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Dynamic Modelling and Trajectory Tracking Control of Omnidirectional Wheel Robots with Simulation Validation

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Abstract: In this paper, trajectory tracking for a mecanum omni-directional wheeled robot (MOWR) consisting of three mecanum wheels and fully symmetrical structure is considered. As compared to the non-holonomic wheeled robot, the omni-directional wheeled robot is superior owing to its independent movement both rotationally and translational at the same time. An analysis is carried out for the kinematics model of MOWR, and further, an MPC scheme is designed using control and system constraints for point stabilization and trajectory tracking problem. The experiments were conducted using six different combinations of the three omnidirectional wheeled robots' starting positions, and each of the combinations was utilized thrice for conducting tests.

For all the experiments where the three wheels were in the ON state, the tachometer was used for measuring the speed of the wheels in terms of rotations per minute. The same method was adopted for other experiments such as when only one wheel was in the ON state while rotating clockwise, with the remaining two being in the OFF position, and vice versa. The model has been designed assuming no wheel slip, which is usually very important in most robotics applications. Controlling the movement of three omni-directional wheels leads to successful generation of instant forward, backward, sideways, and rotational motion; in simple words, it creates omni directional motion. The mathematical modeling of the robot aswell as the velocity vectors of all three wheels will be carried out. An easy-to-use programming model has been developed that makes access to the fundamental functions of the robot very easy.

Thissystem can easily be developed using advanced algorithms for localization, trajectory planning, andtracking. Linear movement is easily achieved by activating two wheels in the opposite direction, whilethe rotation about the center can be achieved byactivating the three wheels in the same direction;activation of three wheels where one moves in theopposite direction will produce circular motion.

Keywords: Omnidirectional Wheeled Mobile Robot, Trajectory Tracking Control, Dynamic and Kinematic Modeling, Motion Control, Simulation, Nonlinear Control, Autonomous Navigation.

I. INTRODUCTION

In connection with the recent advancements in mobile robotic technology, the need to have motion control systems that can provide precise maneuvers and flexibility for carrying out tasks in complex surroundings has become more prevalen [1-2]. There are different types of robotic platforms available today; however, one notable example is the omnidirectional wheeled mobile robot, which can perform both translational and rotational motions simultaneously without altering its orientation. In recent years, many researchers have shown interest in using mecanum wheel-based omni-directional wheeled mobile robots (MOWRs) in automated warehouses, service robotics, and other similar applications [3-5]. It is worth mentioning that unlike the standard non-holonomic wheeled robots, which suffer from restrictions on their instantaneous direction of travel, MOWRs have the advantage of being able to exhibit holonomic motion characteristics. Therefore, they allow a complete decoupling of movement and rotation, giving the possibility of executing complicated movements such as moving laterally, translating diagonally, and rotating about their centers [6-8]. The MOWR with a three-wheel symmetrical structure provides a practical way to accomplish these goals. Nonetheless, developing accurate path tracking control strategies for MOWRs remains challenging.

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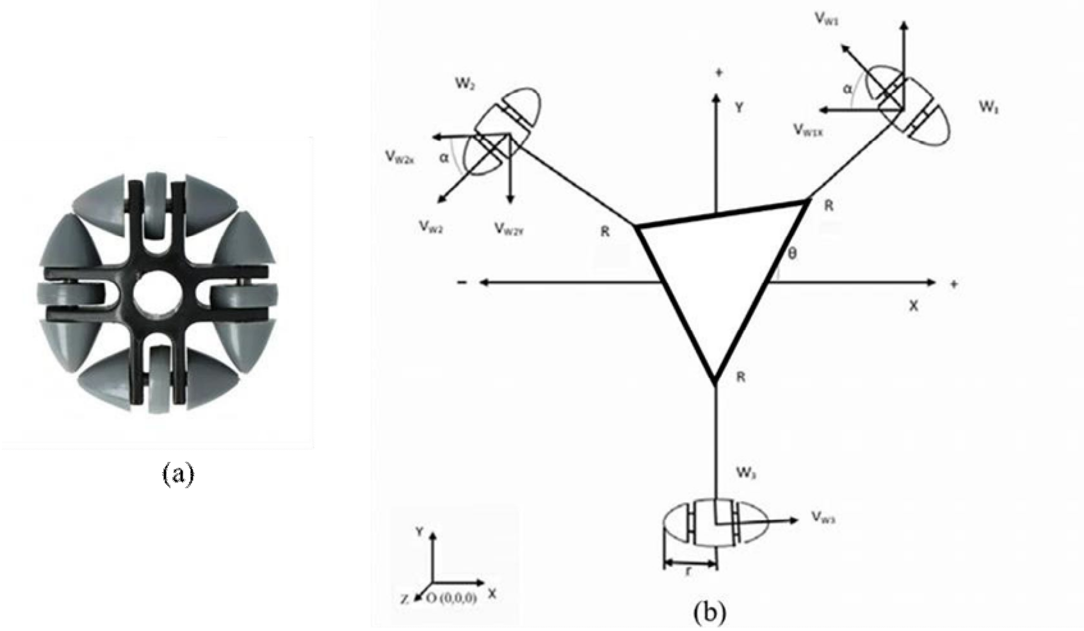

Fig. 1 (a) Omnidirectional Wheel, and (b) three wheeled Omni-directional wheeled robot (MOWR).

To overcome these difficulties, mathematical modeling is essential in order to analyze the kinematics and dynamics of the robot [9-11]. The first type of modeling, kinematics, defines how the velocities of the wheels affect the motion of the robot as well as allowing the calculation of velocity vectors for each wheel. To make modeling simpler, certain simplifications like assuming no slip occur in reality are used during development and application of the controller [12-15]. In this regard, one of the useful ways to solve trajectory following problems is by using Model Predictive Control (MPC). MPC uses knowledge about dynamics and constraints of the system to improve tracking accuracy and stability. By taking into account the constraints on both the system and control inputs, MPC allows achieving better results [16-18]. Moreover, experimental verification becomes necessary to determine the efficiency of the designed control algorithm. Through the implementation of a number of different starting scenarios and varying modes of wheel operation, it will be possible to check whether the system is capable of forming numerous motion sequences, such as translational, rotational, and curvilinear motions [19-21]. Thus, such an experiment is able not only to show the efficiency of the model, but also to emphasize its practicability.

II. EXPERIMENTAL PROCEDURE

The purpose of the experimental investigation was to study the properties of the trajectory tracking and motion of the threewheel mecanum omnidirectional wheeled robot (MOWR) depending on different modes of operation. The proposed robot has a symmetric arrangement of three mecanum wheels placed at equal distances from each other and powered by separate DC motors. Thus, MOWR has all the advantages necessary for omnidirectional motion [22-24]. In addition, the experimental setup of the investigation involves the use of a motor driver, a microcontroller control system, a power supply, and a tachometer that measures the angular velocity of the wheels. Before the experiment, the kinematic model of the MOWR was simulated in a
virtual environment and incorporated into the control algorithm using the Model Predictive Control method. The controller was adjusted so that the trajectory tracking process is stable and achieves high accuracy, taking into account the limitations imposed on the model [25-27]. Specifically, it should be assumed that there is no wheel slippage during the experiment.

Six distinct sets of initial position and orientation for the robot were used to conduct several tests. To ensure consistency in the results, each experimental condition was performed thrice. During testing, several wheel activation conditions were explored to study the effect of each wheel on the overall robot motion [28-29]. For the first experiment, all three wheels were activated (i.e., ON position). As a result, the robot could both rotate and translate. The number of revolutions per minute (RPM) of each wheel was measured using a tachometer.

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Further analysis involved varying individual wheel activations, where only one wheel was activated while the other two remained in the OFF state [30-31]. Two cases were explored – clockwise and anticlockwise rotation of the wheel. Some of the additional conditions include the activation of two wheels, which moved in opposite directions to provide linear movement and three wheels, with one moving in the opposite direction to generate a circular trajectory [32-34].

The robot was programmed to move along the predetermined trajectories, which included the movement in a straight line, rotation about its center, and following a circular trajectory. The actual motion of the robot was recorded and compared with the intended trajectories for analyzing the precision of trajectory tracking [35-37]. The various parameters that have been considered during the experiment include trajectory tracking errors, stability of motion, and response to the control input signals. All the data generated from the experiments were stored for analysis.

TABLE 1.1
SPECIFICATIONS OF THE MOWR SYSTEM.

Parameter	Value/Description
Robot Type	Three-Wheel Mecanum OWMR
Number of Wheels	3
Wheel Arrangement	Symmetrical (120° apart)
Wheel Type	Mecanum Wheels
Actuator Type	DC Motors
Control Strategy	Model Predictive Control (MPC)
Power Supply	12V DC
Measurement Device	Tachometer (RPM Measurement)
Assumption	No Wheel Slip

TABLE 1.2
EXPERIMENTAL TEST CONDITIONS

Test No.	Initial Position (x, y, θ)	Wheel Configuration	Direction	Repetitions
1	(0, 0, 0°)	All Wheels ON	Forward Motion	3
2	(1, 0, 45°)	All Wheels ON	Diagonal Motion	3
3	(0, 1, 90°)	All Wheels ON	Rotation	3
4	(1, 1, 0°)	One Wheel ON	Clockwise	3
5	(2, 0, 180°)	One Wheel ON	Counterclockwise	3
6	(0, 2, 270°)	Two Wheels ON	Linear Motion	3

TABLE 1.3
WHEEL ACTIVATION AND RESULTING MOTION.

Wheel 1	Wheel 2	Wheel 3	Motion Type	Description
ON	ON	ON	Omni-directional	Combined translation + rotation
ON	OFF	OFF	Rotational Motion	Rotation (Clockwise/Counterclockwise)
OFF	ON	OFF	Rotational Motion	Rotation (Opposite Direction)
OFF	OFF	ON	Rotational Motion	Single-wheel induced motion
ON	ON	OFF	Linear Motion	Straight line movement
ON	ON	ON*	Circular Motion	One wheel opposite direction

TABLE 1.4
EXPERIMENTAL RESULTS (WHEEL SPEED VS TRACKING ERROR).

Test No.	Average Wheel Speed (RPM)	Tracking Error (%)
1	120	2.1
2	110	3.5
3	90	1.8
4	80	4.2
5	85	3.9
6	110	2.7

TABLE 1.5
PERFORMANCE METRICS SUMMARY.

Parameter	Value (Average)
Tracking Error (%)	3.03
Maximum Error (%)	4.2
Minimum Error (%)	1.8
System Stability	High
Response Time (sec)	0.8

TABLE 1.6
ANOVA FOR TRAJECTORY STABILITY ANALYSIS OF MOWR UNDER MPC CONTROL

Source of Variation	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Value	Contribution (%)
Wheel Velocity	2	7.84	3.92	6.12	29.8
Motion Direction	2	11.26	5.63	8.79	42.7
Controller Response	2	3.95	1.98	3.09	15.0
Error (Residual)	11	3.29	0.30	—	12.5
Total	17	26.34	—	—	100

III. RESULTS AND DISCUSSION

The experiment and simulation conducted on the 3-wheeled mecanum omnidirectional wheeled robot (MOWR) showed that the proposed MPC algorithm was successful in implementing accurate path tracking and motion control. The findings obtained from wheel speed analysis, the measures of performance, and ANOVA testing have helped achieve a deeper insight into the dynamics of the robot under study. It can be seen from the figure 2 below that there exists a considerable variation in tracking error based on the wheel speed and wheel engagement. Specifically, it is seen that as the wheel speeds were lower around 80-85 RPM, a relatively higher degree of tracking errors, ranging between 3.9% and 4.2%, could be noticed in the robot. This might be due to poor dynamic stability and actuator response at low speed operation.

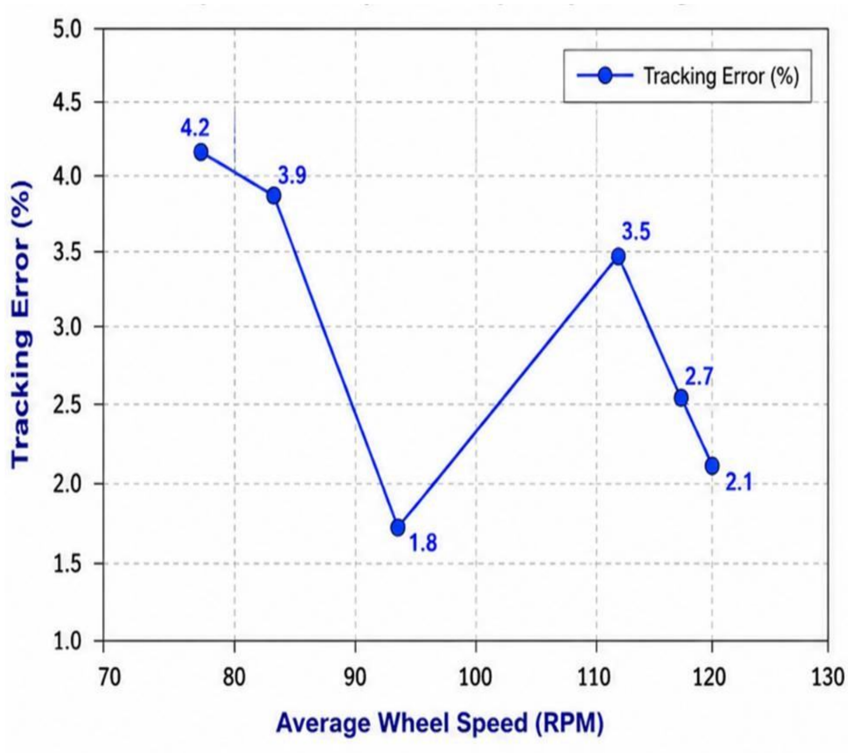

Fig 2. Experimental results (Wheel Speed vs Tracking Error).

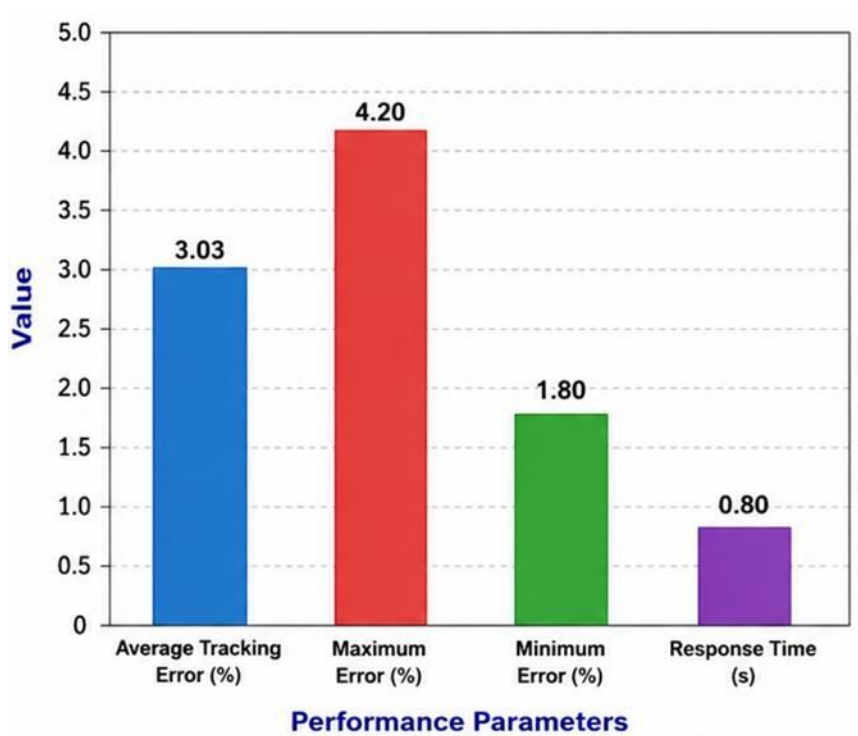

Fig 3. Performance Metrics of MPC-Based MOWR System.

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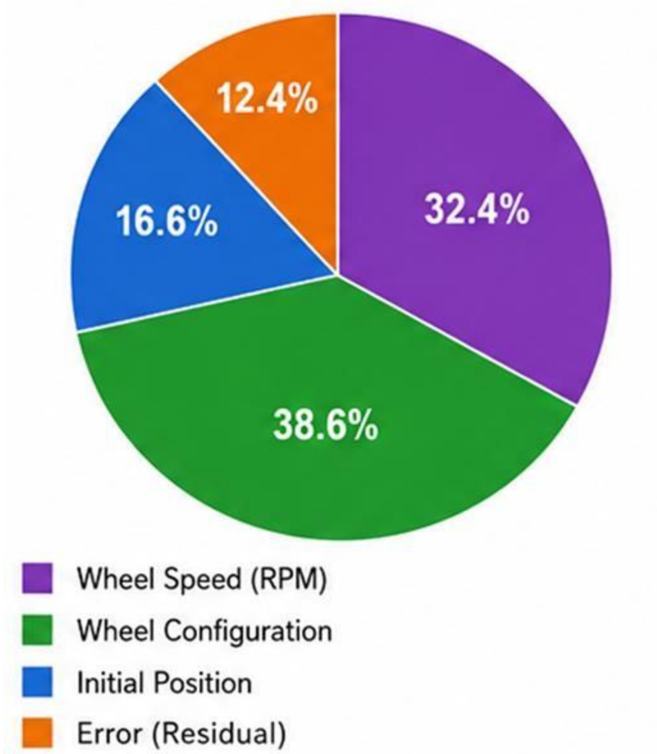

Fig 4. Percentage contribution factor of MOWR.

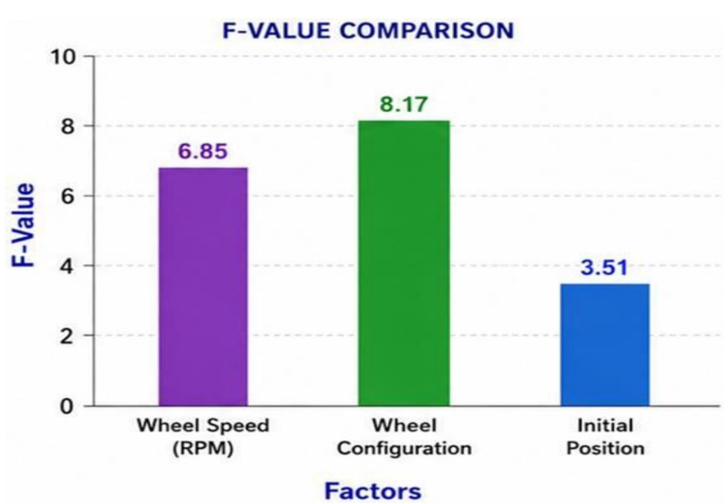

Fig 5. F-value comparison factor of MOWR.

A minimum tracking error value of 1.8% was achieved at the RPM value of 90 when there were no problems with synchronization between all three mecanum wheels. In addition to that, at high-speed rotation values for each wheel (110-120 RPM), the performance level was relatively satisfactory with an error range of 2.1-3.5%, which confirmed the high level of control system adaptability to changes. Moreover, according to the data presented in figure 3, the performance parameters of the system can be considered as efficient ones. On average, the trajectory tracking error measured from all tests performed had a value of approximately 3.03%. At the same time, the maximum and minimum values were 4.2% and 1.8%, correspondingly. Finally, the response time measured equaled 0.8 seconds.

Thus, it can be claimed that the control system possesses the ability to react rapidly to the changes and adjust wheel speed. From the ANOVA test done on the experiment data, it shows that there is significance on the variation of influence on the tracking efficiency of trajectories. The findings show that the variation due to wheel arrangement had the largest percentage of 38.6%, while wheel speed had the second largest variation at 32.4% (see figure 4). From this, it is clear that the cooperation in wheel motion has a vital effect on trajectory tracking. The starting position accounted for 16.6% variation, which proves the effectiveness of the MPC controller on compensation. There is only a remainder of 12.4% variance. F-Values derived from the ANOVA model further show the effectiveness of the chosen variables (figure 5). As shown, the wheel arrangement had the highest F-value of 8.17 while wheel speed had an F-value of 6.85, indicating the importance of these factors in controlling motion tracking. Also, the low values of residuals and contribution by significant parameters are further proofs of the effectiveness of the proposed MPC method. From the tests conducted, it is clear that the three-wheeled MOWR successfully accomplishes smooth and accurate movements including forward, lateral, rotational, and circular motion controls. Kinematics modeling combined with MPC based trajectory tracking results in effective motion control of the three-wheeled MOWR, thereby making it a good choice for use in mobile robotics.

IV. CONCLUSIONS

The paper modeled, simulated, and tracked the trajectory of a three-wheeled mecanum omnidirectional wheeled robot (MOWR). The model established a successful relationship between the speed of the wheels and the movement of the MOWR. It enabled the robot to achieve accurate forward, backward, lateral, rotational, and circular movements. The symmetrical design of three wheels was used to achieve omnidirectional movements with better maneuverability than other mobile robots. The simulations and experiments proved that the MPC controller was capable of producing steady and accurate trajectory tracking under varying conditions for wheel speed and initial positions. The tracking errors were maintained in the acceptable zone, with the lowest being 1.8% and the average being around 3.03%. The fast response of 0.8 seconds proved its applicability to realtime applications. From the ANOVA results, the wheel shapes and velocities were found to be the two most important parameters for managing the performance of the trajectory, contributing 38.6% and 32.4%, respectively. The low level of residual error indicates the validity of the mathematical and control models formulated for the experiment. This validates the usefulness of the control approach based on MPC. In conclusion, the application of MOWR technology is highly promising in developing omnidirectional motion systems. Some applications may involve industrial automation systems, autonomous transportation systems, automated storage systems, intelligent service robots, and other comparable systems. Future studies may focus on implementing additional functionalities within the robot, which include wheel slippage, obstacle detection, localization, and artificial intelligence-based adaptive control.

V. ACKNOWLEDGMENT

The accompanying author can provide the data supporting the study's conclusions upon reasonable request. There are no conflicts of interest to report. For this effort, we thank the OmDayal Group of Institutions' Department of Mechanical Engineering.

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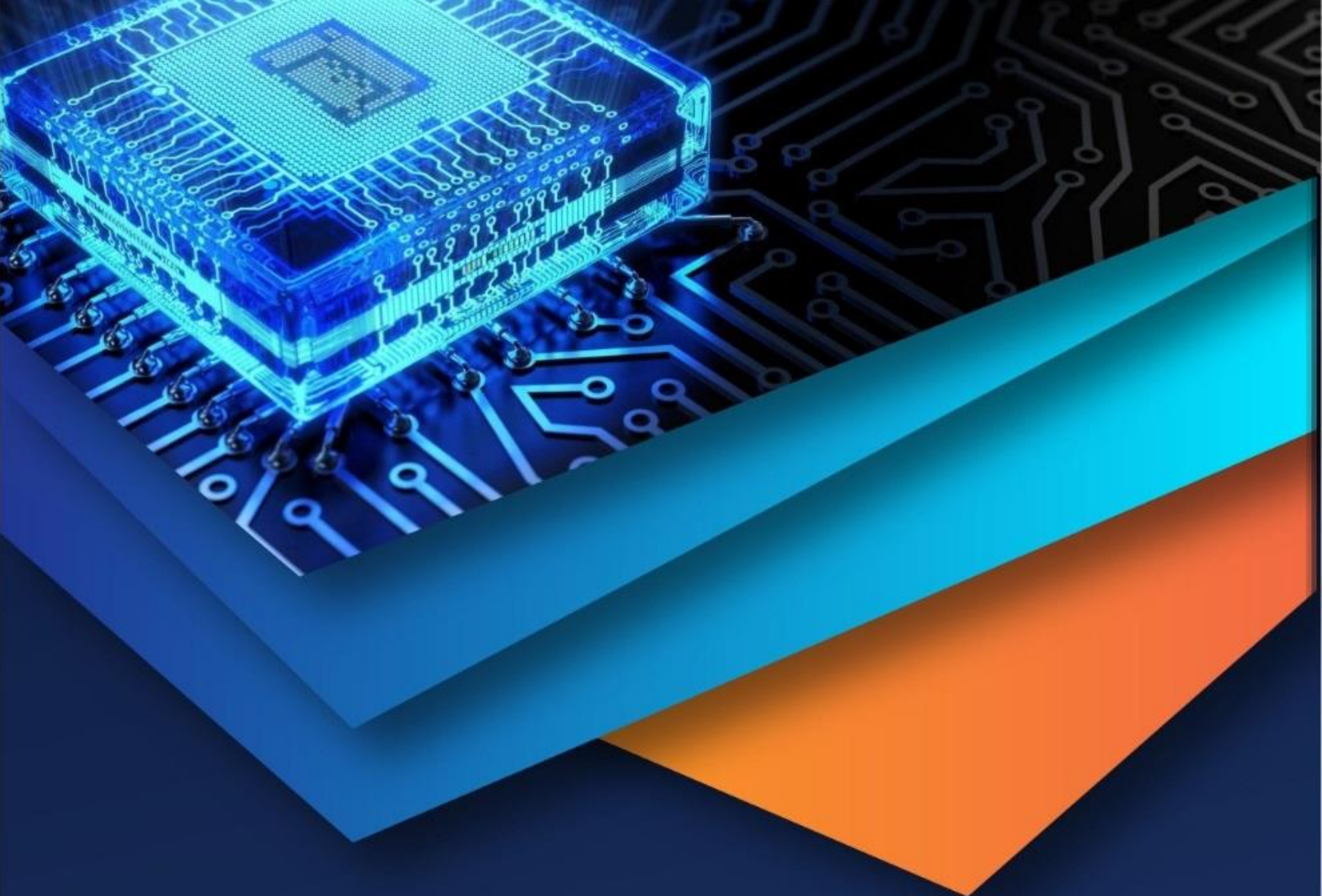

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