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Extension of Results of Saurabh Manro ET. Al in Fuzzy Metric Space

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***Abstract*: Saurabh Manro et. al[4] proved fixed point results for four self mappings of a fuzzy metric space using an inequality, CLR-property / JCLR-property, weakly compatibility of two pairs of the self mappings. In this paper, we mainly extended the above for six self mappings by using commutativity of certain pairs of mappings. Supporting examples are given to our claims.**
2010 Mathematics Subject Classifications — 47H10, 54H25.
***Keywords*: Fuzzy metric space, weakly compatible mappings, CLR-property, JCLR-property, common fixed point.**

I. INTRODUCTION

The concept of a fuzzy set is initiated by Zadeh[6]. The notion of fuzzy metric space is introduced by Kramosil and Michalek[3]. George and Veeramani[2] modified the above notion to get a Haussdorff topology on this space. Sintauravant and Kumam[5] coined the notion "common limit in the range"(CLR)-property and obtained common fixed point for a pair of self mappings. Chauhan along with the above two authors[1] defined the generalized notion "joint common limit in the ranges"(JCLR)-property and established common fixed point results for two pairs of self mappings. Recently, Saurabh Manro & Calogero Vetro [4] proved existence theorems for four self mappings using the above properties. In this paper, we extend and generalize the main results of the above authors. We get their results as corollaries of our theorems.

II. PRELIMINARIES AND BASIC RESULTS

We hereunder, give the necessary definitions and results needed for a clear understanding of our findings.

A. Definition 2.1

([2]) A mapping : [0, 1] x[0, 1] $\rightarrow$ [0, 1] is called a triangular norm (or t-norm) if and only if

1) *(0, 0) = 0 and *(a, 1) = a for all a $\in$ [0, 1],

2) * (a, b) = * (b, a), for all a, b $\in$ [0, 1],

3) * (a, b) $\leq$ *(c, d) whenever one of a, b $\leq$ c and the other is $\leq$ d,

4) *(*(a, b), c) = *(a, *(b, c)) for all a, b, c $\in$ [0, 1]. If * is continuous then we say that *is a continuous t-norm.

B. Definition 2.2

([2]) An ordered triple (X, M, *) is said to be a fuzzy metric space if and only if X is a non-empty set, * is a continuous triangular norm and M is a fuzzy set on X^2x(0, 1) satisfying the following: for any x, y, z$\in$ X and t, s > 0,

1) M(x, y, t) > 0,

2) M(x, y, t) = 1 if and only if x = y,

3) M(x, y, t) = M(y, x, t),

4) M(x, y, $\sqcup$) : (0, 1) $\rightarrow$ [0, 1] is continuous and

5) M(x, z, t + s) $\geq$ M(x, y, t) * M(y, z, s).

C. Definition 2.3

([2]) (X, M, *) is a fuzzy metric space. M is said to be continuous on X^2x(0, 1) if and only if $\lim_{n\to\infty} M(x_n, y_n, t_n)$ exists and $= M(x, y, t)$ whenever $\{(x_n, y_n, t_n)\}$ is a sequence in X^2x(0, 1) converging to a point (x, y, t) of X^2x(0, 1),

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i.e, $\lim_{n\to\infty} M(x_n, x, t) = \lim_{n\to\infty} M(y_n, y, t) = 1$ and $\lim_{n\to\infty} M(x, y, t_n) = M(x, y, t)$.

D. Definition 2.4

Self mappings f and g of a Fuzzy metric space (X, M, *) are said to be weakly compatible if and only if for any t > 0, M(fx, gx, t) = 1 for some $x \in X$ implies M(fgx, gfx, t) = 1, i.e, fx = gx for some $x \in X$ implies fgx = gfx.

E. Definition 2.5

([5]) Let (X, M, *) be a fuzzy metric space, where * denotes a continuous t-norm and f, g, h, k be self mappings on X. The pairs {f, g} and {h, k} are said to satisfy the "common limit in the range of g (CLRg) property" if and only if there exist sequences $\{x_n\}$ and $\{y_n\}$ in X such that for some $x \in X$ and for all t>0,

$$\lim_{n\to\infty} M(fx_n, gx, t) = \lim_{n\to\infty} M(gx_n, gx, t) = \lim_{n\to\infty} M(hy_n, gx, t) = \lim_{n\to\infty} M(ky_n, gx, t) = 1.$$

F. Definition 2.6

([1]) Let (X, M, *) be a fuzzy metric space, where * denotes a continuous t-norm and f, g, h, k be self mappings on X. The pairs {f, g} and {h, k} are said to satisfy the "joint common limit in the ranges of g and k ($JCLR_{gk}$) property" if and only if there exist sequences $\{x_n\}$ and $\{y_n\}$ in X such that for some $x \in X$, gx=kx and for all t>0,

$$\lim_{n\to\infty} M(fx_n, gx, t) = \lim_{n\to\infty} M(gx_n, gx, t) = \lim_{n\to\infty} M(hy_n, gx, t) = \lim_{n\to\infty} M(ky_n, gx, t) = 1.$$

G. Result 2.7

([2]) (X, M, *) is a fuzzy metric space. Then M(x, y, $\cdot$) is monotonic increasing for all $x, y \in X$.

H. Result 2.8

([2]) (X, M, *) is a fuzzy metric space. If there is a $\lambda \in (0, 1)$ such that $M(x, y, \lambda t) \geq M(x, y, t)$ for all $x, y \in X$ and t > 0 then y = x.

Hereunder, Φ stands for the class of all functions $\phi : [0, 1] \to [0, 1]$ satisfying the following properties: ϕ is continuous and monotone increasing on [0, 1], $\phi(t) > t$, for all $t \in (0, 1)$.

We now give the main results of Saurabh Manro et.al[4].

I. Result 2.9

Let A, B, S and T be self mappings of a fuzzy metric space (X, M, *) satisfying the following conditions:

$A(X) \subseteq T(X)$,

for all $x, y \in X$ and t > 0 and 0 < M(Ax, By, t) < 1, there exists a $\phi \in \Phi$ such that

M(Ax, By, t) > ϕ (min{M(Sx, T y, t), M(Ax, Sx, t), M(By, T y, t), M(By,Sx,t), M(Ax, T y, t)}),

the pairs {A, S} and {B, T} share the CLR_S-property,

the pairs {A, S} and {B, T} are weakly compatible mappings.

Then A, B, S and T have a unique common fixed point in X.

J. Result 2.10

Let A, B, S and T be self mappings of a fuzzy metric space (X, M, *) satisfying the following conditions:

for all $x, y \in X$ and t > 0 and 0 < M(Ax, By, t) < 1, there exists a $\phi \in \Phi$ such that

M(Ax, By, t) > ϕ (min{M(Sx, T y, t), M(Ax, Sx, t), M(By, T y, t), M(By,Sx,t), M(Ax, T y, t)}),

the pairs {A, S} and {B, T} share the $JCLR_{ST}$-property,

the pairs {A, S} and {B, T} are weakly compatible mappings.
Then A, B, S and T have a unique common fixed point in X.

III. MAIN RESULTS

The following theorems are generalization of the main results of Saurabh Manro et. al[4]. We get their results as corollaries of our theorems.

A. *Theorem 3.1*

Let A, B, H, K, S and T be self mappings of a fuzzy metric space (X, M, *) satisfying the following conditions:
AH(X)   T (X),
for all x, y $\in$ X and t > 0 and 0 < M(AHx, BKy, t) < 1, there exists a $\phi \in \Phi$ such that

$$M(AHx, BKy, t) > \phi\,(\min\{M(Sx, Ty, t), M(AHx, Sx, t), M(BKy, Ty, t), M(BKy, Sx, t), M(AHx, Ty, t)\}),$$

the pairs {AH, S} and {BK, T} share the CLR_S-property,
the pairs {AH, S} and {BK, T}are weakly compatible mappings,
AH = HAand either AS = SA or HS = SH,
BK = KB and either TB = BT or TK = KT .
Then A, B, H, K, S and T have a unique common fixed point in X.

1) *Proof:* Since the pairs {AH, S}and {BK, T}share the common limit in the range of S property, there exist sequences $\{x_n\}$ and $\{y_n\}$ in X and a u $\in$ X such that

$$\lim_{n\to\infty} AHx_n = \lim_{n\to\infty} Sx_n = \lim_{n\to\infty} BKy_n = \lim_{n\to\infty} Ty_n = Su.$$

First, we assert that AHu = Su or equivalently, M(AHu, Su, t) = 1 for all t > 0. Suppose not; so 0 < M(AHu, Su, t) < 1, for all t > 0.
Then by taking x = u and y = y_n in (ii), we get that

$$M(Ahu, BKy_n, t) > \phi\,(\min\{M(Su, T y_n, t), M(AHu, Su, t), M(BKy_n, T y_n, t), M(BKy_n, Su, t), M(AHu, T y_n, t)\}).$$

As, $n \to \infty$, we get that

$$\begin{aligned} M(AHu, Su, t) &> \phi\,(\min\{M(Su, Su, t), M(AHu, Su, t), M(Su, Su, t), M(Su, Su, t), M(Ahu, Su, t)\}) \\ &= \phi\,(\min\{1, M(AHu, Su, t), 1, 1, M(AHu, Su, t)\}) \\ &> \phi\,(\min\{M(AHu, Su, t), M(AHu, Su, t), M(AHu, Su, t), M(AHu, Su, t), M(AHu, Su, t)\}) \\ &= \phi\,(M(AHu, Su, t)). \end{aligned}$$

Thus M(AHu, Su, t) > ϕ (M(AHu, Su, t)) > M(AHu, Su, t), which is a contradiction. Therefore, AHu = Su.
Since AH(X) $\subseteq$ T (X), there exists v $\in$ X such that AHu = Tv.
Secondly, we assert that BKv = Tv. if not follows that 0 < M(T v, BKv, t) < 1, for all t > 0; then by taking x = u and y = v in (ii), we get that

$$\begin{aligned} M(Tv, BKv, t) &> \phi\,(\min\{M(Tv, Tv, t), M(Tv, Tv, t), M(BKv, Tv, t), M(BKv, Tv, t), M(Tv, Tv, t)\}). \\ &= \phi\,(\min\{1, 1, M(BKv, Tv, t), M(BKv, Tv, t), 1\}) \\ &> \phi\,(\min\{M(BKv, Tv, t), M(BKv, Tv, t), M(BKv, Tv, t), M(BKv, Tv, t), M(BKv, Tv, t)\}) \\ &= \phi\,(M(BKv, Tv, t)). \end{aligned}$$

Thus M(Tv, BKv, t) > ϕ (M(BKv, Tv, t)) > M(BKv, Tv, t), which is a contradiction. Therefore, BKv = Tv.

Thus AHu = Su = BKv = Tv = z(say). (3.1)(I)
Since {AH, S} and {BK, T}are weakly compatible, AH(Su) = S(AHu) and BK(Tv) = T(BKv). i.e, AHz = Sz and BKz = Tz.
Now we assert that AHz = z.
Again suppose not; that is $0 < M(AHz, BKv = z, t) < 1$ for all $t > 0$.
Then by taking x = z and y = v in (ii), we get that

$$\begin{aligned} M(AHz, BKv = z, t) > \phi\,(\min\{&M(Su = AHz, Tv = z, t), M(AHz, Sz = AHz, t),\\ &M(BKv = z, Tv = z, t), M(BKv = z, Sz = AHz, t),\\ &M(AHz, Tv = z, t)\})\\ = \phi\,(\min\{&M(AHz, z, t), 1, 1, M(z, AHz, t), M(AHz, z, t)\})\\ \geq \phi\,(\min\{&M(AHz, z, t), M(AHz, z, t), M(AHz, z, t),\\ &M(AHz, z, t), M(AHz, z, t)\})\\ = \phi\,(&M(AHz, z, t)) \end{aligned}$$

Thus $M(AHz, z, t) > \phi\,(M(AHz, z, t)) > M(AHz, Sz, t)$, which is a contradiction.
Therefore, AHz = z.
Similarly, we can prove that BKz = z. Hence AHz = Sz = z = BKz = Tz.
Suppose SA = AS.
Since AH = HA, we have AHAz = AAHz = Az and SAz = ASz = Az.
We now assert that Az = z. If not, by taking x = Az and y = z in (ii), we get that

$$\begin{aligned} M(Az, z, t) &> \phi\,(\min\{M(Az, z, t), M(Az, Az, t), M(z, z, t), M(z, Az, t), M(Az, z, t)\})\\ &= \phi\,(\min\{M(Az, z, t), 1, 1, M(z, Az, t), M(Az, z, t)\})\\ &> \phi\,(\min\{M(Az, z, t), M(Az, z, t), M(Az, z, t), M(Az, z, t), M(Az, z, t)\})\\ &= \phi\,(M(Az, z, t). \end{aligned}$$

Thus $M(Az, z, t) > \phi\,(M(Az, z, t)) > M(Az, Sz, t)$, which is a contradiction.
Therefore, Az = z.
Since AHz = z, follows that Hz = z. Thus Az = Hz = Sz = z.
Suppose SH = HS. Similarly, by taking x = Hz and y = z in (ii), we get that Hz = z.
Thus Az = Hz = Sz = z.
Similarly (v) $\Rightarrow$ Bz = Kz = Tz = z.
Hence Az = Bz = Hz = Kz = Sz = Tz = z.
Uniqueness of the common fixed point follows trivially from (ii).

B. Remarks 3.2

1) The above Theorem is also valid when (i) is replace by $BK(X) \subseteq S(X)$ and (iii) is replaced by CLR_T -property.
2) If (i) is replaced by $AH(X) \subseteq T(X)$ and $BK(X) \subseteq S(X)$, then the Theorem holds when (iii) is replaced by any one of the following: CLR_S-property, CLR_T -property, $CLR_{(AH)}$-property, $CLR_{(BK)}$-property.

Taking H = K = I(the identity mapping on X), we get Result (2.3) of Saurabh Manro et. al[4].

C. Remark 3.3

1) The above Corollary is also valid when (i) is replace by $B(X) \subseteq S(X)$ and (iii) is replaced by CLR_T -property.
2) If (i) is replaced by $A(X) \subseteq T(X)$ and $B(X) \subseteq S(X)$, then the Theorem holds when (iii) is replaced by any one of the following: CLR_S-property, CLR_T -property, CLR_A-property, CLR_B-property. Now, we prove a similar result where CLR-property is replaced by with JCLR-property; we observe that the condition (i) of Theorem (3.1)(i) is not necessary for establishing this.

D. Theorem 3.4: Let A, B, H, K, S and T be self mappings of a fuzzy metric space (X, M, *) satisfying the following conditions:

1) for all $x, y \in X$ and $t > 0$ and $0 < M(AHx, BKy, t) < 1$, there exists a $\phi \in \Phi$ such that

M(AHx, BKy, t) > ϕ (min{M(Sx, Ty, t), M(AHx, Sx, t), M(BKy, Ty, t),
M(BKy,Sx,t), M(AHx, Ty, t)}),

2) the pairs {AH, S} and {BK, T} share the $JCLR_{ST}$-property,
3) the pairs {AH, S} and {BK, T} are weakly compatible mappings,
4) AH = HA and either AS = SA or HS = SH,
5) BK = KB and either TB = BT or TK = KT.

Then A, B, H, K, S and T have a unique common fixed point in X.

: Sinc the pairs {AH, S}and {BK, T}share the "joint common limit in the ranges of S and T" property, there exist sequences $\{x_n\}$ and $\{y_n\}$ in X and a $u\in X$ such that

$$\lim_{n\to\infty} AHx_n = \lim_{n\to\infty} Sx_n = \lim_{n\to\infty} BKy_n = \lim_{n\to\infty} Ty_n = Su = Tu.$$

First, we assert that AHu = Su or equivalently, M(AHu, Su, t) = 1 for all t > 0.
Suppose not; so 0 < M(AHu, Su, t) < 1, for all t > 0.
Then by taking x = u and y = y_n in (ii), we get that

M(AHu, BKy_n, t) > ϕ (min{M(Su, T y_n, t), M(AHu, Su, t), M(BKy_n, T y_n, t),
M(BKy_n, Su, t), M(AHu, T y_n, t)}).

As, $n\to\infty$, we get that

M(AHu, Su, t) > ϕ (min{M(Su, Su, t), M(AHu, Su, t), M(Su, Su, t),
M(Su, Su, t), M(AHu, Su, t)})

1, 1, M(AHu, Su, t)})
> ϕ (min{M(AHu, Su, t), M(AHu, Su, t), M(AHu, Su, t),
M(AHu, Su, t), M(AHu, Su, t)})
= ϕ (M(AHu, Su, t)).

Thus M(AHu, Su, t) > ϕ (M(AHu, Su, t)) > M(AHu, Su, t), which is a contradiction.

Therefore, AHu = Su.

Now, we assert that BKu = Tu; if not, that is 0 < M(Tu, BKu, t) < 1 for all t > 0, then by taking x = u and y = u in (ii), we get that

M(Tu, BKu, t) > ϕ (min{M(Tu, Tu, t), M(Tu, Tu, t), M(BKu, Tu, t),
M(BKu, Tu, t), M(Tu, Tu, t)}).
= ϕ (min{1, 1, M(BKu, Tu, t), M(BKu, Tu, t), 1})
> ϕ (min{M(BKu, Tu, t), M(BKu, Tu, t), M(BKu, Tu, t),
M(BKu, Tu, t), M(BKu, Tu, t)})
= ϕ (M(BKu, Tu, t)).

Thus M(Tu, BKu, t) > ϕ (M(BKu, Tu, t)) > M(BKu, Tu, t), which is a contradiction. Therefore, BKu = Tu.

Thus AHu = Su = BKu = Tu = z(say). (that is (3.1)(I))

From this stage, the proof of the theorem is same as that of Theorem(3.1). By taking H = K = I, we get Result (2.10) of Saurabh Manro et. al[4].

E. *Remark 3.5:* The above theorem is also valid when the condition (ii) is replaced by any one of the following: $JCLR_{(AH)(BK)}$-property, $JCLR_{(AH)T}$ -property, $JCLR_{S(BK)}$-property.

We hereunder give examples in support of our theorems.

F. *Example 3.6:* (X, M, *) is a Fuzzy metric space, where X=[0, ∞) with the standard metric,

$$M(x,y,t) = \begin{cases} 0 & \text{if } x = y \text{ and } t > 0, \\ 1 & \textit{otherwise} \end{cases}$$

and * is the min t-norm, i.e, $a*b=\min\{a,b\}$, for all $a,b\in[0,1]$.

Let A, B, H, K, S and T be the self mappings on X, defined by

$$A(x)=\begin{cases}0 & if\ x\le 16,\\ 1 & if\ x>16,\end{cases}\qquad S(x)=\begin{cases}0 & if\ x\le 16,\\ x^{1/2} & if\ x>16,\end{cases}$$

Bx=0, Hx=x, Kx=$\frac{x}{5}$ and Tx=x^2, for all $x\in X$.

Define $\phi:[0,1]\to[0,1]$ by $\phi(t)=t^{1/2}$, for all $t\in[0,1]$.

Take $x_n=y_n=\frac{1}{n^2}$. Then $\lim\limits_{n\to\infty}AHx_n=\lim\limits_{n\to\infty}Sx_n=\lim\limits_{n\to\infty}BKy_n=\lim\limits_{n\to\infty}Ty_n=0=S(0)$.

So, {AH, S} and {BK, T} share the CLR_S-property.

1) *Case 1:* $x\le 16$ and $y\in X$. L.H.S.=M(AHx, BKy, t)=M(0, 0, t)=1. Hence L.H.S.$\ge$ R.H.S.

2) *Case 2:* $x>16$ and $y\in X$

L.H.S.=M(AHx, BKy, t)=M(1, 0, t)=0.

$$\text{R.H.S.}=\begin{aligned}&\phi(min\{M(Sx,\ Ty,\ t),\ M(AHx,\ Sx,\ t),\ M(BKy,\ Ty,\ t),\\ &M(BKy,Sx,t),\ M(AHx,\ Ty,\ t)\})\end{aligned}$$

$$=\begin{aligned}&min\{M(x^{1/2},y^2,\ t),\ M(1,\ x^{1/2},\ t),\ M(0,\ y^2,t),\\ &M(1,y^2,t),\ M(0,x^{1/2},\ t)\}^{1/2}\end{aligned}$$

$$\le\ M(0,x^{1/2},t)^{1/2}=0\ \ (\text{since } x^{1/2}>0)$$

= L.H.S.

The remaining conditions of the Theorem(3.1) are clearly satisfied. It follows that '0' is the unique common fixed point of A, B, H, K, S and T (in X).

G. *Example 3.7:* (X, M, *) is a Fuzzy metric space, where X=[0, 20) with the standard metric,

$$M(x,y,t)=\begin{cases}0 & \text{if } x=y \text{ and } t>0,\\ 1 & otherwise\end{cases}$$

and * is the min t-norm, i.e, $a*b=\min\{a,b\}$, for all $a,b\in[0,1]$.

Let A, B, H, K, S and T be the self mappings on X, defined by

$$A(x)=\begin{cases}0 & if\ 0\le x<4,\\ 1 & if\ 4\le x<20,\end{cases}\qquad S(x)=\begin{cases}0 & if\ 0\le x<4,\\ x^{1/2} & if\ 4\le x<20.\end{cases}$$

Bx=0, Hx=x, Kx=$\frac{x}{5}$ and Tx=x^2, for all $x\in X$.

Define $\phi:[0,1]\to[0,1]$ by $\phi(t)=t^{1/2}$, for all $t\in[0,1]$.

Take $x_n=y_n=\frac{1}{n}$. Then $\lim\limits_{n\to\infty}AHx_n=\lim\limits_{n\to\infty}Sx_n=\lim\limits_{n\to\infty}BKy_n=\lim\limits_{n\to\infty}Ty_n=0=T(0)=S(0)$.

So, {AH, S} and {BK, T} share the $JCLR_{ST}$-property.

1) *Case 1:* $0\le x<4$ and $y\in X$ .L.H.S.=M(AHx, BKy, t)=M(0, 0, t)=1.Hence L.H.S.$\ge$ R.H.S.

2) Case 2: $4\le x<20$ and $y\in X$

L.H.S.=M(AHx, BKy, t)=M(1, 0, t)=0.

R.H.S.= $\phi(min\{M(Sx, Ty, t), M(AHx, Sx, t), M(BKy, Ty, t), M(BKy, Sx, t), M(AHx, Ty, t)\})$

$$= min\{M(x^{1/2}, y, t), M(1, x^{1/2}, t), M(0, y, t), M(1, y, t), M(0, x^{1/2}, t)\}^{1/2}$$

$$\leq M(0, x^{1/2}, t)^{1/2} = 0 \ \ (\text{since } x^{1/2} > 0)$$

= L.H.S.

The other conditions of the Theorem(3.4) are trivially satisfied. Clearly, '0' is the unique common fixed point of A, B, H, K, S and T (in X).

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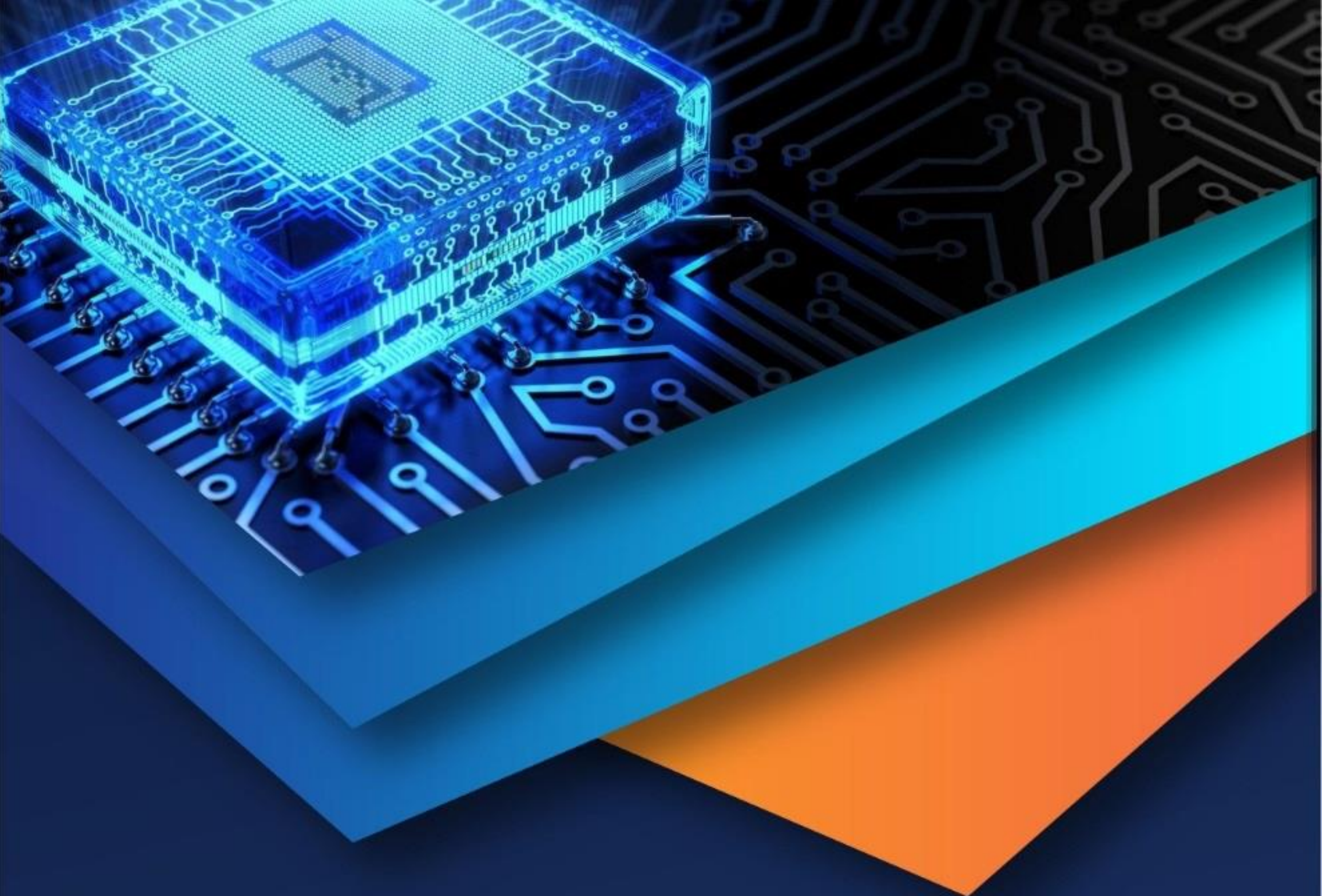

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