

On Metric-Like Spaces: A Survey

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Abstract

This paper presents a survey of various fixed point results on metric-like spaces. Some important results from beginning upto now related with metric-like spaces are incorporated in this paper which will be very helpful for researchers.

Keywords: Fixed points, complete metric-like spaces, b – metric-like spaces, weakly compatible, common fixed points.

1. INTRODUCTION

Fixed point theory is regarded as a branch of a non-linear analysis deals with finding solutions of various problems of social and natural sciences, using the concept of fixed points. Due to flourishing area of research much work has been done in this field.

As it is well known that metric space is the milestone of not only mathematics but several other sciences. The notion of metric space was first introduced by French mathematician Maurice Frechet in 1906. After that a lot of generalizations of metric space came into existence based on modifying or reducing the metric axioms.

As one of the generalizations of metric space, by introducing the conception of metric-like space in 2000, Hitzler [23] gave a valuable contribution in fixed point theory, permitting self-distance to be non zero, as that can not be possible in metric space. At that time, during his work, he studied the metric-like space under the name of ‘Dislocated metric space’ and that was Amini-Harandi [21] who re-introduced the dislocated metric space by a new name as metric-like space.

In the same manner, with some specific characteristics, the generalizations of metric-like space: b-metric-like and rectangular metric-like spaces were familiarized to us by Alghamdi et al. [3] and Mlaiki et al. [34] respectively. Also theorem related to discontinuous maps will also depicted here.

Based on the type of maps such as single valued or multivalued or single self-map or two self-maps or more, a number of fixed point results, related to metric-like spaces, have been discussed in this survey paper.

2. PRELIMINARIES

Here are some basic definitions and conventions which will be used throughout this survey paper.

Definition 2.1[44]. Let U be a non-empty set. A **metric** on U is a function $d : U \times U \rightarrow [0, \infty)$ assigning, to each ordered pair

(u, v) of points of U , a non-negative real number $d(u, v)$, such that

- (i) $d(u, u) = 0$;
- (ii) if $u \neq v$ then $d(u, v) > 0$; (*strict positivity*)
- (iii) $d(u, v) = d(v, u)$; (*symmetry*)
- (iv) $d(u, v) \leq d(u, w) + d(w, v)$; (*triangle inequality*)

for all u, v, w in U .

The set U together with the metric d defined above, i.e. the pair (U, d) , is known as metric space.

Definition 2.2[21]. Let U be a non-empty set. A function $\sigma : U \times U \rightarrow [0, \infty)$ is said to be a metric-like (dislocated metric) on U if for any $u, v, w \in U$, the following conditions hold:

- (σ 1) $\sigma(u, v) = 0 \Rightarrow u = v$;
- (σ 2) $\sigma(u, v) = \sigma(v, u)$;
- (σ 3) $\sigma(u, v) \leq \sigma(u, w) + \sigma(w, v)$.

Then the pair (U, σ) with σ as metric-like is known as **metric-like (or a dislocated metric) space**.

Example 2.3. Let $U = \{0, 2, 4\}$, and define σ as

$$\sigma(u, v) = \begin{cases} 7 & \text{when } u = v = 0 \\ 5 & \text{otherwise} \end{cases}$$

Then (U, σ) is a metric-like space as all the axioms of definition 2.2 are satisfied here.

Definition 2.4[21]. Let (U, σ) be a metric-like space. Then

- (i) a sequence $\{u_n\}$ in U **converges** to a point $u \in U$ if and only if $\sigma(u, u) = \lim_{n \rightarrow \infty} \sigma(u, u_n)$.
- (ii) a sequence $\{u_n\}$ in U is said to be a **Cauchy sequence** if $\lim_{n, m \rightarrow \infty} \sigma(u_n, u_m)$ exists and is finite.
- (iii) the space (U, σ) is said to be **complete** if every Cauchy sequence $\{u_n\}$ in U converges to a point $u \in U$ such that $\lim_{n \rightarrow \infty} \sigma(u, u_n) = \sigma(u, u) = \lim_{n, m \rightarrow \infty} \sigma(u_n, u_m)$.

Definition 2.5[21]. Let (U, σ) be a metric-like space. Then the following statements hold in metric-like space:

- (i) In a Cauchy sequence, every subsequence will also be a Cauchy sequence.
- (ii) If a Cauchy sequence has a convergent subsequence, then that Cauchy sequence will converge.
- (iii) Convergent sequence has unique limits.
- (iv) A metric-like σ is continuous, i.e., for $\{u_n\}$ converges to u and $\{v_n\}$ converges to v imply that $\sigma(u_n, v_n) \rightarrow \sigma(u, v)$ as $n \rightarrow \infty$.

Definition 2.6[34]. Let U be a non-empty set and $\rho_r : U \times U \rightarrow [0, \infty)$ be a function. If the following conditions are satisfied for all u, v in U and $x, y \in X \setminus \{u, v\}$:

- (1) $\rho_r(u, v) = 0 \Rightarrow u = v$;
- (2) $\rho_r(u, v) = \rho_r(v, u)$;
- (3) $\rho_r(u, v) \leq \rho_r(u, x) + \rho_r(x, y) + \rho_r(y, v)$;
 (*rectangular inequality*)

then the pair (U, ρ_r) is known as **rectangular metric-like space**.

Example 2.7. Let $U = \{1, 2, 3, 4\}$ and define the function $\rho_r : U \times U \rightarrow [0, \infty)$ by

$$\rho_r(u, v) = \begin{cases} 2 & \text{for } u \neq v \\ 4 & \text{for } u = v = 1 \\ 0 & \text{otherwise} \end{cases}.$$

Then (U, ρ_r) is rectangular metric-like space.

Definition 2.8[3]. A b-metric-like on a non-empty set U is a function

$\mathcal{D} : U \times U \rightarrow [0, \infty)$ such that for all $u, v, w \in U$ and a constant $K \geq 1$ the following three conditions hold:

- (\mathcal{D}_1) $\mathcal{D}(u, v) = 0 \Rightarrow u = v$;
- (\mathcal{D}_2) $\mathcal{D}(u, v) = \mathcal{D}(v, u)$;
- (\mathcal{D}_3) $\mathcal{D}(u, v) \leq K(\mathcal{D}(u, w) + \mathcal{D}(w, v))$.

The pair (U, \mathcal{D}) is known as **b-metric-like space**. Sometimes, we also denote b-metric-like space by (U, \mathcal{D}, K) .

Example 2.9[3]. Let us take $U = [0, \infty)$. Define $\mathcal{D} : U \times U \rightarrow [0, \infty)$ such that

$$\mathcal{D}(u, v) = u + v$$

Then, using definition 2.8, (U, \mathcal{D}) is a b-metric-like space with the constant $K = 1$.

Definition 2.9.1[13]. Let f and g be two self-mappings on a set U .

If $\omega = fu = gu$ for some u in U , then u is called a **coincidence point** of f and g , where ω is called a point of coincidence of f and g .

3. MAIN RESULTS

There are many results in metric fixed point theory regarding the derivation of fixed points of various types of maps either of single-valued or multi-valued satisfying some contraction conditions. All these results are generalizations of Banach's contraction principle.

Suzuki's [47], generalization of Banach contraction principle, is a valuable concept in its own way as it characterise the metric completeness.

The fixed point result given by Aydi et al. [6], is based on multivalued non-self almost contractions where results (in [2]) are extended to the class of convex metric-like spaces. The term almost contraction was first introduced and defined by Berinde [10].

In 2012, Harandi [21] gave generalizations of well-known fixed point theorems of Ćirić [14] and Rakotch [39] which are as follows:

Theorem (1.3.1) [21]:- Let (U, σ) be a complete metric-like space, and let $T : U \rightarrow U$ be a map such that

$$\sigma(Tu, Tv) \leq \psi(M(u, v)),$$

for all $u, v \in U$, where

$$M(u, v) = \max\{\sigma(u, v), \sigma(u, Tu), \sigma(v, Tv), \sigma(u, Tv), \sigma(v, Tu), \sigma(u, u), \sigma(v, v)\},$$

where $\psi : [0, \infty) \rightarrow [0, \infty)$ is a non-decreasing function satisfying

$$\psi(t) < t \quad \text{for all } t > 0, \quad \lim_{s \rightarrow t^+} \psi(s) < t \quad \text{for all } t > 0 \text{ and}$$

$$\lim_{t \rightarrow \infty} (t - \psi(t)) = \infty.$$

Then T has a fixed point.

Theorem (1.3.2) [21]:- Let (U, σ) be a complete metric-like space, and let $T : U \rightarrow U$ be a map such that

$$\sigma(Tu, Tv) \leq \sigma(u, v) - \varphi(\sigma(u, v)),$$

for all $u, v \in U$, where $\varphi : [0, \infty) \rightarrow [0, \infty)$ is a non-decreasing continuous function such that

$\varphi(t) = 0$ if and only if $t = 0$. Then T has a unique fixed point.

Theorem (1.3.3) [21]:- Let (U, σ) be a complete metric-like space, and let $T : U \rightarrow U$ be a mapping satisfying

$$\sigma(Tu, Tv) \leq \alpha(\sigma(u, v))\sigma(u, v),$$

for each $u, v \in U$ with $u \neq v$, where $\alpha : [0, \infty) \rightarrow [0, 1)$ is non-increasing. Then T has a unique fixed point.

In 2013, Shobkolaei et al. [45] introduced interesting fixed

point results related to Banach fixed-point principle and introduced fundamental lemma for the convergence of sequences in metric-like spaces, which are as follows:

Theorem (1.3.4) [45]:- Let (U, σ) be a complete metric-like space, and let $T : U \rightarrow U$ be a self-map, and let $\theta =: [0, 1) \rightarrow$

$\left(\frac{1}{2}, 1\right]$ be defined by

$$\theta(r) = \left\{ \begin{array}{ll} 1 & , \quad 0 \leq r \leq \frac{\sqrt{5}-1}{2} \\ \frac{1-r}{r^2} & , \quad \frac{\sqrt{5}-1}{2} \leq r \leq \frac{1}{\sqrt{2}} \\ \frac{1}{1+r} & , \quad \frac{1}{\sqrt{2}} \leq r \leq 1 \end{array} \right.$$

Assume that there exists $r \in [0, 1)$, such that

$$\theta(r) \sigma(u, Tu) \leq \sigma(u, v) \implies \sigma(Tu, Tv) \leq r \sigma(u, v)$$

for all $u, v \in U$, then \exists a unique fixed point z of T . Moreover,

$$\lim_{n \rightarrow \infty} T^n u = z$$

for all $u \in U$ i.e. the sequence $\{T^n u\}$ converges to z .

Theorem (1.3.5) [45]:- Let (U, σ) be a complete metric-like space. Let $S, T : U \rightarrow U$ be two self-mappings. Suppose that there exists $r \in [0, 1)$ such that

$$\max\{\sigma(S(u), TS(u)), \sigma(T(u), ST(u))\} \leq r \min\{\sigma(u, S(u)), \sigma(u, T(u))\}$$

for every $u \in U$ and that

$$\alpha(v) = \inf\{\sigma(u, v) + \min\{\sigma(u, S(u)), \sigma(u, T(u))\} : u \in U\} > 0$$

for every $v \in U$ with v that is not a common fixed point of S and T . Then $\exists z \in U$ such that $z = S(z) = T(z)$. Moreover, if $w = S(w) = T(w)$, then $\sigma(w, w) = 0$.

In 2015, Aydi et al. [6] gave a fixed point theorem for multi-valued non-self almost contractions on convex metric-like spaces, which is as follows:

Theorem (1.3.6) [6]:- Let (U, σ) be a complete metric-like space and K a non-empty closed subset of U such that if $u \in K$ and $y \notin K$, then \exists a point $z \in \partial K$ (the boundary of K) such that

$$\sigma(u, v) = \sigma(u, z) + \sigma(z, v).$$

Suppose that $T : K \rightarrow CB^\sigma(U)$ is a multi-valued almost contraction, i.e.,

$$H_\sigma(Tu, Tv) \leq k \sigma(u, v) + L \sigma(v, Tu) \quad \text{for all } u, v \in K$$

with $k \in (0, 1)$ and some $L \geq 0$ such that $(1 + L)(k + 2L) < 1$. If T satisfies Rothe's type condition, i.e., $u \in \partial K \implies Tu \subset K$, then $\exists u^* \in K$ such that $u^* \in Tu^*$, i.e., T has a fixed point in K .

In 1966, Jungck [26] introduced the concept of weak compatibility. Since then, many interesting fixed point theorems of compatible and weakly compatible maps under various contractive conditions have been obtained by a number of authors. We give common fixed point results for four weakly compatible maps where Bannani et al. [8] improved the result of Panthi and Jha [36] and He [22] improved the result of Bannani et al. [8] in metric-like space.

In 2015, Panthi et al. [37] gave the following common fixed point theorem related to two pair of mappings in metric-like spaces:

Theorem (1.4.1) [37]:- Let (U, σ) be a complete metric-like space. Suppose that A, B, S and T are four self-mappings of U satisfying the following conditions:

- (i) $T(u) \subseteq A(u)$ and $S(u) \subseteq B(u)$
- (ii) $\sigma(Su, Tv) \leq \phi(m(u, v))$ where ϕ is an upper semi-continuous contractive modulus and

$$m(u, v) = \max\{\sigma(Au, Bv), \sigma(Au, Su), \sigma(Bv, Tv), \frac{1}{2} \sigma(Au, Tv), \frac{1}{2} \sigma(Bv, Su)\}$$
- (iii) The pairs (S, A) and (T, B) are weakly compatible.

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

In 2015, Fei He [22] gave common fixed point theorem related to four self maps in metric-like space which is as follows:

Theorem (1.4.2) [22]:- Let (U, σ) be a complete metric-like space and let A, B, T and S be four self maps on U such that $TU \subset AU$ and $SU \subset BU$. Suppose that there exists a real number λ with $\lambda \in \left[0, \frac{1}{2}\right)$, satisfying for all $u, v \in U$

$$\sigma(Su, Tv) \leq \lambda M(u, v)$$

where $M(u, v) = \max\{\sigma(Au, Tv), \sigma(Bv, Su), \sigma(Au, Su), \sigma(Bv, Tv), 2\sigma(Au, Bv)\}$.

If the range of one of the mappings A, B, S and T is a complete subspace of U then

- (i) B and T have a coincidence point x ,
- (ii) A and S have a coincidence point y and
- (iii) $Ay = Sy = Bx = Tx$.

Moreover, if the pairs $\{A, S\}$ and $\{B, T\}$ are weakly compatible, then A, B, S and T have a unique common fixed point y and $\sigma(y, y) = 0$.

In 2015, Bannani et al. [8] improved the result given by Panthi et al. [36] on four self maps. Bannani et al. [8] gave the following result:

Theorem (1.4.3) [8]:- Let A, B, T and S be four self-mappings of a metric-like space (U, σ) such that

- (i) $TU \subset AU$ and $SU \subset BU$;
- (ii) The pairs (S, A) and (T, B) are weakly compatible;
- (iii) For all $u, v \in U$ and $\alpha, \beta, \gamma \geq 0$ satisfying $\alpha + \beta + \gamma < \frac{1}{4}$, we have

$$\sigma(Su, Tv) \leq \alpha [\sigma(Au, Tv) + \sigma(Bv, Su)] + \beta [\sigma(Au, Su) + \sigma(Bv, Tv)] + \gamma \sigma(Au, Bv);$$
- (iv) The range of one of the mappings A, B, S or T is a complete subspace of U.

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

Rectangular metric-like space was introduced by Mlaiki et al. [34] which is considered as the generalization of metric-like space. The basic difference between metric-like and rectangular metric-like space is that the triangle inequality in metric-like space is replaced by rectangular inequality.

In 2010, Mlaiki et al. [34] introduced some fixed point theorems associated with rectangular metric-like spaces which are as follows:

Theorem (1.5.1) [34]:- Let (U, ρ_r) be a ρ_r - complete rectangular metric-like space, and T a self mapping on U. If there exists $0 < k < 1$ such that

$$\rho_r(Tu, Tv) \leq k \rho_r(u, v) \quad \text{for all } u, v \in U.$$

Then T has a unique fixed point w in U, where $\rho_r(w, w) = 0$.

Theorem (1.5.2) [34]:- Let (U, ρ_r) be a ρ_r - complete rectangular metric-like space, and T a self mapping on U. If there exists $0 < k < 1$ such that

$$\rho_r(Tu, Tv) \leq k \max \{ \rho_r(u, v), \rho_r(u, u), \rho_r(v, v) \} \quad \text{for all } u, v \in U.$$

Then T has a unique fixed point w in U, where $\rho_r(w, w) = 0$.

Theorem (1.5.3) [34]:- Let (U, ρ_r) be a ρ_r - complete rectangular metric-like space, and T a self mapping on U. If there exists $0 < k < 1$ such that

$$\rho_r(Tu, Tv) \leq k \max \{ \rho_r(u, v), \rho_r(u, Tu), \rho_r(v, Tv) \} \quad \text{for all } u, v \in U.$$

Then T has a unique fixed point w in U, where $\rho_r(w, w) = 0$.

As the literature of fixed point theory contains several generalizations of metric spaces, b-metric-like space is one of them. b-metric-like space, which is considered as the generalization of b-metric, metric-like and partial metric space, was introduced by Alghamdi et al. [3]. A lot of fixed point results have been given in b-metric-like space, which generalize and improve some well known results in the

literature.

In 2013, Alghamdi et al. [3] gave some interesting fixed point results on expansive mappings which are as follows:

Theorem (1.6.1) [3]:- Let (U, \mathcal{D}, K) be a complete b-metric-like space. Assume that the mapping $T : U \rightarrow U$ is onto and satisfies

$$\mathcal{D}(Tu, Tv) \geq [R + L \min \{ \mathcal{D}^s(u, Tu), \mathcal{D}^s(v, Tv), \mathcal{D}^s(u, Tv), \mathcal{D}^s(v, Tu) \}] \mathcal{D}(u, v)$$

for all $u, v \in U$, where $R > K, L \geq 0$. Then T has a fixed point.

Theorem (1.6.2) [3]:- Let (U, \mathcal{D}, K) be a complete b-metric-like space. Assume that the mapping $T : U \rightarrow U$ is onto and satisfies

$$\mathcal{D}(Tu, Tv) \geq \mathcal{B}(\mathcal{D}(u, v)) \mathcal{D}(u, v) \quad \text{for all } u, v \in U,$$

where $\mathcal{B} \in \Psi_B^K$. Then T has a fixed point.

In 2015, Chen et al. [13] gave some common fixed point theorems in b-metric-like spaces which are as follows:

Theorem (1.6.3) [13]:- Let (U, \mathcal{D}) be a complete b-metric-like space with the constant $s \geq 1$ and let $T : U \rightarrow U$ be a mapping such that

$$\mathcal{D}(Tu, Tv) \leq \frac{\mathcal{D}(u, v)}{s} - \varphi(\mathcal{D}(u, v))$$

for all $u, v \in U$, where $\varphi \in \Phi$. Then T has a unique fixed point.

Theorem (1.6.4) [13]:- Let (U, \mathcal{D}) be a complete b-metric-like space with the constant $s \geq 1$ and let $T : U \rightarrow U$ be a surjection such that

$$\mathcal{D}(Tu, Tv) \geq a_1 \mathcal{D}(u, v) + a_2 \mathcal{D}(u, Tu) + a_3 \mathcal{D}(v, Tv) + a_4 \mathcal{D}(u, Tv)$$

for all $u, v \in U$, where $a_i \geq 0$ ($i = 1, 2, 3, 4$) satisfy

$$s(a_1 + a_2) + a_4 + s^2(a_3 - a_4) > s^2 \text{ and } 1 - a_3 + a_4 > 0. \text{ Then T has a fixed point.}$$

As there are some maps also which are discontinuous and for answering the question of fixed points in case of discontinuous maps a theorem is also provided here. The feature of this result is to provide a common fixed point theorem which shows that for having unique common fixed point, it is not necessary that the mappings involved be continuous.

Following is that fixed point result:

Theorem (1.7.1)[38]:- Let (U, ρ_r) be a complete rectangular metric-like space and let S, T : $U \rightarrow U$ be mappings such that

$$\rho_r(Su, Tv) \leq h \max \left\{ \rho_r(u, v), \rho_r(u, Su), \rho_r(v, Tv), \frac{(\rho_r(u, Tv) + \rho_r(v, Su))}{2} \right\}$$

for all $u, v \in U$ and $0 < h < 1$. Then S and T have unique common fixed point.

4. CONCLUSION

We can conclude from this survey paper that the various fixed point results related to metric-like spaces were provided by many famous researchers based on the difference of some metric-like axioms. This is the most active research area of the present era. So it has been discovered upto discontinuous maps in its extended generalizations such as rectangular metric-like space. In the future, there will also be some very interesting fixed point results, will be helpful in solving various problems using the concept of fixed points.

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