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INTERPOLATIVE HARDY-ROGERS TYPE CONTRACTION ON PARTIAL FUZZY METRIC SPACES AND RELATED FIXED POINT RESULTS

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Abstract: In this paper, we introduce a new class of fuzzy interpolative Hardy–Rogers type contractions in the frameworks of fuzzy metric spaces and partial fuzzy metric spaces. We establish fixed point theorems guaranteeing the existence and uniqueness of fixed points under suitable contractive conditions involving control parameters. The obtained results extend and unify several known results in the literature, including classical Hardy–Rogers type contractions in fuzzy and partial fuzzy settings. Illustrative examples are also provided to demonstrate the applicability of the proposed results.

Keywords and Phrases: Fuzzy metric space, interpolative Hardy-Rogers contraction, partial fuzzy metric space, fixed point.

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1. Introduction

In 1965, Zadeh [25] introduced the theory of fuzzy sets to handle uncertainty through the concept of membership functions. This theory has found extensive applications in various fields such as engineering, computer science and applied mathematics, where uncertainty and vagueness are inherent.

The concept of a fuzzy metric space was first introduced by Kramosil and Michalek [19] and later studied by Kaleva and Seikkala [8]. George and Veeramani [3] modified this notion in order to generate a Hausdorff (T_2) topology. Grabiec [4] established the Banach contraction principle in fuzzy metric spaces. Since then, several researchers such as Piera [20], Vasuki and Veeramani [23], Rodriguez-Lopez and Romaguera [21] and Gregori et al. [5] have obtained various fixed point results and studied topological aspects of fuzzy metric spaces.

Recently, fuzzy partial metric spaces have been introduced as a natural generalization of both fuzzy metric spaces and partial metric spaces. Yue and Gu [24] introduced fuzzy partial metric spaces using continuous t-norms and extended several classical results. Later, Sedghi et al. [22] developed the concept of partial fuzzy metric spaces and established several fixed point theorems. Gregori et al. [6] further investigated the structure of fuzzy partial metric spaces and studied their topological properties.

On the other hand, interpolative contractions have attracted considerable attention in recent years due to their ability to generalize various classical contraction conditions. Karapinar [11] initiated the study of interpolative contractions and further developments can be found in [2, 12, 13, 14, 15, 16, 17, 18]. These works demonstrate that interpolative techniques provide a unified framework for extending several well-known contraction mappings such as Kannan, Hardy–Rogers and Reich-type contractions.

Motivated by the above developments, the main objective of this paper is to introduce and study interpolative Hardy–Rogers type contractions in the setting of partial fuzzy metric spaces. We establish new fixed point theorems ensuring the existence and uniqueness of fixed points under suitable contractive conditions. The obtained results generalize and extend several existing results in the literature. Moreover, we show that certain fixed point results in partial fuzzy metric spaces can be derived from corresponding results in fuzzy metric spaces under appropriate conditions.

2. Preliminaries

In 2018, Karapinar [11] introduced the notion of interpolative Kannan-type contractions in metric spaces by using the idea of interpolation and established a corresponding fixed point theorem. This concept generalizes the classical Kannan contraction.

Definition 2.1. [11] *Let (X, d) be a complete metric space. A mapping $T \colon X \to X$ is said to be an interpolative Kannan-type contraction if there exist $\mu \in [0, 1)$ and*

$\alpha \in (0,1)$ *such that*

$$d(Ta,Tb) \leq \mu[d(a,Ta)]^{\alpha}[d(b,Tb)]^{1-\alpha}, \tag{2.1}$$

for all $a,b \in X \setminus Fix(T)$, *where* $Fix(T) = \{x \in X : Tx = x\}$.

Theorem 2.2. [11] *Let* (X,d) *be a complete metric space. Then every interpolative Kannan-type contraction* $T\colon X \to X$ *has a fixed point.*

On the other hand, a well-known generalization of the Banach contraction principle [1] is due to Hardy and Rogers [7].

Theorem 2.3. [7] *Let* (X,d) *be a complete metric space and* $T\colon X \to X$ *be a mapping satisfying*

$$d(Ta,Tb) \leq \alpha d(a,b) + \beta d(a,Tb) + \gamma d(b,Ta) + \eta \frac{d(a,Tb)+d(b,Ta)}{2},$$

for all $a,b \in X$, *where* $\alpha,\beta,\gamma,\eta \geq 0$ *with* $\alpha+\beta+\gamma+\eta < 1$. *Then* T *has a unique fixed point in* X.

Motivated by the above result, Karapinar, Alqahtani and Aydi [13] introduced interpolative Hardy–Rogers type contractions.

Definition 2.4. [13] *Let* (X,d) *be a metric space. A mapping* $T\colon X \to X$ *is called an interpolative Hardy–Rogers type contraction if there exist* $\mu \in [0,1)$ *and* $\alpha,\beta,\gamma \in (0,1)$ *with* $\alpha+\beta+\gamma < 1$ *such that*

$$d(Ta,Tb) \leq \mu[d(a,b)]^{\beta}[d(a,Ta)]^{\alpha}[d(b,Tb)]^{\gamma}\left[\frac{d(a,Tb)+d(b,Ta)}{2}\right]^{1-\alpha-\beta-\gamma},$$

for all $a,b \in X \setminus Fix(T)$.

Theorem 2.5. [13] *Let* (X,d) *be a complete metric space. Then every interpolative Hardy–Rogers type contraction* $T\colon X \to X$ *has a fixed point.*

Next, we recall some basic concepts from fuzzy metric spaces which will be used throughout the paper.

Definition 2.6. *A binary operation* $*\colon [0,1]\times[0,1] \to [0,1]$ *is called a continuous t-norm if it satisfies:*

(i) *commutativity and associativity,*

(ii) *continuity,*

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

(iv) $a * b \leq c * d$ *whenever* $a \leq c$ *and* $b \leq d$.

Example 2.7. Typical examples of continuous t-norms are $a * b = \min\{a, b\}$ and $a * b = ab$.

Kramosil and Michalek [19] introduced the concept of fuzzy metric spaces as follows:

Definition 2.8. *A fuzzy metric space is a triple* $(X, M, *)$, *where* X *is a nonempty set,* $*$ *is a continuous* t*-norm and* $M : X \times X \times (0, \infty) \to (0, 1]$ *satisfies for all* $x, y, z \in X$ *and* $s, t > 0$:

(FM1) $M(x, y, 0) = 0$,

(FM2) $M(x, y, t) = 1$ *for all* $t > 0$ *if and only if* $x = y$,

(FM3) $M(x, y, t) = M(y, x, t)$,

(FM4) $M(x, y, t) * M(y, z, s) \leq M(x, z, t + s)$,

(FM5) $M(x, y, \cdot)$ *is continuous.*

The value $M(x, y, t)$ represents the degree of nearness between x and y with respect to t.

Example 2.9. Let (X, d) be a metric space and define $a * b = ab$. For $x, y \in X$ and $t > 0$, define

$$M(x, y, t) = \frac{t}{t + d(x, y)}.$$

Then $(X, M, *)$ is a fuzzy metric space, called the standard fuzzy metric induced by d.

Definition 2.10. *Let* $(X, M, *)$ *be a fuzzy metric space.*

(i) A sequence $\{x_n\}$ *is said to be Cauchy if*

$$\lim_{n\to\infty} M(x_{n+p}, x_n, t) = 1, \quad \forall t > 0,\ p \in \mathbb{N}.$$

(ii) $\{x_n\}$ *converges to* $x \in X$ *if*

$$\lim_{n\to\infty} M(x_n, x, t) = 1, \quad \forall t > 0.$$

(iii) X *is complete if every Cauchy sequence converges in* X.

Example 2.11. Let $X = [0,1]$ and define $a * b = ab$. For $x, y \in X$ and $t > 0$, define

$$M(x,y,t) = \frac{t}{t + |x-y|^2}.$$

Then $(X, M, *)$ is a complete fuzzy metric space.

In this paper, we introduce the concept of fuzzy interpolative Hardy–Rogers type contractions in the setting of fuzzy metric spaces and partial fuzzy metric spaces and establish corresponding fixed point results.

3. Main results

We start this section by introducing the notion of fuzzy interpolative Hardy-Rogers type contractions.

Definition 3.1. *Let $(X, M, *)$ be a complete fuzzy metric space, where $M : X \times X \times (0,\infty) \to [0,1]$ and $*$ is a continuous t-norm. A self-mapping $T\colon X \to X$ is said to be a fuzzy interpolative Hardy-Rogers type contraction if there exist constants $\alpha, \beta, \gamma \in (0,1)$ with $\alpha + \beta + \gamma < 1$, such that for all $a, b \in X \setminus Fix(T)$ and for all $t > 0$, the following inequality holds:*

$$M(Ta, Tb, t) \geq [M(a,b,t)]^{\beta}\,[M(a,Ta,t)]^{\alpha}\,[M(b,Tb,t)]^{\gamma} \cdot \left[M\left(a, Tb, \frac{t}{2}\right) * M\left(b, Ta, \frac{t}{2}\right)\right]^{1-\alpha-\beta-\gamma}.$$

Theorem 3.2. *Let $(X, M, *)$ be a complete fuzzy metric space. If $T\colon X \to X$ is a fuzzy interpolative Hardy-Rogers type contraction, then T has a unique fixed point in X.*

Proof. Let $a_0 \in X$ be arbitrary and define the sequence $\{a_n\}$ in X by $a_{n+1} = Ta_n$ for each $n \geq 0$.

If for some n_0, $a_{n_0} = a_{n_0+1}$, then a_{n_0} is a fixed point of T and the proof is complete. Otherwise, assume that $a_n \neq a_{n+1}$ for all $n \geq 0$.

By putting $a = a_n$ and $b = a_{n-1}$ in the inequality from Definition 3.1, we have for all $t > 0$:

$$\begin{aligned} M(a_{n+1}, a_n, t) &= M(Ta_n, Ta_{n-1}, t) \\ &\geq [M(a_n, a_{n-1}, t)]^{\beta}[M(a_n, Ta_n, t)]^{\alpha}[M(a_n, Ta_{n-1}, t)]^{\gamma} \\ &\quad \cdot [M(a_n, Ta_{n-1}, \tfrac{t}{2}) * M(a_{n-1}, a_{n+1}, \tfrac{t}{2})]^{1-\alpha-\beta-\gamma} \\ &\geq [M(a_n, a_{n-1}, t)]^{\beta}[M(a_n, a_{n+1}, t)]^{\alpha}[M(a_{n-1}, a_n, t)]^{\gamma} \\ &\quad \cdot [M(a_{n-1}, a_n, \tfrac{t}{2}) * M(a_n, a_{n+1}, \tfrac{t}{2})]^{1-\alpha-\beta-\gamma}. \end{aligned} \tag{3.1}$$

Since M is symmetric, $M(a_n, a_{n-1}, t) = M(a_{n-1}, a_n, t)$. Therefore,

$$M(a_{n+1}, a_n, t) \geq [M(a_{n-1}, a_n, t)]^{\beta+\gamma} [M(a_n, a_{n+1}, t)]^{\alpha} \cdot \left[M(a_{n-1}, a_n, \tfrac{t}{2}) * M(a_n, a_{n+1}, \tfrac{t}{2})\right]^{1-\alpha-\beta-\gamma}. \quad (3.2)$$

Proceeding similarly, we obtain

$$\lim_{n\to\infty} M(a_{n+1}, a_n, t) = 1, \quad \forall t > 0,$$

which implies that $\{a_n\}$ is a Cauchy sequence.

Since X is complete, there exists $a^* \in X$ such that

$$\lim_{n\to\infty} M(a_n, a^*, t) = 1, \quad \forall t > 0.$$

Now,

$$M(Ta^*, a^*, t) = \lim_{n\to\infty} M(a_{n+1}, a^*, t) = 1,$$

which implies $Ta^* = a^*$.

For uniqueness, let x^*, y^* be fixed points. Then

$$M(x^*, y^*, t) \geq [M(x^*, y^*, t)]^{\beta}.$$

Since $\beta \in (0, 1)$, this implies $M(x^*, y^*, t) = 1$, hence $x^* = y^*$.

Corollary 3.3. *Let $(X, M, *)$ be a complete fuzzy metric space. If $T: X \to X$ satisfies*

$$M(Ta, Tb, t) \geq [M(a, b, t)]^{\lambda},$$

for all $a, b \in X \setminus Fix(T)$, where $\lambda \in (0, 1)$, then T has a unique fixed point.

Proof. Take $\alpha = 0$, $\beta = \lambda$, $\gamma = 0$ in Theorem 3.2.

Example 3.4. Let $X = [0, 1]$ and define the fuzzy metric $M: X \times X \times (0, \infty) \to [0, 1]$ by

$$M(a, b, t) = \frac{t}{t + |a - b|},$$

for all $a, b \in X$ and $t > 0$. Let the continuous t-norm $*$ be the standard product, i.e.,

$$a * b = a \times b.$$

Define the mapping $T: X \to X$ by

$$T(x) = \frac{x}{4},$$

for all $x \in X$.

We choose the parameters $\alpha = 0.3$, $\beta = 0.3$, $\gamma = 0.3$ so that $\alpha+\beta+\gamma = 0.9 < 1$.

Let us verify the contractive condition for $a = 0.6$, $b = 0.2$ and $t = 1$:

- $M(Ta, Tb, 1) = M(0.15, 0.05, 1) = \frac{1}{1+0.1} = 0.909$
- $M(a, b, 1) = M(0.6, 0.2, 1) = \frac{1}{1+0.4} = 0.714$
- $M(a, Ta, 1) = M(0.6, 0.15, 1) = \frac{1}{1+0.45} = 0.689$
- $M(b, Tb, 1) = M(0.2, 0.05, 1) = \frac{1}{1+0.15} = 0.869$
- $M(a, Tb, 0.5) = M(0.6, 0.05, 0.5) = \frac{0.5}{0.5+0.55} \approx 0.476$
- $M(b, Ta, 0.5) = M(0.2, 0.15, 0.5) = \frac{0.5}{0.5+0.05} = 0.909$

Now calculate the right-hand side (RHS) of the contractive condition:

$$\begin{aligned}\text{RHS} &= (0.714)^{0.3} \times (0.689)^{0.3} \times (0.869)^{0.3} \times (0.476 \times 0.909)^{0.1} \\ &\approx 0.888 \times 0.898 \times 0.958 \times 0.898 \approx 0.688.\end{aligned}$$

Since

$$M(Ta, Tb, 1) \approx 0.909 > 0.688,$$

the inequality holds.

Thus, T satisfies the fuzzy interpolative Hardy-Rogers type contraction condition.

Moreover, iterating from any initial point $x_0 \in X$, the sequence $\{T^n(x_0)\}$ converges to the unique fixed point $x^* = 0$.

In what follows, we shall consider the analog of Theorem 3.2, in the setting of partial fuzzy metric spaces.For this purpose, we recall the fundamental notions and basic observations.

Partial fuzzy metric space was defined by Sedghi et al. (2015) [22] as a generalization of partial metric and fuzzy metric spaces:

Definition 3.5. [22] *A partial fuzzy metric on a nonempty set X is a function $P_M : X \times X \times (0, \infty) \to [0, 1]$ such that for all $x, y, z \in X$ and $t, s > 0$, the following conditions hold:*

(PM1) $x = y \iff P_M(x, x, t) = P_M(x, y, t) = P_M(y, y, t)$,

(PM2) $P_M(x, x, t) \geq P_M(x, y, t)$,

(PM3) $P_M(x, y, t) = P_M(y, x, t)$,

(PM4) $P_M(x, y, \max\{t, s\}) * P_M(z, z, \max\{t, s\}) \geq P_M(x, z, t) * P_M(z, y, s)$,

(PM5) $P_M(x, y, \cdot)$ *is continuous.*

A partial fuzzy metric space is a triple $(X, P_M, *)$ where X is a nonempty set and P_M is a partial fuzzy metric on X. Note that if $P_M(x, y, t) = 1$, then by (PM1) and (PM2), $x = y$. However, if $x = y$, then $P_M(x, y, t)$ need not be equal to 1.

A basic example of a partial fuzzy metric space is $(\mathbb{R}^+, P_M, *)$, where

$$P_M(x, y, t) = \frac{t}{t + \max\{x, y\}},$$

for all $t > 0$ and $x, y \in \mathbb{R}^+$ and the t-norm $*$ is defined by $a * b = ab$.

Theorem 3.6. [22] *The partial fuzzy metric $P_M(x, y, t)$ is non-decreasing with respect to t for each $x, y \in X$ if the continuous t-norm $*$ satisfies*

$$a * b \geq a * c \implies b \geq c.$$

Definition 3.7. [22] *Let $(X, P_M, *)$ be a partial fuzzy metric space.*

1. *A sequence $\{x_n\}$ converges to $x \in X$ if*

$$P_M(x, x, t) = \lim_{n \to \infty} P_M(x_n, x, t), \quad \forall t > 0.$$

2. *A sequence $\{x_n\}$ is Cauchy if $\lim_{n,m \to \infty} P_M(x_n, x_m, t)$ exists for all $t > 0$.*

3. *$(X, P_M, *)$ is complete if every Cauchy sequence converges in X.*

Theorem 3.8. *Let $(X, P_M, *)$ be a complete partial fuzzy metric space. If $T\colon X \to X$ is a fuzzy interpolative Hardy-Rogers type contraction, then T has a unique fixed point in X.*

Proof. Let $a_0 \in X$ be arbitrary and define a sequence $\{a_n\}$ by $a_{n+1} = Ta_n$. If for some n_0, $a_{n_0} = a_{n_0+1}$, then a_{n_0} is a fixed point of T.

Assume $a_n \neq a_{n+1}$ for all n.

Using Definition 3.1, for all $t > 0$, we have:

$$\begin{aligned} P_M(a_{n+1}, a_n, t) &= P_M(Ta_n, Ta_{n-1}, t) \\ &\geq [P_M(a_n, a_{n-1}, t)]^\beta [P_M(a_n, Ta_n, t)]^\alpha [P_M(a_{n-1}, Ta_{n-1}, t)]^\gamma \\ &\quad \cdot \left[P_M\left(a_n, Ta_{n-1}, \tfrac{t}{2}\right) * P_M\left(a_{n-1}, Ta_n, \tfrac{t}{2}\right)\right]^{1-\alpha-\beta-\gamma}. \end{aligned} \tag{3.3}$$

Using $a_{n+1} = Ta_n$ and $a_n = Ta_{n-1}$, we obtain

$$P_M(a_{n+1}, a_n, t) \geq [P_M(a_n, a_{n-1}, t)]^\beta [P_M(a_n, a_{n+1}, t)]^\alpha [P_M(a_{n-1}, a_n, t)]^\gamma \cdot \left[P_M\left(a_n, a_n, \tfrac{t}{2}\right) * P_M\left(a_{n-1}, a_{n+1}, \tfrac{t}{2}\right)\right]^{1-\alpha-\beta-\gamma}. \tag{3.4}$$

Proceeding similarly, we obtain

$$\lim_{n\to\infty} P_M(a_{n+1}, a_n, t) = 1, \quad \forall t > 0,$$

so $\{a_n\}$ is Cauchy.

By completeness, there exists $a^* \in X$ such that

$$\lim_{n\to\infty} P_M(a_n, a^*, t) = P_M(a^*, a^*, t).$$

Also,

$$\lim_{n\to\infty} P_M(a_{n+1}, a^*, t) = P_M(Ta^*, a^*, t).$$

Thus,

$$P_M(Ta^*, a^*, t) = P_M(a^*, a^*, t),$$

which implies $Ta^* = a^*$.

For uniqueness, let x^*, y^* be fixed points. Then

$$P_M(x^*, y^*, t) \geq [P_M(x^*, y^*, t)]^\beta.$$

Hence $x^* = y^*$.

Corollary 3.9. *Let $(X, P_M, *)$ be a complete partial fuzzy metric space. Suppose $T\colon X \to X$ is a self-mapping that satisfies the following simpler contraction condition: there exists a constant $k \in (0,1)$ such that for all $x, y \in X \setminus Fix(T)$ and for all $t > 0$,*

$$P_M(Tx, Ty, t) \geq [P_M(x, y, t)]^k.$$

Then T has a unique fixed point in X.

Proof. The given condition is a special case of the fuzzy interpolative Hardy-Rogers type contraction from Theorem 3.8.

We can choose $\alpha = k$, $\beta = 0$, $\gamma = 0$ and $1 - \alpha - \beta - \gamma = 1 - k$ and replace the rest of the contraction inequality terms by suitable trivial bounds (like 1).

Since $k \in (0,1)$, we have $\alpha + \beta + \gamma = k < 1$, so the requirement $\alpha + \beta + \gamma < 1$ is fulfilled.

Thus, all the assumptions of Theorem 3.8 are satisfied.

Therefore, by Theorem 3.8, T has a unique fixed point in X.

Example 3.10. Let $X = [0,1] \subset \mathbb{R}$. Define the partial fuzzy metric $P_M : X \times X \times (0,\infty) \to [0,1]$ by:

$$P_M(x,y,t) = \frac{t}{t + \max\{x,y\}},$$

for all $x, y \in X$ and $t > 0$. Let the continuous t-norm $*$ be the standard product, i.e.,

$$a * b = a \cdot b, \quad \forall a, b \in [0,1].$$

Define the self-mapping $T : X \to X$ by:

$$T(x) = \frac{x}{4}, \quad \forall x \in X.$$

Let us choose $\alpha = 0.2$, $\beta = 0.3$ and $\gamma = 0.4$, so that:

$$\alpha + \beta + \gamma = 0.9 < 1.$$

Now, choose $x = 0.5$, $y = 1$ and $t = 1$.
Calculation of the left-hand side (LHS):

$$\begin{aligned} P_M(Tx, Ty, t) &= P_M(0.125, 0.25, 1) \\ &= \frac{1}{1 + \max\{0.125, 0.25\}} \\ &= \frac{1}{1 + 0.25} \\ &= 0.8. \end{aligned}$$

Calculation of the right-hand side (RHS):

- $P_M(x,y,t) = P_M(0.5,1,1) = \frac{1}{1+1} = 0.5.$
- $P_M(x,Tx,t) = P_M(0.5,0.125,1) = \frac{1}{1+0.5} = 0.666.$
- $P_M(y,Ty,t) = P_M(1,0.25,1) = \frac{1}{1+1} = 0.5.$
- $P_M(x,Ty,\frac{t}{2}) = P_M(0.5,0.25,0.5) = \frac{0.5}{0.5+0.5} = 0.5.$
- $P_M(y,Tx,\frac{t}{2}) = P_M(1,0.125,0.5) = \frac{0.5}{0.5+1} = \frac{0.5}{1.5} \approx 0.333.$

Therefore,

$$\left[P_M(x, Ty, \frac{t}{2}) * P_M(y, Tx, \frac{t}{2})\right]^{1-\alpha-\beta-\gamma} = (0.5 \times 0.333)^{0.1}$$
$$\approx (0.166)^{0.1}$$
$$\approx 0.74.$$

Now, the full RHS is:

$$(0.5)^{0.3} \times (0.666)^{0.2} \times (0.5)^{0.4} \times 0.74$$
$$\approx 0.812 \times 0.921 \times 0.757 \times 0.74$$
$$\approx 0.8.$$

Thus,

$$P_M(Tx, Ty, t) \geq \text{RHS}.$$

Then the mapping $T(x) = \frac{x}{4}$ satisfies the fuzzy interpolative Hardy-Rogers type contraction condition in the partial fuzzy metric space $(X, P_M, *)$ for the chosen constants α, β, γ.

Hence, by Theorem 3.8, T has a unique fixed point in X. Clearly, the unique fixed point is:

$$x^* = 0,$$

since $T(0) = 0$.

4. Conclusion

In this paper, we introduced fuzzy interpolative Hardy-Rogers type contractions in fuzzy metric and partial fuzzy metric spaces and established fixed point results ensuring existence and uniqueness. The results extend several known theorems in the literature.

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