Int. J. Nonlinear Anal. Appl. 6 (2015) No. 1, 1-8
ISSN: 2008-6822 (electronic)
http://dx.doi.org/10.22075/ijnaa.2015.201

A common fixed point theorem for weakly compatible maps satisfying common property $(E.A.)$ and implicit relation in Intuitionistic fuzzy metric spaces

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(Communicated by M. Eshaghi Gordji)

Abstract

In this paper, employing the common property $(E.A)$, we prove a common fixed theorem for weakly compatible mappings via an implicit relation in Intuitionistic fuzzy metric space. Our results generalize the results of S. Kumar [S. Kumar, *Common fixed point theorems in Intuitionistic fuzzy metric spaces using property (E.A)*, J. Indian Math. Soc., 76 (1-4) (2009), 94–103] and C. Alaca et al. [C. Alaca, D. Turkoglu and C. Yildiz, *Fixed points in Intuitionistic fuzzy metric spaces*, Chaos Solitons and Fractals, 29 (2006), 1073–1078].

Keywords: Intuitionistic fuzzy metric space; weakly compatible mappings; common property $(E.A)$; implicit relation.
2010 MSC: Primary 54H25; Secondary 47H10.

1. Introduction

In 1986, Jungck [8] introduced the notion of compatible maps for a pair of self mappings. However, the study of common fixed points of non-compatible maps is also very interesting (see [16]). Aamri et al. [1] generalized the concept of non-compatibility by defining the notion of property $(E.A)$ and in 2005, Liu et al. [13] defined common property $(E.A)$ in metric spaces and proved common fixed point theorems under strict contractive conditions. Jungck et al. [9] initiated the study of weakly compatible maps in metric space and showed that every pair of compatible maps is weakly

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Received: May 2013 *Revised:* May 2014

compatible but reverse is not true. In the literature, many results have been proved for contraction maps satisfying property $(E.A.)$ in different settings such as probabilistic metric spaces [5, 7]; fuzzy metric spaces [12, 15]; Intuitionistic fuzzy metric spaces [11, 19]. In this paper, employing the common property $(E.A)$, we prove a common fixed theorem for weakly compatible mappings via an implicit relation in Intuitionistic fuzzy metric space. Our results generalize the results of S. Kumar [11] and C. Alaca et al. [2].

2. Preliminaries and Definitions

The concepts of triangular norms (t-norms) and triangular conorms (t-conorms) are known as the axiomatic skelton that we use are characterization fuzzy intersections and union respectively. These concepts were originally introduced by Menger [14] in study of statistical metric spaces.

Definition 2.1. [18] A binary operation $* : [0,1][0,1] \to [0,1]$ is continuous t-norm if * satisfies the following conditions:
(i) * is commutative and associative;
(ii) * is continuous;
(iii) $a * 1 = a$ for all $a \in [0,1]$
(iv) $a * b \leq c * d$ whenever $a \leq c$ and $b \leq d$ for all $a, b, c, d \in [0,1]$.

Definition 2.2. [18] A binary operation $\diamondsuit : [0,1][0,1][0,1]$ is continuous t-conorm if $\diamondsuit$ satisfies the following conditions:
(i) $\diamondsuit$ is commutative and associative;
(ii) $\diamondsuit$ is continuous;
(iii) $a \diamondsuit 0 = a$ for all $a \in [0,1]$
(iv) $a \diamondsuit b \leq c \diamondsuit d$ whenever $a \leq c$ and $b \leq d$ for all $a, b, c, d \in [0,1]$

Alaca et al. [2] using the idea of Intuitionistic fuzzy sets, defined the notion of Intuitionistic fuzzy metric space with the help of continuous t-norm and continuous t-conorms as a generalization of fuzzy metric space due to Kramosil et al. [10] as:

Definition 2.3. [2] A 5-tuple $(X, M, N, *, \diamondsuit)$ is said to be an Intuitionistic fuzzy metric space if X is an arbitrary set, * is a continuous t-norm, $\diamondsuit$ is a continuous t-conorm and M, N are fuzzy sets on $X^2[0, \infty)$ satisfying the following conditions:
(i) $M(x, y, t) + N(x, y, t) \leq 1$ for all $x, y \in X$ and $t > 0$;
(ii) $M(x, y, 0) = 0$ for all $x, y \in X$;
(iii) $M(x, y, t) = 1$ for all $x, y \in X$ and if and only if $x = y$;
(iv) $M(x, y, t) = M(y, x, t)$ for all $x, y \in X$ and $t > 0$;
(v) $M(x, y, t) * M(y, z, s) \leq M(x, z, t + s)$ for all $x, y \in X$ and $s, t > 0$;
(vi) for all $x, y \in X$, $M(x, y, .) : [0, \infty) \to [0,1]$ is left continuous;
(vii) $lim_{t \to \infty} M(x, y, t) = 1$ for all $x, y \in X$ and $t > 0$;
$(viii)$ $N(x, y, 0) = 1$ for all $x, y \in X$;
(ix) $N(x, y, t) = 0$ for all $x, y \in X$ and $t > 0$ if and only if $x = y$;
(x) $N(x, y, t) = N(y, x, t)$ for all $x, y \in X$ and $t > 0$;
(xi) $N(x, y, t) \diamondsuit N(y, z, s) \geq N(x, z, t + s)$ for all $x, y \in X$ and $s, t > 0$;
(xii) for all $x, y \in X$, $N(x, y, .) : [0, \infty) \to [0,1]$ is right continuous;

$(xiii)$ $lim_{t\to\infty} N(x, y, t) = 0$for all $x, y \in X$ and $t > 0$.
Then (M, N) is called an Intuitionistic fuzzy metric space on X. The functions $M(x, y, t)$ and $N(x, y, t)$ denote the degree of nearness and the degree of non-nearness between x and y w.r.t. t respectively.

Remark 2.4. [2] Every fuzzy metric space $(X, M, *)$ is an Intuitionistic fuzzy metric space of the form $(X, M, 1 - M, *, \Diamond)$ such that t-norm * and t-conorm $\Diamond$ are associated as
$x\Diamond y = 1 - ((1 - x) * (1 - y))$ for all $x, y \in X$.

Remark 2.5. [2] In Intuitionistic fuzzy metric space $(X, M, N, *, \Diamond)$, $M(x, y, .)$ is non-decreasing and $N(x, y, .)$ is non-increasing for all $x, y \in X$.

Alaca et al.[2] introduced the following notions:

Definition 2.6. Let $(X, M, N, *, \Diamond)$ be an Intuitionistic fuzzy metric space. Then
(a) a sequence $\{x_n\}$ in X is said to be Cauchy sequence if, for all $t > 0$ and $p > 0$,
$lim_{n\to\infty} M(x_{n+p}, x_n, t) = 1$ and $lim_{n\to\infty} N(x_{n+p}, x_n, t) = 0$;
(b) a sequence $\{x_n\}$ in X is said to be convergent to a point $x \in X$ if, for all $t > 0$, $lim_{n\to\infty} M(x_n, x, t) = 1$ and $lim_{n\to\infty} N(x_n, x, t) = 0$.

Definition 2.7. [2] An Intuitionistic fuzzy metric space $(X, M, N, *, \Diamond)$ is said to be complete if and only if every Cauchy sequence in X is convergent.

Example 2.8. [2] Let $X = \{\frac{1}{n} : n \in N\} \cup \{0\}$ and let * be the continuous t-norm and $\Diamond$ be the continuous t-conorm defined by and respectively, for all $a, b \in [0, 1]$. For each $t \in (0, \infty)$ and $x, y \in X$, define (M, N) by
$M(x, y, t) = \frac{t}{t+|x-y|}$ if $t > 0$;
$M(x, y, 0) = 0$
and
$N(x, y, t) = \frac{|x-y|}{t+|x-y|}$ if $t > 0$;
$N(x, y, 0) = 1$
Clearly, $(X, M, N, *, \Diamond)$ is complete Intuitionistic fuzzy metric space.

Definition 2.9. [1] A pair of self mappings (T, S) of an Intuitionistic fuzzy metric space $(X, M, N, *, \Diamond)$ is said to satisfy the property $(E.A)$ if there exist a sequence $\{x_n\}$ in X such that $lim_{n\to\infty} Tx_n = lim_{n\to\infty} Sx_n = z$ for some $z \in X$.

Example 2.10. Let $X = [0, \infty)$. Consider $(X, M, N, *, \Diamond)$ be an Intuitionistic fuzzy metric space as in Example 2.8. Define $T, S : X \to X$ by $Tx = \frac{x}{5}$ and $Sx = \frac{2x}{5}$ for all $x \in X$. Clearly, for sequence $\{x_n\} = \{\frac{1}{n}\}$, T and S satisfies property $(E.A)$.

Definition 2.11. [9] Two pairs (A, S) and (B, T) of self mappings of an Intuitionistic fuzzy metric space $(X, M, N, *, \Diamond)$ are said to satisfy the common property $(E.A)$ if there exist two sequences $\{x_n\}$ and $\{y_n\}$ in X such that $lim_{n\to\infty} Ax_n = lim_{n\to\infty} Sx_n = lim_{n\to\infty} By_n = lim_{n\to\infty} Ty_n = z$ for some $z \in X$.

Example 2.12. Let $X =$ [-1,1]. Consider $(X, M, N, *, \diamondsuit)$ be an Intuitionistic fuzzy metric space as in Example 2.8. Define self mappings A, B, S and T on X as $Ax = \frac{x}{3}, Bx = \frac{-x}{3}, Sx = x, Tx = -x$ for all $x \in X$. Then, with sequences $\{x_n\} = \{\frac{1}{n}\}$ and $\{y_n\} = \{\frac{-1}{n}\}$ in X, one can easily verify that $lim_{n\to\infty} Ax_n = lim_{n\to\infty} Sx_n = lim_{n\to\infty} By_n = lim_{n\to\infty} Ty_n = 0$. Therefore, pairs (A, S) and (B, T) satisfies the common property $(E.A)$.

Definition 2.13. [9] A pair of self mappings (T, S) of an Intuitionistic fuzzy metric space $(X, M, N, *, \diamondsuit)$ is said to be weakly compatible if they commute at coincidence points i.e. if $Tu = Su$ for some $u \in X$, then $TSu = STu$.

3. Main Results

Implicit relations play important role in establishing of common fixed point results. Let M_4 be the set of all real continuous functions $\psi, \phi : [0, 1]^4 \to R$, non-decreasing in the first argument and satisfying the following conditions:
(A) $\phi(u, 1, u, 1) \geq 0 \Rightarrow u \geq 1$,
(B) $\phi(u, 1, 1, u) \geq 0 \Rightarrow u \geq 1$,
(C) $\phi(u, u, 1, 1) \geq 0 \Rightarrow u \geq 1$,
(D) $\psi(u, 0, u, 0) \leq 0 \Rightarrow u \leq 0$,
(E) $\psi(u, 0, 0, u) \leq 0 \Rightarrow u \leq 0$,
(F) $\psi(u, u, 0, 0) \leq 0 \Rightarrow u \leq 0$
for all $u \geq 0$.

Example 3.1. Define $\psi, \phi : [0, 1]^4 \to R$ as $\phi(t_1, t_2, t_3, t_4) = 14t_1 - 12t_2 + 6t_3 - 8t_4$ and $\psi(t_1, t_2, t_3, t_4) = 12t_1 - 9t_2 + 8t_3 - 11t_4$. Clearly, and satisfies all conditions (A), (B), (C), (D), (E) and (F). Therefore, $\psi, \phi \in M_4$

We begin with following observation:

Lemma 3.2. *Let $\{A_i\}$, S and T be self mappings of an Intuitionistic fuzzy metric space $(X, M, N, *, \diamondsuit)$ satisfying the following:*
(3.1) *the pair (A_0, T) satisfies the property (E.A.);*
(3.2) *for any $x, y \in X$, and $\psi, \phi \in M_4$ and for all $t > 0$, there exists $k \in (0, 1)$ such that,*
$\phi(M(A_ix, A_0y, kt), M(Sx, Ty, t), M(Sx, A_ix, t), M(Ty, A_0y, t)) \geq 0$;
$\psi(N(A_ix, A_0y, kt), N(Sx, Ty, t), N(Sx, A_ix, t), N(Ty, A_0y, t)) \leq 0$;
(3.3) $A_i(X) \subseteq T(X)$ *or* $A_0(X) \subseteq S(X)$.
Then the pairs (A_i, S) and (A_0, T) share the common (E.A.) property.

Proof . As the pair (A_0, T) satisfies property $(E.A.)$, then there exist a sequence $\{x_n\}$ in X such that $lim_{n\to\infty} A_0x_n = lim_{n\to\infty} Tx_n = z$ for some $z \in X$. Since $A_0(X) \subseteq S(X)$, hence for each $\{x_n\}$, there exist $\{y_n\}$ in X such that $A_0x_n = Sy_n$.
Therefore, $lim_{n\to\infty} A_0x_n = lim_{n\to\infty} Sy_n = lim_{n\to\infty} Tx_n = z$. Now, we claim that $lim_{n\to\infty} A_iy_n = z$. Suppose not, then applying inequality (3.2), we obtain
$\phi(M(A_iy_n, A_0x_n, kt), M(Sy_n, Tx_n, t), M(Sy_n, A_iy_n, t), M(Tx_n, A_0x_n, t)) \geq 0$;
$\psi(N(A_iy_n, A_0x_n, kt), N(Sy_n, Tx_n, t), N(Sy_n, A_iy_n, t), N(Tx_n, A_0x_n, t)) \leq 0$;
which on making $n \to \infty$ reduces to

$\phi(M(lim_{n\to\infty}A_iy_n, z, kt), M(z, z, t), M(z, lim_{n\to\infty}A_iy_n, t), M(z, z, t)) \geq 0;$
$\psi(N(lim_{n\to\infty}A_iy_n, z, kt), N(z, z, t), N(z, lim_{n\to\infty}A_iy_n, t), N(z, z, t)) \leq 0;$
As ϕ and ψ is non-decreasing in the first argument, we have
$\phi(M(lim_{n\to\infty}A_iy_n, z, t), M(z, z, t), M(z, lim_{n\to\infty}A_iy_n, t), M(z, z, t)) \geq 0;$
$\psi(N(lim_{n\to\infty}A_iy_n, z, t), N(z, z, t), N(z, lim_{n\to\infty}A_iy_n, t), N(z, z, t)) \leq 0;$
Using (B) and (E), we get
$M(lim_{n\to\infty}A_iy_n, z, t) \geq 1$ and $N(lim_{n\to\infty}A_iy_n, z, t) \leq 0$.
Hence $M(lim_{n\to\infty}A_iy_n, z, t) = 1$ and $N(lim_{n\to\infty}A_iy_n, z, t) = 0$.
Therefore, $lim_{n\to\infty}A_iy_n = z$. Hence, the pairs (A_i, S) and (A_0, T) share the common $(E.A.)$ property.
□

Theorem 3.3. *Let $\{A_i\}$, S and T be self mappings of a Intuitionistic fuzzy metric space $(X, M, N, *, \Diamond)$ satisfying the conditions (3.2) and*
(3.4) *the pair (A_i, S) and (A_0, T) share the common property (E.A);*
(3.5) *$S(X)$ and $T(X)$ are closed subsets of X.*
Then the pairs and have a point of coincidence each. Moreover, $\{A_i\}$, S and T have a unique common fixed point provided both the pairs (A_i, S) and (A_0, T) are weakly compatible.

Proof . In view of (3.4), there exist two sequences $\{x_n\}$ and $\{y_n\}$ in X such that $lim_{n\to\infty}A_0y_n = lim_{n\to\infty}A_ix_n = lim_{n\to\infty}Sx_n = lim_{n\to\infty}Ty_n = z$ for some $z \in X$. Since $S(X)$ is a closed subset of X, therefore, there exists a point $u \in X$ such that $z = Su$. We claim that $A_iu = z$. If $A_iu \neq z$, then by (3.2), take $x = u, y = y_n$,
$\phi(M(A_iu, A_0y_n, kt), M(Su, Ty_n, t), M(Su, A_iu, t), M(Ty_n, A_0y_n, t)) \geq 0;$
on making $n \to \infty$, we get
$\phi(M(A_iu, z, kt), M(z, z, t), M(z, A_iu, t), M(z, z, t)) \geq 0;$
$\phi(M(A_iu, z, kt), 1, M(z, A_iu, t), 1) \geq 0;$
and
$\psi(N(A_iu, A_0y_n, kt), N(Su, Ty_n, t), N(Su, A_iu, t), N(Ty_n, A_0y_n, t)) \leq 0;$
on making $n \to \infty$, we get
$\psi(N(A_iu, z, kt), N(z, z, t), N(z, A_iu, t), N(z, z, t)) \leq 0;$
$\psi(N(A_iu, z, kt), 0, N(z, A_iu, t), 0) \leq 0;$
As ϕ and ψ is non-decreasing in the first argument, we have
$\phi(M(A_iu, z, t), 1, M(z, A_iu, t), 1) \geq 0;$
and
$\psi(N(A_iu, z, t), 0, N(z, A_iu, t), 0) \leq 0;$
Using (A) and (D), we get $M(A_iu, z, t) \geq 1$ and $N(A_iu, z, t) \leq 0$.
Hence $M(A_iu, z, t) = 1$ and $N(A_iu, z, t) = 0$.
Therefore, $A_iu = z = Su$ which shows that u is a coincidence point of the pair (A_i, S).
Since $T(X)$ is also a closed subset of X, therefore $lim_{n\to\infty}Ty_n = z$ in $T(X)$ and hence there exists $v \in X$ such that $Tv = z = A_iu = Su$.
Now, we show that $A_0v = z$. If not, then by using inequality (3.2), take $x = u, y = v$, we have
$\phi(M(A_iu, A_0v, kt), M(Su, Tv, t), M(Su, A_iu, t), M(Tv, A_0v, t)) \geq 0;$
$\phi(M(z, A_0v, kt), 1, 1, M(z, A_0v, t)) \geq 0;$
and
$\psi(N(A_iu, A_0v, kt), N(Su, Tv, t), N(Su, A_iu, t), N(Tv, A_0v, t)) \leq 0;$
$\psi(N(z, A_0v, kt), 0, 0, N(z, A_0v, t)) \leq 0;$
As ϕ and ψ is non-decreasing in the first argument, we have

$\phi(M(z, A_0v, kt), 1, 1, M(z, A_0v, t)) \geq 0$;
and
$\psi(N(z, A_0v, kt), 0, 0, N(z, A_0v, t)) \leq 0$;
Using (B) and (E), we get $M(z, A_0v, kt) \geq 1$ and $N(z, A_0v, kt) \leq 0$.
Hence $M(z, A_0v, kt) = 1$ and $N(z, A_0v, kt) = 0$. Therefore, $A_0v = z = Tv$ which shows that v is a coincidence point of the pair (A_0, T).
Since the pairs (A_i, S) and (A_0, T) are weakly compatible and $A_iu = Su, A_0v = Tv$, therefore, $A_iz = A_iSu = SA_iu = Sz, A_0z = A_0Tv = TA_0v = Tz$. If $A_iz \neq z$, then by using inequality (3.2), we have
$\phi(M(A_iz, A_0v, kt), M(Sz, Tv, t), M(Sz, A_iz, t), M(Tv, A_0v, t)) \geq 0$;
$\phi(M(A_iz, z, kt), M(A_iz, z, t), M(A_iz, A_iz, t), M(z, z, t)) \geq 0$;
$\phi(M(A_iz, z, kt), M(A_iz, z, t), 1, 1) \geq 0$;
and
$\psi(N(A_iz, A_0v, kt), N(Sz, Tv, t), N(Sz, A_iz, t), N(Tv, A_0v, t)) \leq 0$;
$\psi(N(A_iz, z, kt), N(A_iz, z, t), N(A_iz, A_iz, t), N(z, z, t)) \leq 0$;
$\psi(N(A_iz, z, kt), N(A_iz, z, t), 0, 0) \leq 0$;
As ϕ and ψ is non-decreasing in the first argument, we have
$\phi(M(A_iz, z, t), M(A_iz, z, t), 1, 1) \geq 0$;
and
$\psi(N(A_iz, z, kt), N(A_iz, z, t), 0, 0) \leq 0$;
Using (C) and (F), we get
$M(A_iz, z, t) \geq 1$ and $N(A_iz, z, t) \leq 0$.
Hence $M(A_iz, z, t) = 1$ and $N(A_iz, z, t) = 0$.
Therefore, $A_iz = z = Sz$.
Similarly, one can prove that $A_0z = Tz = z$. Hence $A_0z = A_iz = Sz = Tz$ and z is common fixed point of A_i, A_0, S and T.
Uniqueness: Let z and w be two common fixed points of A_i, A_0, S and T. If $z \neq w$, then by using inequality (3.2), we have
$\phi(M(A_iz, A_0w, kt), M(Sz, Tw, t), M(Sz, A_iz, t), M(Tw, A_0w, t)) \geq 0$;
$\phi(M(z, w, kt), M(z, w, t), M(z, z, t), M(w, w, t)) \geq 0$;
$\phi(M(z, w, t), M(z, w, t), M(z, z, t), M(w, w, t)) \geq 0$;
$\phi(M(z, w, t), M(z, w, t), 1, 1) \geq 0$;
and
$\psi(N(A_iz, A_0w, kt), N(Sz, Tw, t), N(Sz, A_iz, t), N(Tw, A_0w, t)) \leq 0$;
$\psi(N(z, w, kt), N(z, w, t), N(z, z, t), N(w, w, t)) \leq 0$;
$\psi(N(z, w, t), N(z, w, t), N(z, z, t), N(w, w, t)) \leq 0$;
$\psi(N(z, w, t), N(z, w, t), 0, 0) \leq 0$;
Using (C) and (F), we have
$M(z, w, t) \geq 1$ and $N(z, w, t) \leq 0$.
Hence, $M(z, w, t) = 1$ and $N(z, w, t) = 0$.
Therefore, $z = w$. □

By choosing A_i, A_0, S and T suitably, one can derive corollaries involving two or more mappings. As a sample, we deduce the following natural result for a pair of self mappings by setting $A_0 = A_i$ and $T = S$ in above theorem:

Corollary 3.4. Let A_i and S be self mappings of an Intuitionistic fuzzy metric space $(X, M, N, *, \Diamond)$ satisfying the following:

(3.6) the pair (A_i, S) satisfies the property $(E.A.)$;
(3.7) for any $x, y \in X$, ϕ and ψ in M_4 and for all $t > 0$,
$\phi(M(A_ix, A_iy, kt), M(Sx, Sy, t), M(Sx, A_ix, t), M(Sy, A_iy, t)) \geq 0$;
$\psi(N(A_ix, A_iy, kt), N(Sx, Sy, t), N(Sx, A_ix, t), N(Sy, A_iy, t)) \leq 0$;
(3.8) $S(X)$ is a closed subset of X.
Then, A_i and S have a point of coincidence each. Moreover, if the pairs (A_i, S) is weakly compatible, then A_i and S have a unique common fixed point.

The following example illustrates Theorem 3.3.

Example 3.5. Let $(X, M, N, *, \Diamond)$ be an Intuitionistic fuzzy metric space as in Example 2.8 where $X = [0, 2)$ and define $\psi, \phi : [0, 1]^4 \to R$ as $\phi(t_1, t_2, t_3, t_4) = 14t_1 - 12t_2 + 6t_3 - 8t_4$ and $\psi(t_1, t_2, t_3, t_4) = 12t_1 - 9t_2 + 8t_3 - 11t_4$. Clearly, all conditions $(A), (B), (C), (D), (E)$ and (F) hold. Therefore $\psi, \phi \in M_4$
Define A_i, A_0, S and T by
$A_ix = A_0x = 1$,
$Sx = 1$ if $x \in Q, Sx = \frac{2}{3}$ otherwise
and
$Tx = 1$ if $x \in Q, Tx = \frac{1}{3}$ otherwise
for all $x, y \in X = [0, 2)$ and $t > 0$. Then with sequences $\{x_n = \frac{1}{n}\}$ and $\{y_n = \frac{-1}{n}\}$ in X, we have $lim_{n\to\infty}A_0x_n = lim_{n\to\infty}A_iy_n = lim_{n\to\infty}Sy_n = lim_{n\to\infty}Tx_n = 1 \in X$ which shows that pairs (A_i, S) and (A_0, T) share the common property $(E.A)$. By a routine calculation, one can verify the condition (3.2). Thus, all the conditions of Theorem 3.3 are satisfied and $x = 1$ is the unique common fixed point of A_i, A_0, S and T.

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