad rotor transits across the waypoints without sudden variation in the velocity and acceleration.

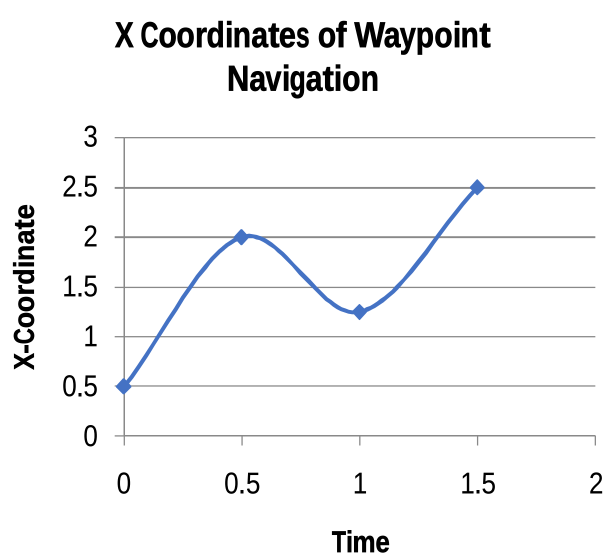

Fig 5 Minimum Jerk Waypoint Navigation

Considering a trajectory as shown in figure 5 with three paths between the intermediate points, Solving for,

$$x(t) = \begin{Bmatrix} x_1(t) = c_{1,5}t^5 + c_{1,4}t^4 + c_{1,3}t^3 + c_{1,2}t^2 + c_{1,1}t + c_{1,0} \\ x_2(t) = c_{2,5}t^5 + c_{2,4}t^4 + c_{2,3}t^3 + c_{2,2}t^2 + c_{2,1}t + c_{2,0} \\ x_3(t) = c_{3,5}t^5 + c_{3,4}t^4 + c_{3,3}t^3 + c_{3,2}t^2 + c_{3,1}t + c_{3,0} \end{Bmatrix}$$

Considering the terms up to snap to be equal at the waypoints, which is for smooth motion: velocity, acceleration, jerk and snap are same when entering and leaving a waypoint (and zero at initial and final position). Such a method is chosen to reduce jerk conditions to minimum. The above equation is solved using a calculus solver.

VIII. IMAGE ANALYSIS

Different modules deliver differing mapping techniques. Laser Cameras in expensive modules can be used for High-Res terrain mapping and accurate yield analysis. Yield mapping can be done spontaneously and high yielding plants can be identified such that in following harvest cycle, the crops planted are from seeds of those plants.

Thermal cameras are able to detect cooler, well-watered field regions as well as dry hot patches. Farmers can use this data to adjust field irrigation and avoid wasting excess water or identify weaker crops and provide them with extra nourishment.

We generated a code to count oranges using Matlab® Image Processing Toolbox (figure 6). The following steps were used:

A. Degenerating blue colour (160 level) to differentiate bright leaves and oranges.
B. Thresholding R, G and B components up to 0.6, 1, 0.1 levels respectively.
C. Producing a binary black & white image.
D. Filling minor holes.
E. Identifying and plotting the boundaries

Fig 6 Fruit Counting using MATLAB®

The actual number of oranges in the original image was 36 and detected oranges were 38. Three false detections were two bright leaves at the lower right corner and one bright leaf at upper centre and one orange at left central was missed. However, this technique is still efficient in figuring out rough number of oranges and can be used to segregate oranges based on size and colour.

IX. CLOUD BASED SOLUTIONS

Figure 7 is a flow process of sharing and visualizing data using cloud based platforms. The data from the ground controller is uploaded to cloud services like Amazon® AWS™. This data can then be analyzed and interpreted. This data can be shared to national servers where nationwide analysis is possible without visiting these farms. From these results, it’s easier for government to roll out schemes and policies for boosting agricultural revenue. Farmers can remotely access all details of their farm. Regular updates on farm conditions and alerts are instantly notified to farmer even if he/she is not present at the farm. UAVs can be deployed and controlled by farmers from any corner of the world. Instant service calls in case of malfunction can be given without approaching a 3rd party Service provider. Updates from weather satellites about incoming storms reach faster than even Television or newspapers.

X. CONCLUSIONS

UAV industry is expected to grow to $127 billion by 2020, currently worth $2 billion. The Internet of Things (IoT) is emerging as the most disruptive technology of early 21st century. Tapping and combining resources from both these industries would be revolutionary.

Inspired by Google Ara smartphone project, modular UAVs help farmers stay technologically up to date by updating only the components they wish to. With evolution of Additive manufacturing industry, cost of manufacturing using these techniques will reduce and can be factory-less by 3-d printers present in Drone-shops in each taluk reducing the infrastructure cost drastically. Moreover, elimination of cast and die components will enable easy creation of custom-made UAV parts as per liking of farmers. This is not possible in mass manufacturing factories where possible configurations are limited. Furthermore, with a swarm of Super-abled drones, large farms can be efficiently managed.

In the near future, we will Improve our image processing, to accurately determine more features and start fabricating a prototype utilizing a Pixhawk Flight Controller.

XI. ACKNOWLEDGMENT

A. Google® Ara™ Modular phone project.
B. Coursera® University of Pennsylvania – Aerial Robotics
C. Matlab® Image Processing Toolbox
D. SOLIDWORKS®
E. Amazon® AWS™

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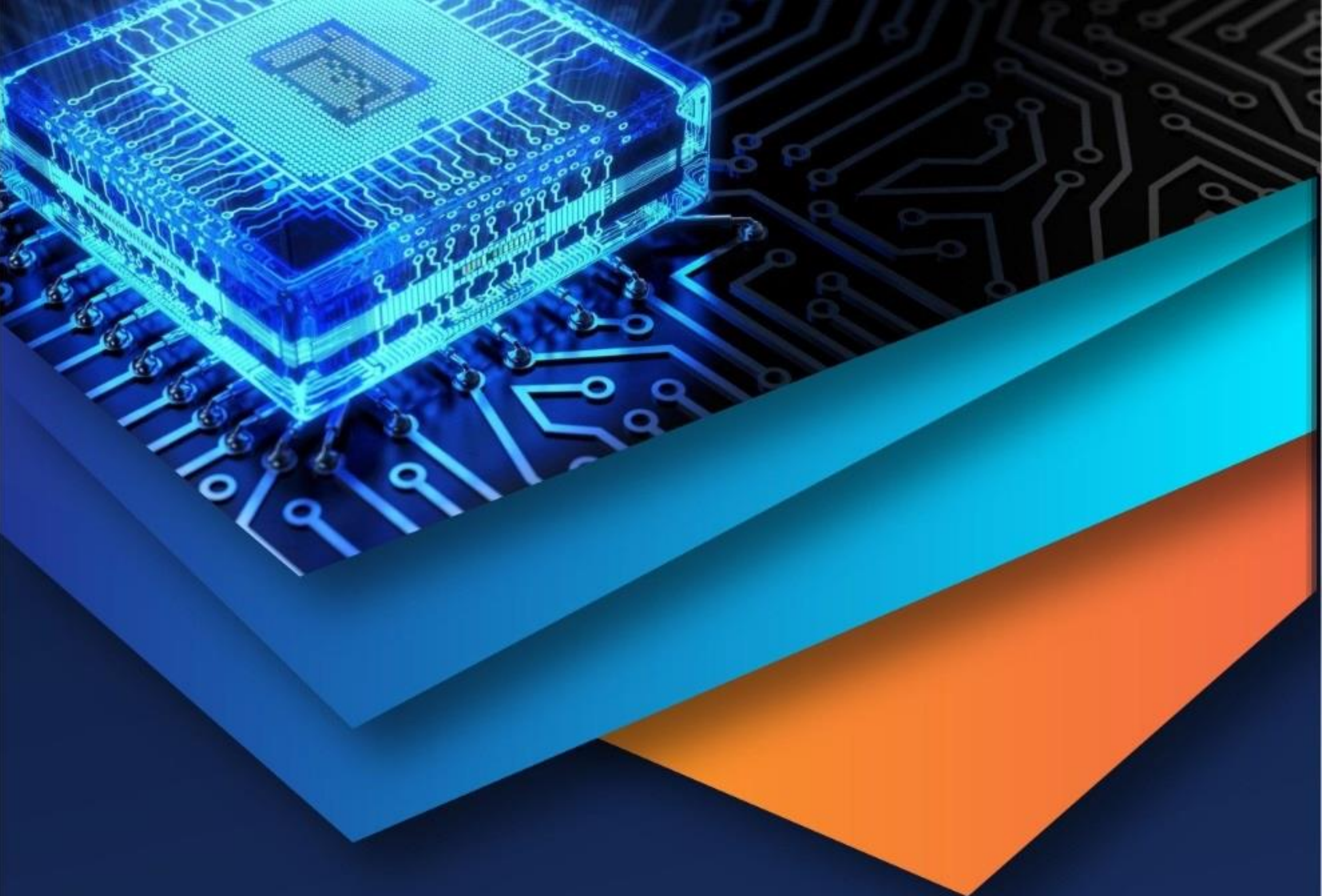

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