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Design and Demonstration of Optical Radar

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Abstract: Most of the research concentrates on ground based laser system but only very little attention is given to Space - Based laser system. Optical Radars are one of the identified technologies that shall provide essential information to the spacecraft/ Aircraft guidance, Navigation and control system. It's possible to say that one of the most interesting laser applications is Optical Radar. Difference in laser return times and wavelength can then be used to make digital 3D representation of the target. In electrical design the electronics include all the sensors, detectors, Data Acquisition system, control system, synchronization circuitry, computers and datalink. The design presented here is implemented in such a way that it allows, Its expendability to a 3D scanning laser range finding and imaging will help to improve autonomous abilities of building a map of an unknown environment, navigation, object avoidance and qualification.
Keywords: Laser System, Optical Radar, Sensor, 3D Scanning, Navigation.

I. INTRODUCTION

Today's societal needs require a more holistic approach to engineering design. Keeping in mind the demand of a more sustainable environment, the purpose of this research is to design and develop a low cost and lightweight pulsed laser rangefinder that could measure distances of up to 60-meters. Pulsed Laser rangefinders are high resolution systems used to measure targets whose distance ranges from centimeters to kilometers. A pulsed laser rangefinder operates on the time-of-flight (TOF) principle which measures the flight time (delay time) of a light from a pulsed laser to be reflected off the target and back to the receiver. By measuring the TOF of the laser signal, the range can be determined since the value of the speed of light is well established. The advantage of a pulsed TOF method over many other distance measurement methods, such as triangulation or phase modulation, is that unambiguous centimeter-level accuracy is already available in a single measurement. The principles of Optical Radar are much the same as those used by radar. The key difference is that radar systems detect radio waves that are reflected by objects while Optical Radar uses laser signals. Both techniques usually employ the same type of time of flight method to determine an object's distance. However, as the wavelength of laser light is much shorter than that of radio waves, Optical Radar systems deliver superior measurement accuracy. Optical Radar systems can also examine other properties of the reflected light, such as the frequency content or polarization, to reveal additional information about the object. Optical Radar systems are now being employed in an ever-increasing variety of applications. This includes autonomous driving, geological and geographical mapping, seismology, meteorology, atmospheric physics, surveillance, altimetry, forestry, navigation, vehicle tracking, surveying, and environmental protection.

Figure 1: Optical Radar

Optical Radar is a laser altimeter system that determines the distance by measuring pulse travel time. The data from the Optical Radar systems provide unique information on the vertical structure of land covers. Compared to ground-based and airborne Optical Radar providing a high-resolution digital surface model, space-borne Optical Radar can provide important information about the vertical profile of the atmosphere in a global scale.

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A. Classification

The classification of Optical Radar instruments can be broad and subjective, depending upon the context of application. Nonetheless, this instrument is commonly classified using the three types of information capturing functionality, namely spatial, spectral, and temporal. Spatial information-capturing is a fundamental functionality of every Optical Radar instrument. This information is typically obtained using the time of flight (TOF) measurement. Optical Radar systems that are able to gather spatial information are available in three varieties:

1) One-dimensional (1D)
2) Two-dimensional (2D)
3) Three-dimensional (3D)

With the 2D and 3D spatial information gathering achieved with the aid of optical deflecting systems. The spatial information is essential for constructing an accurate 3D map of the environment. However, spatial information alone is not sufficient for application requiring object detection. The second class of Optical Radar instruments is capable of measuring the spectral information of a material such as the laser return intensity (LRI). LRI refers to the reflectance because of the interaction between the wavelength of the transmitted pulse from the Optical Radar instrument and the targeted material. Since the LRI is characteristic to a specific material type, it is potentially useful for identification of surface properties of a target material. However, to avoid ambiguities in LRI readings, at least two wavelengths of laser are required. On top of that, some applications require temporal information gathering functionality in addition to spatial and spectral information.

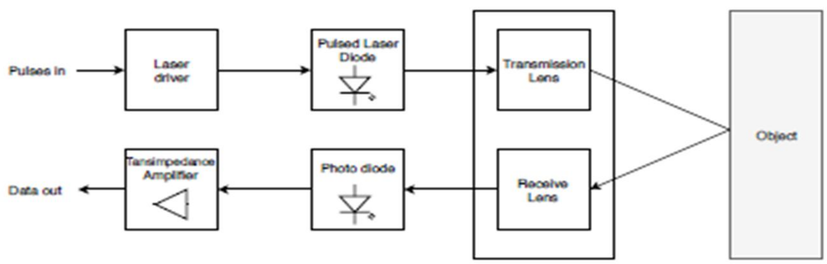

Figure 2: Schematic View Of Simple Optical Radar System

This can be achieved by using the repeated Optical Radar technique. Repeated Optical Radar is a process of collecting temporal data of a target environment over a finite period of time. It was observed that the major portion of the literature is dedicated for theoretical analysis of Optical Radar principle. The understanding of Optical Radar principle helps the designer to select an appropriate technique for his application of interest. Besides that, conceptual frameworks were introduced in the past to describe the Optical Radar architectures. The Optical Radar instrument is a composition of multiple subsystems such as power supply, range finding, control, and beam deflection. As mentioned earlier, the low Size, Weight and Price (SWaP) specifications have significantly influenced the improvement of selected subsystems, especially the power supply and range finding. This serves as a guideline for the design and development of Optical Radar systems at the component level.

B. Scanning Mechanisms

Albeit the number of review articles published in the past, there is still a lack of review articles dedicated specifically to the scanning mechanisms of Optical Radar instruments. Consequently, the Optical Radar beam scanning literature continues to expand in different focus areas without appropriate organization. Being an integral component of the 2D and 3D Optical Radar architecture, the scanning mechanism is an important feature because it influences the Size, Weight and Power (SWaP) specifications of the overall design. Furthermore, there is a need for the designer to be aware of state-of-the-arts scanning mechanisms as the trends of Optical Radar instruments in the market are changing rapidly. Hence, the aim of this paper is to provide a comprehensive survey of Optical Radar scanning mechanisms by reviewing past research works as well as commercial datasheets. We propose a classification scheme for various Optical Radar scanning mechanisms into four main classes:

1) Opto-Mechanical
2) Electro-Mechanical
3) Micro Electo-mechanical Systems (MEMS)
4) Solid-State Based

C. Components

Optical Radar is a remote sensing technology used to acquire elevation data about the Earth's surface. A Optical Radar system consisted of three main components: the laser ranging system, Global Positioning System (GPS) and Inertial Measurement Unit (IMU). The laser ranging system transmits a laser pulse down to the Earth's surface, and the time delay between the transmission of the laser pulse and its return to the sensor is measured. This two-way travel time is then converted into a range or distance from the sensor to the target. The range has a time stamp based on the precise GPS time and is related to the Optical Radar sensor scan angle and the aircraft position. The aircrafts' 3-D (x,y,z) position is maintained by the precise survey GPS and the IMU is used to measure the roll, pitch and heading of the aircraft so that the ranges measured by the Optical Radar sensor can be converted to points and georeferenced (x,y,z coordinates) and represented as a Optical Radar point cloud. To match the many different applications, Optical Radar systems come in a wide range of designs and configurations. Each system requires suitable optical to electrical sensors and appropriate data acquisition electronics.

The light detection system is either incoherent, where direct energy is measured by amplitude changes in the reflected signals, or coherent, where shifts in the reflected signal's frequency, such as those caused by a Doppler Effect, or its phase are observed. Similarly the light source can be a low power micro-pulse design, where intermittent pulse trains are transmitted, or a high energy one. Micro-pulse systems are ideal for applications where "eye-safe" operation is essential (such as in surveying and ground based vehicle tracking), while the high-energy systems are typically deployed where long distances and low-level reflections are to be encountered (like in atmospheric physics and meteorology studies.

II. DESIGN THEORY AND SPECIFICATION

This chapter derives a set of the steps taken toward the design of the sending and receiving channels of the laser rangefinder. The chapter then goes on to a breakdown of each of the subsystems in these channels and detail the theory of operation of each subsystem as well as the design considerations taken into consideration for the design of each subsystem.

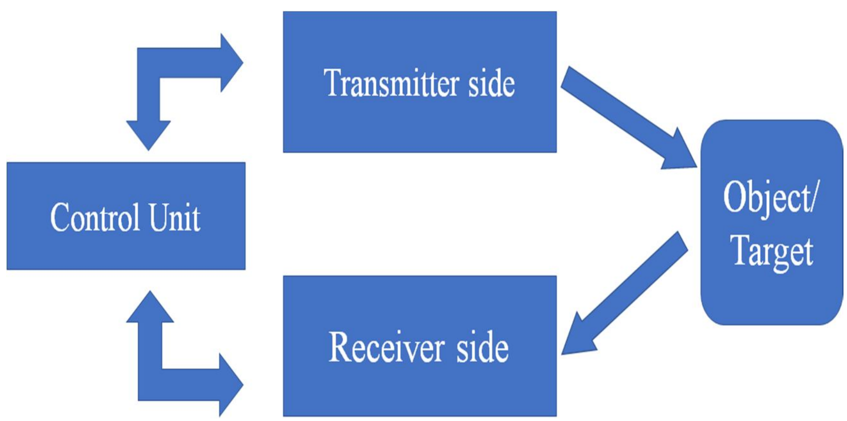

Figure 3: Overall Block Diagram

A transmit stage consisting of laser diode together with a laser driver are necessary to convert an arbitrary timing signal to a laser pulse that leaves the system. Also, a receiving stage consisting of a photo diode, together with the necessary data processing was needed to in fact retrieve the light and process the data. The focusing of the beam is not considered in the scope of the electrical part of the Optical Radar because this is mainly a mechanical issue. The system described here does not have any form of beam steering and can thus only measure one point. However, the Optical Radar has to measure multiple points in space, thus some sort of beam steering has to be implemented. Furthermore, The data has to be processed and all actions, such as choosing a point in space to measure the distance or sending out a laser pulse, have to be coordinated. This is why we came to the following subsystem division.

A. A transmitting stage
B. A receiving stage
C. A beam Steering stage
D. A Data processing stage

III. SENDING CHANNEL HARDWARE

This section describes how the laser light Transmitting circuit must be implemented. The sending channel fires a short and powerful pulse of light towards a measurement target object. The light projector circuit contains a light emitting device such as a pulsed laser diode (PLD) and a PLD driving device. The nano-seconds driving pulses are sent from a microcontroller. of a continuous wave (CW) laser beam emitted from a laser diode (LD) at a certain frequency *fm*. The driver circuit should allow for varying *fm* over a wide range of frequencies fairly easy.

It should also provide stable and low noise biasing of the LD, since these are sensitive components which may be damaged by exceeding their rated output power even for short amounts of time. The authors chose to design their own driver circuit. The alternative would have been to employ a commercial driver circuit and some investigation into this was carried out. However, it was the authors impression that designing the circuit themselves would provide more flexibility which would allow for a greater variety of modulation schemes. The approach to modulate the LD bias current directly seemed to be sufficiently simple to implement while simultaneously being an instructive task aimed to improve the authors understanding of the system. All of the design considerations for the optical medium for the transmission stage are thoroughly discussed and documented. The main points of interest for choosing the most suitable optical medium is that the optical signal should be the color green and should have high optical output power.

A. Optical Lens

The main objective of the receiver optics is to collect as much light to the photodetector as possible. This could be done with either mirrors or lenses. The advantage that mirrors usually provide is that there is no chromatic aberration which could be a problem for lenses. In this study this is not a problem however since monochromatic light will be used. Mirrors have the disadvantage of being difficult to mount in the test environment, and therefore a lens is used in this study.

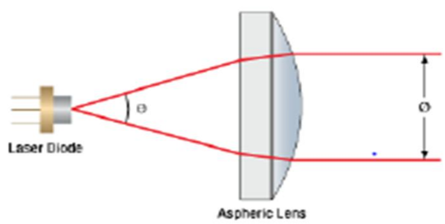

Figure 4: Illustration of The Collimation Of A Laser Diode Beam

Plano-convex lenses are used since a more advanced optical system is not expected to be required. The size of the lens sets the amount of light focused on the photodetector. The three different diameter lenses that will be investigated are 25 mm, 50 mm and 75 mm. To estimate the received power, *Pr*, for a certain transmitted power, *Pt*, it is assumed that no power is lost on the way to the target which is at an distance *d*. The atmospheric attenuation of visible light is neglectably small for the distances considered and so this approximation is valid. The minimum received Optics power is calculated for different lenses in a worst case scenario in the problem description. Maximum distance 50 m and Minimum reflectivity of 6 %. If 1 MW is transmitted minimum received power is obtained for different sizes of lenses.

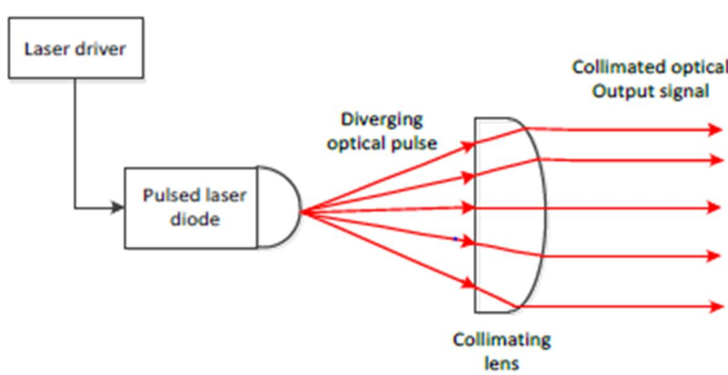

Figure 5: Optical Collimating Lens

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The infrared (IR) light pulses emitted by the PLD are collimated by the transmitter lens. Collimating lens used to reduce to a minimize the divergence of the laser beam such that the laser light does not disperse with distance. The optical power reflected from the measurement target object is collected, focused and filtered by a plano-convex lens and an optical band-pass filter with an AR coating for 600- 1050nm wavelength. The plano-convex lens is used to focus the collimated reflected laser beam of the target on the APD. The band-pass filter is integrated in the APD and it is used to further block the surrounding light. Using an AR coated lens and a band-pass filter helps to achieve a better signal-to-noise ratio, and minimize the effect of the background light.

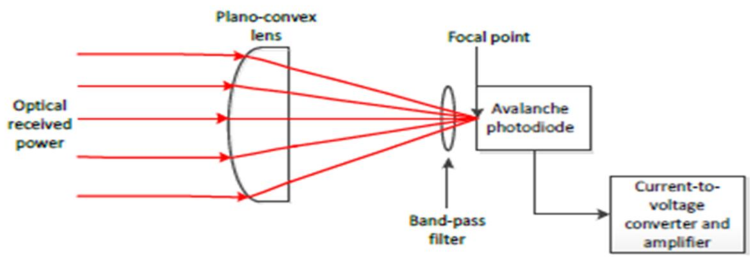

Figure 6: Optical Receiving Lens

IV. RECEIVING CHANNEL HARDWARE

A small fraction of the light beam emitted by the PLD is received by an optical receiver and focus on the APD which photo-electrically convert the pulse of light received. The small pulse of current generated by the APD is converted into a TTL voltage level signal using a two-stage trans- impedance amplifier. This voltage signal serves as the STOP signal for the time counter. The receiver stage captures the backscattered light pulse and generates a pulse when an object is detected. This is then converted to a TDC reading of the event. This is accomplished in three stages:

1) Opto-Electrical Transduction & Amplification
2) Pulse Detection
3) Time To Digital Conversion

A. Photodetectors

At the beginning of the receiver chain, after any focusing and filtering optics but before the electrical processing stages, an element which converts the incident light, i.e. optical signal, to an equivalent electrical signal is needed. Ideally, this opto-electrical element would perform the conversion instantly. Keeping the SNR and produce an identical electrical copy of the signal suitable for amplification and further processing. Sensors which convert optical power to electrical power, using the photoelectric effect, are called photodetectors. There is a variety of such devices available, each of them adapted to a specific application. Sadly, none of them exhibit the ideal properties described above. Instead, one needs to compare the different devices with respect to certain parameters in order to find the one best suited to the problem at hand. Some concepts from semiconductor physics will be necessary to discuss the properties of different detectors, and these will be introduced as they are needed. However, since it is not the main topic of this thesis, it will be brief, and only meant to support the discussion and motivate certain decisions. Basic knowledge of semiconductor processing and devices, such as doping and PN-junctions, is assumed to be somewhat familiar to the reader.

B. PRE- and POST-AMPLIFIERS

A small fraction of the reflected focused on the APD is converted to a voltage signal using a two trans-impedance amplifiers. This conversion represents one of the major challenges of the design because bandwidth, gain, and input referred noise are coupled together. Furthermore, to control the trans-impedance gain such that the variation of the amount of current generated by the APD does not saturate the system is another challenge.

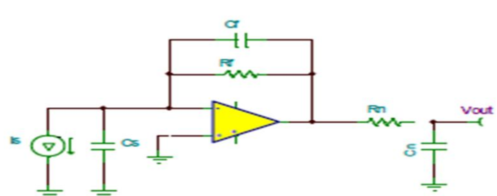

Figure 7: Trans-Impedance Equivalent Circuit

The figure above shows the equivalent circuit for a trans-impedance amplifier. This represents the output current generated by the current source. C_s is the sum of the output capacitance of the current source and the input capacitance of the op amp. R_f is used to convert I_s to a voltage. Therefore, R_f is the gain of the trans-impedance amplifier.

At low frequencies, the op amp's inverting input is forced to be at ground potential and I_s must flow through R_f. This combination of effects creates an output voltage of I_s*R_f. At higher frequencies, C_f affects the circuit respond and together with C_s, has a strong effect on the stability of the amplifier. R_n and C_n are used to reduce the output noise of the amplifier.

V. MICROCONTROLLER UNIT

This section outlines the functions of the microcontroller in the operation of the laser rangefinder. The main function of the microcontroller is to record the time measurement from the time-measuring unit, average the time measurements and calculate the distance. After the distance is calculated, the data is transmitted to a PC.

The microcontroller sends the signals to start the counter for the time measurement unit and to send the laser light pulse. Also, the microcontroller is used to initiate and set the parameters of the time measurement unit (speed, mode, resolution, etc.) After the time measurement unit calculates the time, the microcontroller reads and stores the time information. At least fifty time measurements are taken from each distance to be measured. The more samples taken the most accurate the results are, but the more time needed to obtain the distance measurement.

Once the microcontroller has obtained the values for the time and computes their average, it calculates the distance value and transmits it to a PC using USART interface. Each distance calculation should take less than 20ms. This time depends on the number of time measurements taken and the duty factor of the pulse laser diode.

VI. CONCLUSION AND FUTUREWORKS

Optical Radar's are intricate systems with many different disciplines involved, as well as being high precision and complex systems. The need for high quality and precision is the main complexity of the system to be most expensive. We create a functioning high performance Optical Radar at a cheap price. Although we were ultimately unable to complete such a system we have shown the possibility and where the difficulties lie so that it can be complete in the future. Also we were able to find the distance measurements and mapping of the target in an accurate manner.

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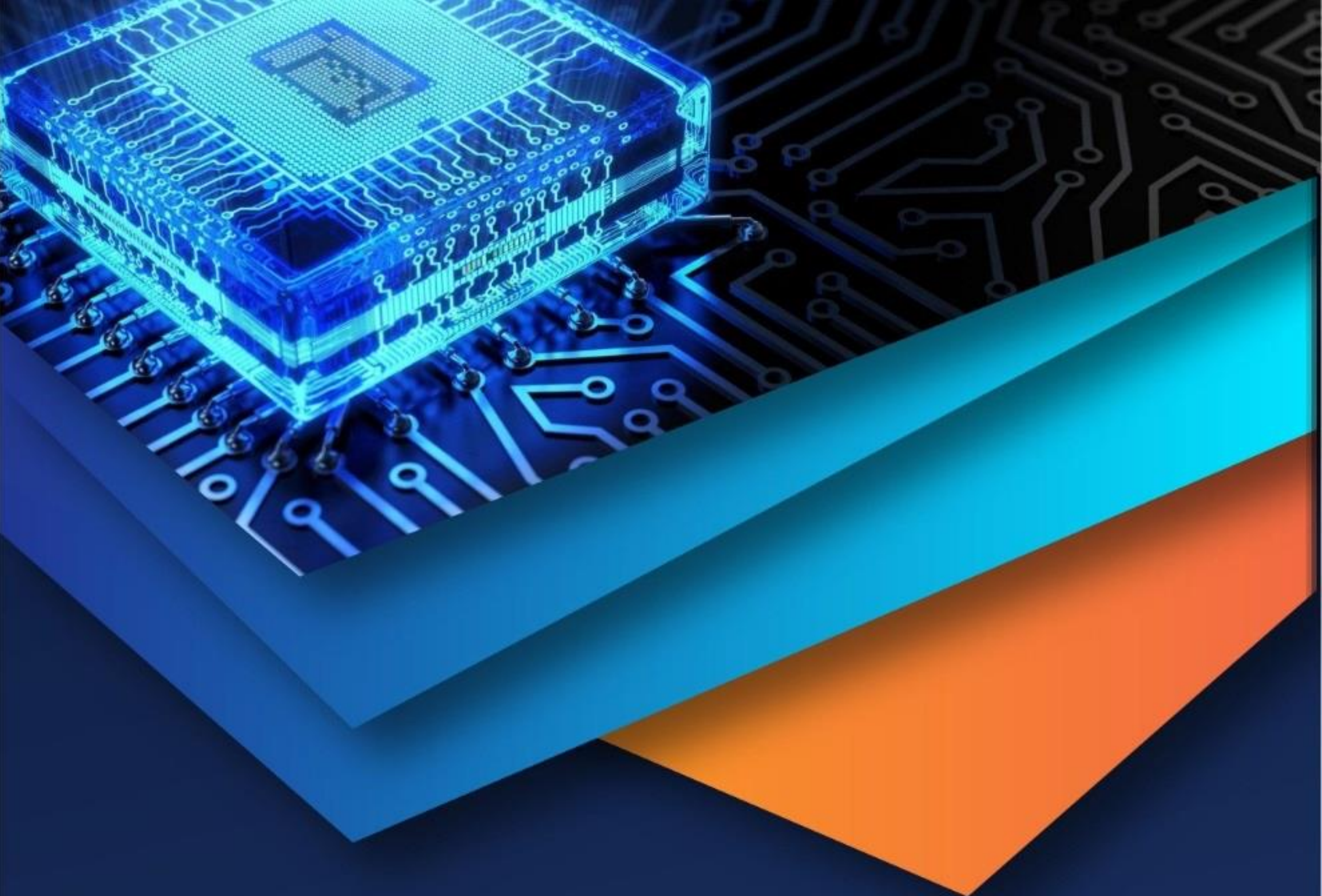

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