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Original Article

Separation axioms on soft bitopological spaces

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Abstract

We introduce the notions of soft relative bitopology. We investigated some properties on the separation axioms in soft bitopological spaces, i.e. soft T_i-spaces for i=1, 2, 3, and 4. Also we have established results on soft regular spaces and soft normal spaces.

Keywords: soft set, soft topology, soft bitopology, soft separation axioms

1. Introduction

Mathematical problems become more challenging if uncertainty is involved. In order to find solutions for such types of problems, at different stages and under different situations, many new notions are introduced. One such notion was the introduction of "soft set" by the Russian mathematician Molodtsov (1999). He was trying to model problems on uncertainty in computer science, engineering physics, economics, social sciences, and medical sciences. The significance of the introduced notion was realized by many in the last two decades who have successfully applied "soft set" in different branches of science, where mathematics plays a role. Many researchers have contributed towards the algebraic structure of soft set theory. Maji, Biswas, and Roy (2003) studied the theory of soft sets. They discussed the basic soft set definition with examples. Shabir and Naz (2011) defined the theory of soft topological space over an initial universe with a fixed set of parameters. They defined soft topology on the collection τ of soft sets over *X*. Soft bitopological space has been studied by many mathematicians including Cagman, Karataş, and Enginoglu (2011), Chen (2013), Hazra, Majumdar, and Samanta (2012), Hida (2014), Hussain (2015), Hussain and Ahmad (2011), Payghan, Samadi, and Tayebi (2014), Renukadevi and Shanthi (2015), Roy and Samanta (2014), Senel and Cagman (2014), Sezgin and Atagun (2011), Tripathy and Acharjee (2017), and Varol, Shostak, and Aygun (2012).

Kelly (1963) first initiated the concept of bitopological space. He defined a bitopological space (X, τ_1, τ_2) to be a set *X* with two topologies τ_1 and τ_2 on *X* and initiated the systematic study of bitopological spaces. Bitopological

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spaces have been studied not exclusively by Acharjee and Tripathy (2018), Tripathy and Acharjee (2014, 2017), Tripathy and Debnath (2013), Tripathy and Sarma (2011), and Tripathy and Sarma (2012).

In this paper, we continue investigating the properties of soft bitopological space, soft open set, and soft closed set. We also define and discuss the properties of separation axiom, soft T_i-spaces for i=1, 2, 3, and 4, soft regular spaces, and soft normal spaces and established their several properties.

2. Preliminaries

Throughout this paper the associated symbol "~" represents that the set or operator under consideration is with respect to soft. In this section, we discuss some basic definitions and notions those are defined by various authors. We procure the following existing definitions and notations that will be used in this article.

Definition 2.1 A soft set F_A on the universe *X* is defined by the set of ordered pairs $F_A = \{(x, f_A(x)) : x \in E\}$, where $f_A : E \to P(X)$ such that $f_A(x) = \varnothing$, if $x \notin A$, here f_A is called approximate function of the soft set F_A. The value of $f_A(x)$ may be arbitrary, some of them may be empty, and others may be non-empty. The set of all soft sets over *X* is denoted by *S*(*X*).

Definition 2.2 Let $F_A \in S(X)$. If $f_A(x) = \varnothing$ for all $x \in E$, then F_A is called an empty set, denoted by F_ϕ. That is $f_A(x) = \varnothing$ means there is no element in *X* related to the parameter $x \in E$.

Definition 2.3 Let $F_A \in S(X)$. If $f_A(x) = X$ for all $x \in A$, then F_A is called an *A*- universal soft set, denoted by $F_{\tilde{A}}$. When *A* = *E*, then the *E*-universal soft set is called a universal soft set, denoted by $\tilde{X}$.

Definition 2.4 Let $F_A, F_B \in S(X)$. Then F_A is a soft subset of F_B denoted by $F_A \subseteq F_B$ if $f_A(x) \subseteq f_B(x)$ for all $x \in E$. Let F_A and F_B be soft equal denoted by $F_A = F_B$ if $f_A(x) = f_B(x)$ for all $x \in E$.

Definition 2.5 Let $F_A, F_B \in S(X)$. Then soft union of F_A and F_B, denoted by $F_A \tilde{\cup} F_B$, is defined by $F_{A \tilde{\cup} B} = F_C$, where $C = A \cup B$ and for all $e \in C$.

$$H(e) = \begin{cases} F(e) & if \quad e \in A \setminus B \\ G(e) & if \quad e \in B \setminus A \\ F(e) \cup G(e) & if \quad e \in A \cap B \end{cases}$$

Definition 2.6 Let $F_A \in S(X)$. The soft power set of F_A is defined by

$$\tilde{P}(F_A) = \{F_{A_i} \subseteq F_A : i \in I\}$$

and its cardinality is defined by $\left|\tilde{P}(F_A)\right| = 2^{\sum_{e \in E} |f_A(x)|}$, where $|f_A(x)|$ is cardinality of *A*(*x*).

Example 2.7 Let $X = \{x_1, x_2\}$, $E = \{e_1, e_2\}$ and $\tilde{X} = \{(e_1, \{x_1, x_2\}), (e_2, \{x_1, x_2\})\}$. Then the soft subsets over $\tilde{X}$ are the following

$$\begin{aligned}
&F_{E_1} = \{(e_1, \{x_1\})\}, && F_{E_9} = \{(e_1, \{x_1\}), (e_2, \{x_1, x_2\})\} \\
&F_{E_2} = \{(e_1, \{x_2\})\}, && F_{E_{10}} = \{(e_1, \{x_2\}), (e_2, \{x_1\})\}, \\
&F_{E_3} = \{(e_1, \{x_1, x_2\})\}, && F_{E_{11}} = \{(e_1, \{x_2\}), (e_2, \{x_2\})\}, \\
&F_{E_4} = \{(e_2, \{x_1\})\}, && F_{E_{12}} = \{(e_1, \{x_2\}), (e_2, \{x_1, x_2\})\}, \\
&F_{E_5} = \{(e_2, \{x_2\})\}, && F_{E_{13}} = \{(e_1, \{x_1, x_2\}), (e_2, \{x_1\})\}, \\
&F_{E_6} = \{(e_2, \{x_1, x_2\})\}, && F_{E_{14}} = \{(e_1, \{x_1, x_2\}), (e_2, \{x_2\})\}, \\
&F_{E_7} = \{(e_1, \{x_1\}), (e_2, \{x_1\})\}, && F_{E_{15}} = \tilde{X}, \\
&F_{E_8} = \{(e_1, \{x_1\}), (e_2, \{x_2\})\}, && F_{E_{11}} = F_\varnothing
\end{aligned}$$

Then we have $\left|\tilde{P}(F_E)\right| = 2^4 = 16$.

Definition 2.8 Let $\tilde{\tau}$ be the collection of soft sets over $\tilde{X}$, then $\tilde{\tau}$ is said to be a soft topology on X if it satisfies the following axioms.

1) $F_{\varnothing}, \tilde{X}$ belong to $\tilde{\tau}$.

2) the union of any member of soft sets in $\tilde{\tau}$ belongs to $\tilde{\tau}$.

3) the intersection of any two soft sets in $\tilde{\tau}$ belongs to $\tilde{\tau}$. The triplet $(\tilde{X}, \tilde{\tau}, E)$ is called soft topological space over *X*. The members of $\tilde{\tau}$ are said to be soft open set.

Example 2.9 Let us consider the soft subsets of $\tilde{X}$ given in Example 2.7. Then $\tilde{\tau}_1 = \{\tilde{X}, F_{\phi}, F_{E_4}, F_{E_{10}}\}$, $\tilde{\tau}_2 = \{\tilde{X}, F_{\phi}, F_{E_1}, F_{E_7}, F_{E_{13}}\}$, $\tilde{\tau}_3 = \{\tilde{P}(F_E)\}$ are soft topologies on $\tilde{X}$.

Definition 2.10 Let $\tilde{X}$ be a nonempty soft set on the universe *X*, and $\tilde{\tau}_1$ and $\tilde{\tau}_2$ are two different soft topologies on $\tilde{X}$. Then $(\tilde{X}, \tilde{\tau}_1, \tilde{\tau}_2)$ is called a soft bitopological space.

Definition 2.11 Let $\left(\tilde{X}, \tilde{\tau}_1, \tilde{\tau}_2\right)$ be a soft bitopological space and $F_A \tilde{\subseteq} \tilde{X}$. Then F_A is called $\tilde{\tau}_{1,2}$ - soft open if $F_A = F_B \tilde{\cup} F_C$, where $F_B \tilde{\in} \tilde{\tau}_1$ and $F_C \tilde{\in} \tilde{\tau}_2$. The complement of $\tilde{\tau}_{1,2}$ - soft open set is called $\tilde{\tau}_{1,2}$ - soft closed set.

Example 2.12 Let us consider the two classes of soft subsets $\tilde{X}$ of Example 2.7 $\tilde{\tau}_1 = \{\tilde{X}, F_{\varnothing}, F_{E_4}, F_{E_{10}}\}$, $\tilde{\tau}_2 = \{\tilde{X}, F_{\varnothing}, F_{E_1}, F_{E_7}, F_{E_{13}}\}$. Then $\tilde{\tau}_{1,2}$ - soft open set are $\{\tilde{X}, F_{\varnothing}, F_{E_1}, F_{E_4}, F_{E_7}, F_{E_{10}}, F_{E_{13}}\}$ and $\tilde{\tau}_{1,2}$ - soft closed sets are $\{\tilde{X}, F_{\varnothing}, F_{E_{12}}, F_{E_{14}}, F_{E_{11}}, F_{E_8}, F_{E_5}\}$.

3. Subspace and Soft Separation Axioms on Bitopological Spaces.

Definition 3.1 Let $\left(\tilde{X}, \tilde{\tau}_1, \tilde{\tau}_2\right)$ be a soft bitopological space and $\tilde{Y}$ be a non-empty soft subset of $\tilde{X}$, then

$\tau_{1Y} = \{\tilde{Y} \cap F_A : F_A \in \tilde{\tau}_1\}$ and $\tau_{2Y} = \{\tilde{Y} \cap F_B : F_B \in \tilde{\tau}_2\}$

are said to be the soft relative bitopology on $\tilde{Y}$ and $(\tilde{Y}, \tilde{\tau}_{1Y}, \tilde{\tau}_{2Y})$ is called a soft subspace of $\left(\tilde{X}, \tilde{\tau}_1, \tilde{\tau}_2\right)$. We can easily verify that τ_{1Y}, τ_{2Y} are in fact, a soft bitopology on *Y*.

Definition 3.2 Let $\left(\tilde{X}, \tilde{\tau}_1, \tilde{\tau}_2\right)$ be a soft bitopological space and $\tilde{Y}$ be a non-empty soft subset of $\tilde{X}$. Then $(\tilde{Y}, \tilde{\tau}_{1Y}, \tilde{\tau}_{2Y})$ is called a soft subspace of $\left(\tilde{X}, \tilde{\tau}_1, \tilde{\tau}_2\right)$. Further F_A is called $\tilde{\tau}_{Y1,2}$ - soft open set, if $F_A = F_B \tilde{\cup} F_C$, where $F_B \tilde{\in} \tilde{\tau}_{Y1}$ and $F_C \tilde{\in} \tilde{\tau}_{Y2}$.

Definition 3.3 Let $\left(\tilde{X}, \tilde{\tau}_1, \tilde{\tau}_2\right)$ be a soft bitopological space and $x, y \in X$ such that $x \neq y$. If there exist two $\tilde{\tau}_{1,2}$ - soft open sets F_A and F_B such that

$x \in F_A$ and $y \notin F_A$ or

$y \in F_B$ and $x \notin F_B$.

Then $\left(\tilde{X}, \tilde{\tau}_1, \tilde{\tau}_2\right)$ is called a $\tilde{\tau}_{1,2}$ soft T_0 - space.

Definition 3.4 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space and $x,y\in X$ such that $x\neq y$. If there exist two $\tilde{\tau}_{1,2}$ - soft open sets F_A and F_B such that $x\in F_A$ and $y\notin F_A$ with $y\in F_B$ and $x\notin F_B$, then $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is called a $\tilde{\tau}_{1,2}$ soft T_1-space.

Proposition 3.5 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space and $\tilde{Y}$ be a non-empty soft subset of $\tilde{X}$. If $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is a $\tilde{\tau}_{1,2}$ soft T_0 - space, then $(\tilde{Y},\tilde{\tau}_{1Y},\tilde{\tau}_{2Y})$ is a $\tilde{\tau}_{1,2}$ soft T_0 - space.

Proof. Suppose $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is a $\tilde{\tau}_{1,2}$ soft T_0 - space.

Let $x,y\in Y$ such that $x\neq y$. Then there exists two $\tilde{\tau}_{1,2}$ soft open sets F_A and F_B such that $x\in F_A$ and $y\notin F_A$ or $y\in F_B$ and $x\notin F_B$.

Now, if $x\in Y$ implies $x\in\tilde{Y}$. So $x\in\tilde{Y}$ and $x\in F_A$. Hence $x\in\tilde{Y}\cap F_A$, where F_A is $\tilde{\tau}_{1,2}$-soft open set. Consider $y\notin F_A$ this means that $y\notin F(\alpha)$ for some $\alpha\in E$. Then $y\notin Y\cap F(\alpha)=Y(\alpha)\cap F(\alpha)$. Therefore, $y\notin\tilde{Y}\cap F_A$.
Similarly it can be established, if $y\in F_B$ and $x\notin F_B$ then $y\in\tilde{Y}\cap F_B$ and $x\notin\tilde{Y}\cap F_B$.

Thus $(\tilde{Y},\tilde{\tau}_{1Y},\tilde{\tau}_{2Y})$ is a $\tilde{\tau}_{1,2}$ -soft T_0 - space.
In view of the proof of proposition 3.5, we formulate the following statement without proof.

Proposition 3.6 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space and $\tilde{Y}$ be a non empty soft subset of $\tilde{X}$. If $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is a $\tilde{\tau}_{1,2}$ soft T_1 - space then $(\tilde{Y},\tilde{\tau}_{1Y},\tilde{\tau}_{2Y})$ is a $\tilde{\tau}_{1,2}$ soft T_1 - space.

Definition 3.7 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space and $x,y\in X$ such that $x\neq y$. If there exist two $\tilde{\tau}_{1,2}$ - soft open sets F_A and F_B such that $x\in F_A$ and $y\in F_B$ and $F_A\tilde{\cap}F_B=\varnothing$, then $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is called a $\tilde{\tau}_{1,2}$ soft T_2 - space.

Remark 3.8 It can be easily verified that,

1) Every $\tilde{\tau}_{1,2}$ soft T_1 - space is a $\tilde{\tau}_{1,2}$ soft T_0 - space.
2) Every $\tilde{\tau}_{1,2}$ soft T_2 - space is a $\tilde{\tau}_{1,2}$ soft T_1 - space.

Proof. Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space and $x,y\in X$ such that $x\neq y$

1) If $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is a $\tilde{\tau}_{1,2}$ soft T_1 - space, then there exists two $\tilde{\tau}_{1,2}$ -soft open sets F_A and F_B such that $x\in F_A$ and $y\notin F_A$ and $y\in F_B$ and $x\notin F_B$. Obviously then we have $x\in F_A$ and $y\notin F_A$ or $y\in F_B$ and $x\notin F_B$. Thus $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is a $\tilde{\tau}_{1,2}$ soft T_0 - space.

2) If $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is a $\tilde{\tau}_{1,2}$ soft T_2 - space, then there exists two $\tilde{\tau}_{1,2}$ - soft open sets F_A and F_B such that, $x\in F_A$, two $\tilde{\tau}_{1,2}$ - soft open sets F_A and F_B such that, $x\in F_A$, $y\in F_B$ and $F_A\tilde{\cap}F_B=\varnothing$.

Since, $F_A\tilde{\cap}F_B=\varnothing$, so $x\notin F_B$ and $y\notin F_A$. Thus $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is a $\tilde{\tau}_{1,2}$ soft T_1 - space.

Proposition 3.9 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space and $\tilde{Y}$ be a non-empty soft subset of $\tilde{X}$. If $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is a $\tilde{\tau}_{1,2}$ soft T_2- space, then $(\tilde{Y},\tilde{\tau}_{1Y},\tilde{\tau}_{2Y})$ is a $\tilde{\tau}_{1,2}$ soft T_2- space.

Proof. $x, y \in Y$ such that $x \neq y$. Then there exists two $\tilde{\tau}_{1,2}$ - soft open sets F_A and F_B such that $x \in F_A$, $y \in F_B$, and $F_A \tilde{\cap} F_B = \varnothing$.

So, for each $\alpha \in E,\ x \in F_A(\alpha),\ y \in F_B(\alpha)$, and $F_A(\alpha) \cap F_B(\alpha) = \varnothing$.

This implies $x \in Y \cap F_A(\alpha),\ y \in Y \cap F_B(\alpha)$, and $F_A(\alpha) \cap F_B(\alpha) \neq \varnothing$.

Hence $x \in \tilde{Y} \cap F_A$, $y \in \tilde{Y} \cap F_B$, and $(\tilde{Y} \cap F_A) \cap (\tilde{Y} \cap F_B) \neq \varnothing$, where $(\tilde{Y} \cap F_A)$ and $(\tilde{Y} \cap F_B)$ are $\tilde{\tau}_{Y1,2}$ - soft open sets. Thus $(\tilde{Y},\tilde{\tau}_{1Y},\tilde{\tau}_{2Y})$ is a $\tilde{\tau}_{1,2}$ soft T_2 - space.

Definition 3.10 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space, G_A be a $\tilde{\tau}_{1,2}$ - soft closed set and $x \in X$ such that $x \in G_A$. If there exist two $\tilde{\tau}_{1,2}$ - soft open sets F_B and F_C such that $x \in F_B$, $G_A \subset F_C$, and $F_B \tilde{\cap} F_C = \varnothing$, then $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is called a $\tilde{\tau}_{1,2}$ soft regular space.

Definition 3.11 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space. Then $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is said to be a $\tilde{\tau}_{1,2}$ soft T_3- space, if it is $\tilde{\tau}_{1,2}$ soft regular space and $\tilde{\tau}_{1,2}$ soft T_1- space.

Definition 3.12 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space, G_A and G_B be two $\tilde{\tau}_{1,2}$-soft closed sets such that $G_A \tilde{\cap} G_B = \varnothing$. If there exist two $\tilde{\tau}_{1,2}$-soft open sets F_C and F_D such that $G_A \tilde{\subset} F_C$, $G_B \tilde{\subset} F_D$ and $F_C \tilde{\cap} F_D = \varnothing$. then $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is called a $\tilde{\tau}_{1,2}$ soft normal space.

Definition 3.13 Let $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ be a soft bitopological space. Then $\left(\tilde{X},\tilde{\tau}_1,\tilde{\tau}_2\right)$ is said to be a $\tilde{\tau}_{1,2}$ soft T_4-space, if it is $\tilde{\tau}_{1,2}$ soft normal space and $\tilde{\tau}_{1,2}$ soft T_1-space.

Remark 3.14 It can be easily verified that

1) every $\tilde{\tau}_{1,2}$ soft T_3-space need not be a $\tilde{\tau}_{1,2}$ soft T_2-space.

2) every $\tilde{\tau}_{1,2}$ soft T_4-space need not be a $\tilde{\tau}_{1,2}$ soft T_3-space.

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