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A FIXED POINT THEOREM IN A CLASS OF RANDOM PARANORMED SPACES

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ABSTRACT.

In this paper a fixed point theorem in a class of random paranormed spaces is proved.

1. In [6] the notion of random paranormed space is introduced and some fixed point theorems in such spaces are proved. In this paper we shall prove a fixed point theorem in paranormed spaces (S,F,t) where T-norm t is of H-type [3].

First, we shall give some notations and definitions. Let $R = (-\infty,\infty)$, $\mathcal{D}^+ = \{F;\ F : R \to [0,1],\ F$ is left continuous, $\inf F = 0$, $\sup F = 1$, F is monotone nondecreasing, $F(0) = 0\}$ and

$$H(t) = \begin{cases} 1, & t > 0 \\ 0, & t \le 0. \end{cases}$$

Let T-norm t_m be defined in the following way: $t_m(a,b) = \max\{a + b - 1, 0\}$. The notion of a random paranormed space is introduced as a generalization of the notions of random normed spaces and paranormed spaces. Let us recall the definition of a random normed space [9].

Definition 1. *Let* S *be a real or complex vector space,* t *a T-norm stronger then* t_m $(t \ge t_m)$ *and the mapping* $F : S \to \mathcal{D}^+$ *satisfies the following conditions* $(F(p) = F_p)$:

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1. $F_p = H \iff p = \theta$ *(θ is the neutral element of S).*

2. *For every* $p \in S$, *every* $u > 0$ *and every* $\delta \in K \setminus \{0\}$ *(K is the scalar field):*

$$F_{\delta p}(u) = F_p(u/|\delta|).$$

3. *For every* $p,q \in S$ *and every* $u,v > 0$:

$$F_{p-q}(u+v) \geq t(F_p(u), F_q(v)).$$

Then (S,F,t) *is a random normed space.*

Every normed space $(E, \|\ \|)$ is a random normed space, where

$$F_x(\varepsilon) = \begin{cases} 1, & \|x\| < \varepsilon \\ 0, & \|x\| \geq \varepsilon \end{cases} \quad (x \in E,\ \varepsilon > 0).$$

Every random normed space is a probabilistic metric space where $F_{x,y} = F_{x-y}$.

Let E be a vector space and $p : E \to [0,\infty)$ so that the following conditions are satisfied:

(i) $p(x) = 0 \iff x = 0$.

(ii) $p(x) = p(-x)$, for every $x \in E$.

(iii) $p(x+y) \leq p(x) + p(y)$, for every $x,y \in E$.

(iv) If $\lambda_n \to \lambda$ (λ_n, λ are from the scalar field) and $p(x_n - x) \to 0$ ($x_n, x \in E$) then $p(\lambda_n x_n - \lambda x) \to 0$.

Then the pair (E,p) is a paranormed space. If the fundamental system of neighbourhoods of zero is given by $\mathcal{V} = \{V_\varepsilon\}_{\varepsilon>0}$, where $V_\varepsilon = \{x;\ x \in E,\ p(x) < \varepsilon\}$, then E is a topological vector space. An example of a paranormed space is the space S(0,1) (all the equivalence classes of real Lebesgue measurable functions defined on the interval (0,1)) with the paranorm p given by:

$$p(\hat{x}) = \int_0^1 \frac{|x(t)|}{1 + |x(t)|}\, dt \quad (\{x(t)\} \in \hat{x})$$

Definition 2. [6] *A random paranormed space is a triple* (E,F,t) *where E is a real or complex vector space,* $F : E \to \mathcal{D}^+$ *and t is a T-norm such that* $t \geq t_m$ *and the following conditions are satisfied:*

1. $F_p = H \Leftrightarrow p = 0$.
2. $F_{-x} = F_x$, *for every* $x \in E$.
3. $F_{x+y}(u_1+u_2) \geq t(F_x(u_1), F_y(u_2))$, *for every* $x, y \in E$ *and every* $u_1, u_2 \geq 0$.
4. If $\lambda_n \to \lambda$ and $F_{x_n-x}(\varepsilon) \to 1, (n \to \infty)$ *for every* $\varepsilon > 0$, *then* $F_{\lambda_n x_n - \lambda x}(\varepsilon) \to 1, (n \to \infty)$ *for every* $\varepsilon > 0$.

It is obvious that every paranormed space (E,p) is also a random paranormed space, where:

$$F_x(\varepsilon) = \begin{cases} 1, & p(x) < \varepsilon \\ 0, & p(x) \geq \varepsilon \end{cases} \quad (x \in E,\ \varepsilon > 0).$$

The topology in a random paranormed space (S,F,t) is introduced by the (ε,λ)-topology given by the following family of neighbourhoods of zero: $N = \{N(\varepsilon,\lambda),\ \varepsilon > 0,\ \lambda \in (0,1)\}$ where:

$$N(\varepsilon,\lambda) = \{x;\ F_x(\varepsilon) > 1-\lambda\}.$$

Let (Ω,A,P) be a probability measure space, (X,p) a separable paranormed space and S the space of all the equivalence classes of measurable mappings $x : \Omega \to X$. If $F : S \to D^+$ is defined by

$$F_x(\varepsilon) = P\{\omega;\ \omega \in \Omega,\ p(x(\omega)) < \varepsilon\},$$

then the triple (S,F,t) is a random paranormed space [6].

If t is a T-norm we shall use the following notation:

$$t_n(x) = \underbrace{t(t(\ldots t(t(x,x),\ldots,x)}_{n\text{-times}},\ n \in \mathbb{N},\ x \in [0,1].$$

A T-norm t is of H-type if the family $\{t_n(x)\}_{n\in\mathbb{N}}$ is equicontinuous at the point $x = 1$. It is known that for every T-norm t which is of H-type there exists a sequence $\{a_n\}$ from $(0,1)$ such that $\lim_{n\to\infty} a_n = 1$ and $t(a_n,a_n) = a_n$ for every $n \in \mathbb{N}$ [4].

In a random paranormed space (S,F,t), where T-norm t is of H--type and strict, the (ε,λ)-toplogy can be introduced by the following family of functions $p_n : S \to \mathbb{R}^+$:

(1) $$p_n(x) = \sup\{u;\ F_x(u) \leq a_n\} \quad (n \in \mathbb{N};\quad x \in S).$$

It is easy to prove that the family $\{p_n\}$ has the following properties:

1. $p_n(x) = 0$, for every $n \in \mathbb{N} \Leftrightarrow x = 0$.
2. $p_n(-x) = p_n(x)$, for every $x \in S$ and every $n \in \mathbb{N}$.
3. $p_n(x+y) \le p_n(x) + p_n(y)$, for every $n \in \mathbb{N}$ and $x,y \in S$.
4. If $\lambda_n \to \lambda$ ($\lambda_n, \lambda \in \mathbb{R}$) and $x_n \to x$ ($x_n, x \in S$) in the (ε,λ)-topology then for every $m \in \mathbb{N}$:

$$p_m(\lambda_n x_n - \lambda x) \to 0.$$

For example the property 3. can be proved in the following way. Let $r_1 > p_n(x)$ and $r_2 > p_n(y)$. Then $F_x(r_1) > a_n$ and $F_y(r_2) > a_n$ which implies that $F_{x+y}(r_1+r_2) \ge t(F_x(r_1), F_y(r_2)) > t(a_n,a_n) = a_n$. This means that $p_n(x+y) < r_1 + r_2$ and so $p_n(x+y) \le p_n(x) + p_n(y)$.

An example of a T-norm t which is of H-type is given in [4].

If (S,F,t) is a Menger space and t is of H-type and strict by $d_n(x,y) = \sup\{u;\ F_{x,y}(u) \le a_n\}$ ($n \in \mathbb{N}$; $x,y \in S$) a family of pseudometrics is defined.

Definition 3. *Let (S,F,t) be a random paranormed space and K a nonempty subset of S. The set K satisfies the probabilistic Zima condition if there exists $C(K) > 0$ so that for every $\lambda \in (0,1)$*

$$F_{\lambda(x-y)}(\lambda\varepsilon) \ge F_{x-y}(\varepsilon/C(K))$$

for every $\varepsilon > 0$ and every $x,y \in K$.

Example. [6]. Let (Ω,A,P) be a probability measure space and X be the space of all the equivalence classes of measurable mappings $x : \Omega \to S(0,1)$. Further, let $s > 0$ and:

$$\tilde{K}_s = \{\tilde{x};\ \tilde{x} \in X,\ \tilde{x}(\omega) \in K_s, \text{ for every } \omega \in \Omega\},$$

where $K_s = \{\bar{x};\ \bar{x} \in S(0,1),\ |x(t)| \le s,\ t \in [0,1]\}$. Let

$$F_{\tilde{x}}(\varepsilon) = P(\{\omega;\ p(\tilde{x}(\omega)) < \varepsilon\}),\ (\varepsilon > 0,\ \tilde{x} \in X).$$

In [6] it is proved that for every $\omega \in \Omega$ and $\lambda > 0$:

$$p(\lambda(\tilde{x}(\omega) - \tilde{y}(\omega))) \le (1 + 2s)\lambda p(\tilde{x}(\omega) - \tilde{y}(\omega)),$$

which implies that:

$$F_{\lambda(\hat{x}-\hat{y})}(\lambda\varepsilon) \geq F_{\hat{x}-\hat{y}}(\varepsilon/(1+2s))$$

for every $\hat{x},\bar{y} \in \tilde{K}_s$, every $\lambda > 0$ and every $\varepsilon > 0$. The probabilistic inner function of noncompactness $b_A(\cdot)$, for every probabilistic bounded subset A of S, where S is a probabilistic metric space, is defined in the following way:

$b_A(u) = \sup\{\rho;\ \rho > 0$, there exists a finite set $A_f \subset A$ such that $h_{AA_f}(u) \geq \rho\}$, $(u \in \mathbb{R}^+)$

where:

$$h_{AB}(u) = \sup_{s<u} \inf_{x\in A} \sup_{y\in B} F_{x-y}(s) \quad (u \in \mathbb{R}^+).$$

2. In Lemma 1 we shall suppose that (S,F,t) is a probabilistic metric space such that t is a strict T-norm which is of H-type. Similarly as it was proved by Tan in [10] we shall prove the following lemma.

Lemma 1. *Let for every probabilistic bounded set* $A \subset S$:

$$\tilde{b}_n(A) = \sup\{u;\ b_A(u) \leq a_n\},\ (n \in \mathbb{N}).$$

Then $b_n(A) \leq \tilde{b}_n(A)$, *for every* $n \in \mathbb{N}$ *where:*

$b_n(A) = \inf\{\varepsilon$; *there exists a finite set* $A_f \subset A$ *such that* $A \subset \bigcup_{x\in A_f} B_n(x;\varepsilon)\}$

and $B_n(x;\varepsilon) = \{y;\ y \in S,\ d_n(x,y) < \varepsilon\}$. *If* $b_A(\cdot)$ *is, for every probabilistic bounded set, A strictly monotone then* $b_n(\cdot) = \tilde{b}_n(\cdot)$, $(u \in \mathbb{N})$.

Proof. The proof of this lemma is similar to the proof of Theorem 4 in [10] but we shall give it here for the completeness. First, we shall prove that $b_n(A) \leq \tilde{b}_n(A)$, for $n \in \mathbb{N}$. Let $a = \tilde{b}_n(A) = \sup\{u;\ b_A(u) \leq a_n\}$. We shall prove that $b_n(A) \leq a$, which means that for every $u_0 > a$ there exists a finite set $A_f \subset A$ such that $A \subseteq \bigcup_{x\in A_f} B_n(x,u_0)$. Let $u_0 > a$. From the definition of $\tilde{b}_n(A)$ it follows that $b_A(u_0) > a_n$ and hence there exists a finite subset $A_f \subset S$ such that $h_{AA_f}(u_0) > a_n$.

From the definition of h_{AB} it follows that $\sup_{s<u_0}\inf_{x\in A}\max_{y\in A_f} F_{x,y}(s) > a_n$ and so there exists $s_0 < u_0$ such that:

$$\inf_{x\in A}\max_{y\in A_f} F_{x,y}(s_0) > a_n.$$

This inequality implies that $A \subseteq \bigcup_{x\in A_f} B_n(x,s_0)$ and so $b_n(A) < s_0 < u_0$. From this we conclude that $b_n(A) \le a$. We shall prove that the assumption that $b_A(\cdot)$ is strictly monotone implies that $\bar{b}_n(\cdot) = b_n(\cdot)$. If for some probabilistic bounded subset $A \subset S$ we have that $b_n(A) < \bar{b}_n(A)$ then there exist b and c $(b > c)$, such that $b_n(A) < c < b < \bar{b}_n(A)$.
Hence, there exists a finite set $A_f \subset A$ such that:

$$A \subset \bigcup_{x\in A_f} B_n(x,c).$$

This implies that $h_{AA_f}(b) \ge a_n$ and so from the definition of b_A, $b_A(b) \ge a_n$. Further, since $b_A(\cdot)$ is nondecreasing and left continuous we have that $b_A(\bar{b}_n(A)) \le a_n$ and so $a_n \le b_A(b) \le$ $\le b_A(\bar{b}_n(A)) \le a_n$ which means that $b_A(b) = b_A(\bar{b}_n(A)) = a_n$. Since $b_A(\cdot)$ is strictly monotone we obtain a contradiction.

Definition 4. *Let (S,F) be a probabilistic metric space, G a nonempty probabilistic bounded subset of S and $T:G \to P(G) \setminus \emptyset$, $q \in (0,1)$. We say that the mapping T is a (b,q) set probabilistic contraction mapping if for every $A \subset G$ and every $u \in \mathbb{R}^+$:*

$$b_{T(A)}(u) \ge b_A(u/q).$$

Lemma 2. *Let (S,F,t) be a probabilistic metric space, G a nonempty probabilistic bounded subset of S, and $T:G \to P(G) \setminus \emptyset$ a (b,q)-set probabilistic contraction mapping where $b_A(\cdot)$ is strictly monotone for every $A \subset G$. Then for every $n \in \mathbb{N}$ and every $A \subset G$*

$$b_n(T(A)) \le q b_n(A).$$

Proof. Since $b_A(\cdot)$ is strictly monotone, for every $A \subset G$, from Lemma 1 it follows that $b_n(A) = \sup\{u;\ b_A(u) \le a_n\}$ for every $n \in \mathbb{N}$ and $A \subset G$. Since T is (b,q)-set probabilistic contraction mapping it follows that $b_{T(A)}(u) \le a_n$ implies that

$b_A(u/q) \le a_n$ and so: $\{u;\ b_{T(A)}(u) \le a_n\} \subseteq \{u;\ b_A(u/q) \le a_n\}$. This implies that

$$b_n(T(A)) = \sup\{u;\ b_{T(A)}(u) \le a_n\} \le$$

$$\le \sup\{u;\ b_A(u/q) \le a_n\} = q \sup\{s;\ b_A(s) \le a_n\} =$$

$$= q \cdot b_n(A).$$

Definition 5. [7] *Let* (S,F) *be a probabilistic metric space,* $\emptyset \ne M \subset S$ *and* $T : M \to P(S) \setminus \emptyset$. *The mapping* T *is a multivalued probabilistic* q *contraction* $(q \in (0,1))$ *if for every* $x,y \in M$ *and every* $u \in Tx$ *there exists* $v \in Ty$ *so that for every* $s > 0$:

$$F_{u,v}(qs) \ge F_{x,y}(s).$$

Lemma 3. *Let* (S,F,t) *be a Menger space with a continuous T-norm* t, G *a nonempty probabilistic bounded subset of* S *and* $T:G \to \mathrm{Com}(G)$ *(the family of all nonempty compact subsets of* G*) a multivalued probabilistic* q *contraction mapping. Then:*

$$b_{T(A)}(qs) \ge b_A(s),\ (s \in \mathbb{R}^+)$$

for every $A \subseteq G$, *i.e.* T *is* (b,q)*-set probabilistic contraction mapping.*

Proof. The same method of the proof we used in a part of the proof of Theorem 1 from [7]. Let $A \subset G$. Since $b_A(\cdot)$ is left continuous it is enough to prove that for every $v \in (0,s)$: $b_A(s-v) \le b_{T(A)}(qs)$. In order to prove this inequality we shall prove that for every $r > 0$, $r < b_A(s-v)$ implies that $r \le b_{T(A)}(qs)$. If $r < b_A(s-v)$ then there exists a finite set $A_f \subset A$ such that:

$$\inf_{x\in A} \max_{y\in A_f} F_{x,y}(s-v) > r$$

and so for every $x \in A$ there exists $y(x) \in A_f$ so that $F_{x,y}(s-v) > r$. Let $x \in A$, $u \in Tx$ and $w \in Ty(x)$ be such that:

$$F_{u,w}(k(s-v)) \ge F_{x,y(x)}(s-v) > r.$$

The existence of w follows from the assumption that T is a multivalued probabilistic q-contraction. Hence for every $u \in T(A)$ there exists $w \in T(A_f)$ so that $F_{u,w}(ks-kv) > r$. Let $\delta \in (0,r)$

and $\lambda_\delta \in (0,1)$ be such that $1 \geq h > 1 - \lambda_\delta$ implies that $t(r,h) > r-\delta$ and $A_f = \{x_1,x_2,\dots,x_n\}$. Since Tx_i is compact for every $i \in \{1,2,\dots,n\}$, there exists, for every $i \in \{1,2,\dots,n\}$ a finite subset $A_f^i \subset T(A)$ such that $Tx_i \subset \bigcup_{p\in A_f^i} N_p\left(\frac{kv}{2},\lambda_\delta\right)\left(N_p\left(\frac{kv}{2},\lambda_\delta\right) = \left\{u;\ F_{u,p}(kv/2) > 1 - \lambda_\delta\right\}\right)$.

Now it is easy to prove that $h_{T(A),B_f}(ks) > r-\delta$, where $B_f = \bigcup_{i=1}^{n} A_f^i$, which implies that $r-\delta \leq b_{T(A)}(ks)$ for arbitrary number $\delta \in (0,r)$. This means that $b_{T(A)}(ks) \geq r$.

From Lemmas 2 and 3 we obtain the following result.

Proposition 1. *Let (S,F,t) be a Menger space with a continuous strict T-norm t of H-type, G a nonempty probabilistic bounded subset of S and $T:G \to \mathrm{Com}(G)$ a multivalued probabilistic q-contraction mapping. Then for every $n \in \mathbb{N}$ and every $A \subset G$:*

$$b_n(T(A)) \leq q\, b_n(A).$$

3. If (S,F,t) is a random normed space with a continuous strict T-norm t of H-type then the family of seminorms $\{p_n\}_{n\in\mathbb{N}}$, which is defined by (1), defines a locally convex topology in S. This fact was used by Constantin and Istratescu in [3] and they obtained some fixed point theorems in such random normed spaces. But, if (S,F,t) is a random paranormed space the family does not define, in general case, a locally convex topology. Hence, in this case the fixed point theory in topological vector spaces have to be used.

If (S,F,t) is a random paranormed space such that t is a strict T-norm of H-type and $G \subset S$ satisfies the probabilistic Zima condition with constant $C(G)$, it is easy to prove that for every $n \in \mathbb{N}$ and every $\lambda \in (0,1)$:

(2) $\quad p_n(\lambda(x-y)) \leq C(G)\lambda p_n(x-y)$, for every $x,y \in G$.

It can be proved, similarly as in [5], that in this case G is σ-admissible in the sense of [8]. The class of σ-admissible subsets of a topological vector space is very important in the fixed point theory [8]. If (S,F,t) is a random paranormed space with a strict T-norm t of H-type we can not prove, in general, that for every probabilistic bounded subset A of S:

(3) $$b_n(\text{co } A) = b_n(A) \quad (n \in \mathbb{N}).$$

It is well known that the equality (3) is important in the fixed point theory in locally convex spaces but if the topology in a topological vector space is defined by the family $\{p_n\}_{n\in\mathbb{N}}$ which satisfies 1., 2., 3. and 4. we shall use the following result which can be proved as in [5].

Proposition 2. *Let $(E,\{p_n\}_{n\in\mathbb{N}})$ be a metrizable topological vector space in which the topology is defined by the family of functionals $\{p_n\}_{n\in\mathbb{N}}$ so that 1., 2., 3. and 4. are satisfied. Let G be a nonempty bounded and convex subset of E such that (2) holds. Then for every $A \subset G$*

(4) $$b_n(\text{co } A) \le C(G)b_n(A), \quad \textit{for every } n \in \mathbb{N}.$$

Using Proposition 2. we obtain the following result.

Proposition 3. *Let $(E,\{p_n\}_{n\in\mathbb{N}})$ be a complete metrizable topological vector space in which the topology is defined by the family of functionals $\{p_n\}_{n\in\mathbb{N}}$ so that the properties 1., 2., 3. and 4. are satisfied. Let G be a nonempty, bounded and convex subset of G such that (2) holds and $T:C \to cc(C)$ (the family of all nonempty closed and convex subsets of C) be an upper semicontinuous mapping such that:*

(5) $$b_n(T(A)) \le q\cdot b_n(A), \quad \textit{for every } n \in \mathbb{N} \textit{ and every } A \subseteq C$$

where $q \in (0,1)$. If $q\cdot C(C) < 1$ then there exists $x \in C$ so that $x \in Tx$.

Proof. By a standard way we can prove that there exists $Z \subseteq C$ such that $Z = \overline{\text{co}}(T(Z) \cup \{z\})$, where z is an arbitrary element from C. Then using (4) and (5) we obtain that:

$$b_n(Z) = b_n(\overline{\text{co}}(T(Z) \cup \{z\})) \le$$

$$\le C(G)b_n(T(Z)) \le q\cdot C(G)\, b_n(Z).$$

From this it follows that $b_n(Z) = 0$, for every $n \in \mathbb{N}$ which implies that Z is compact. Since Z is σ-admissible, which follows from (2), and $T(Z) \subseteq Z$ using Hahn's fixed point theorem it follows that there exists $x \in C$ such that $x \in Tx$.

Remark. It is easy to prove that Propositions 2. and 3. hold for every topological vector space $(E,\{p_\lambda\}_{\lambda\in\Lambda})$, where p_λ, for every $\lambda \in \Lambda$, has the properties 1., 2., 3. and 4.

Using the preceeding results we obtain the following fixed point theorem which is a generalization of Theorem 2 in [6].

Theorem. *Let (S,F,t) be a complete random paranormed space where t is a strict T-norm of H-type. G a probabilistic bounded, closed and convex subset of S, and $T:G\to cc(G)$ an upper semicontinuous mapping which is a (b,q)-set probabilistic contraction mapping. If G satisfies the probabilistic Zima condition and $qC(G) < 1$ then there exists $x \in G$ so that $x \in Tx$.*

Proof. The proof follows from Proposition 3. and Lemma 2.

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REZIME

TEOREMA O NEPOKRETNOJ TAČKI U JEDNOJ KLASI SLUČAJNIH PARANORMIRANIH PROSTORA

U ovom radu dokazana je jedna teorema o nepokretnoj tački u slučajnim paranormiranim prostorima.

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