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ON *WC*-CONTINUOUS FUNCTIONS (*)

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1. Introduction

In 1970, Gentry and Hoyle [5] defined a function $f: X \to Y$ to be C-continuous if for each $x \in X$ and each open set V containing $f(x)$ and having the compact complement, there exists an open set U containing x such that $f(U) \subset V$. These functions have been investigated by Long and Hendrix [6] and Long and Herrington [8]. In 1980, Long and Hamlett [7] called a function H-continuous by replacing "*compact*" in the definition of C-continuous functions with "*H-closed*" (quasi H-closed relative to Y [10]). The investigation of H-continuous functions has been continued by the second author [9] of the present paper.

Recently, Lo Faro and the first author [1, 2] have introduced and investigated a new weak form of compactness in topological spaces, called weakly compact spaces. In this paper, we introduce and characterize sets called weakly compact relative to a topological space. Then we define a new class of functions called WC-continuous functions analogous to H-continuous functions and C-continuous functions. It will be shown that WC-continuity implies H-continuity and they are equivalent if the range of the function is almost-regular [11].

2. Definitions

Throughout this paper X and Y represent topological spaces on which no separation axioms are assumed unless explicitly stated. Let S be a subset of a space X. The closure and the interior of S in X are deno-

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ted by $\mathrm{Cl}_X(S)$ and $\mathrm{Int}_X(S)$ (or simply $\mathrm{Cl}(S)$ and $\mathrm{Int}(S)$), respectively. A subset S is said to be ***regular open*** (resp. ***regular closed***) if $\mathrm{Int}(\mathrm{Cl}(S))=S$ (resp. $\mathrm{Cl}(\mathrm{Int}(S))=S$). For definitions and notations used in this paper, readers can find them in [2] except for the following.

DEFINITION 2.1. An open cover $\{V_\alpha \mid \alpha \in \nabla\}$ of a space X is said to be ***regular*** [2] if for each $\alpha \in \nabla$ there exists a nonempty regular closed set F_α in X such that $F_\alpha \subset V_\alpha$ and $X=\cup\{\mathrm{Int}(F_\alpha) \mid \alpha \in \nabla\}$.

DEFINITION 2.2. A space X is said to be ***weakly compact*** [2] (resp. *quasi H-closed* [10]) if every regular (resp. open) cover of X has a finite subfamily whose closure is a cover of X.

In [12], Singal and Singal called quasi H-closed spaces *almost compact*. A quasi H-closed Hausdorff space is usually called *H-closed*. Urysohn-closed spaces are characterized by weakly compact Urysohn spaces [3]. It has been shown in [2] that almost compactness is strictly stronger than weak compactness.

DEFINITION 2.3. A space X is said to be ***almost-regular*** [11] if for each regular closed set F of X and each point $x \in X-F$, there exist disjoint open sets U and V such that $F \subset U$ and $x \in V$.

DEFINITION 2.4. A subset K of a space X is said to be ***weakly compact relative to*** X if for each cover $\{V_\alpha \mid \alpha \in \nabla\}$ of K by open sets of X satisfying the following property (P), there exists a finite subset ∇_0 of ∇ such that $K \subset \cup\{\mathrm{Cl}_X(V_\alpha) \mid \alpha \in \nabla_0\}$.

(P) For each $\alpha \in \nabla$, V_α contains a nonempty regular closed set F_α of X and $K \subset \cup\{\mathrm{Int}_X(F_\alpha) \mid \alpha \in \nabla\}$.

DEFINITION 2.5. Let $\mathcal{F}$ be a filter on a space X. A point $x \in X$ is called a *γ-adherence point* of $\mathcal{F}$ [2] if $\mathcal{F} \wedge \mathcal{U}(\bar{\mathcal{U}}_X) \neq O$.

DEFINITION 2.6. Let A be a subset of a space X. A point $x \in X$ is called a *γ-adherence point of* A if $A \cap V \neq \phi$ for every $V \in \mathcal{U}(\bar{\mathcal{U}}_X)$. The set of all γ-adherence points of A is called the *γ-closure* of A. If A contains the γ-closure of A, then it is called *γ-closed*.

3. Sets weakly compact relative to a space

DEFINITION 3.1. A filter $\mathcal{F}$ on a space X is said to be ***quasi-regular*** [2] if there exists an open filter $\mathcal{G}$ on X such that $\mathcal{F}=\mathcal{U}(\bar{\mathcal{G}})$.

REMARK 3.2. It is obvious that for any subset A of a space X $\mathrm{tr}_A\mathcal{F} \neq 0$ if $\mathrm{tr}_A\mathcal{G}\neq 0$, where $\mathrm{tr}_A\mathcal{F}$ denotes the trace of $\mathcal{F}$ on A. However, the converse is not true in general as the following example shows.

EXAMPLE 3.3. Let $X=\{x, y, z, t\}$, $\tau=\{\phi, X, \{x\}, \{z\}, \{z, t\}, \{x, z\}, \{x, y, z\}, \{x, z, t\}\}$ and $A=\{z, t\}$. Let $\mathcal{G}=\ulcorner\overline{\{x\}}\urcorner$. Then the filter $\mathcal{F}=\mathcal{U}(\overline{\mathcal{G}}) = \{\{x, y, z\}, X\}$ is quasi-regular [2, Controesempio 4]. Moreover, $\mathrm{tr}_A\mathcal{F} = \{\{z\}, A\} \neq 0$ but $\mathrm{tr}_A\mathcal{G}=0$ because $\ulcorner\overline{\{x\}}\urcorner \cap \{z, t\}=\phi$.

THEOREM 3.4. *For a subset A of a space X, the following are equivalent:*

(1) *A is weakly compact relative to X.*

(2) *Every open filter $\mathcal{G}$ with $tr_A\mathcal{G}\neq 0$ has a γ-adherence point in A.*

(3) *Every filter $\overline{\mathcal{G}}$ such that $\mathcal{G}$ is an open filter and $tr_A\mathcal{G}\neq 0$ has an r-adherence point in A.*

(4) *Every quasi-regular filter $\mathcal{F}=\mathcal{U}(\overline{\mathcal{G}})$ such that $tr_A\mathcal{G}\neq 0$ has an adherence (δ-adherence or r-adherence) point in A.*

(5) *Every filter $\overline{\mathcal{F}}$ such that $\mathcal{F}$ is a quasi-regular filter $\mathcal{F}=\mathcal{U}(\overline{\mathcal{G}})$ with $tr_A\mathcal{G}\neq 0$ has an adherence (δ-adherence) point in A.*

(6) *Every filter $\overline{\overline{\mathcal{F}}}$ such that $\mathcal{F}$ is a quasi-regular filter $\mathcal{F}=\mathcal{U}(\overline{\mathcal{G}})$ with $tr_A\mathcal{G}\neq 0$ has an adherence (δ-adherence or r-adherence) point in A.*

(7) *Every open ultra filter $\mathcal{G}$ with $tr_A\mathcal{G}\neq 0$ r-converges.*

(8) *Let $\{C_\alpha \mid \alpha\in\nabla\}$ be a family of closed sets of X such that for each $\alpha\in\nabla$ there exists an open set A_α of X satisfying $C_\alpha\subset A_\alpha$ and $\cap\{Cl(A_\alpha) \mid \alpha\in\nabla\}\subset X-A$. Then there exists a finite subset ∇_0 of ∇ such that $\cap\{Int(C_\alpha) \mid \alpha\in\nabla_0\}\subset X-A$.*

Proof. (1)$\Rightarrow$(2): Let $\mathcal{G}$ be an open filter on X with $\mathrm{tr}_A\mathcal{G}\neq 0$. We suppose that $\mathcal{G}\wedge\mathcal{U}(\overline{\mathcal{U}}_x)=0$ for every $x\in A$. Then, there exist open sets $G_x\in\mathcal{G}$, $U_x\in\mathcal{U}_x$ and $A_x\in\mathcal{U}(\overline{\mathcal{U}}_x)$ such that $G_x\cap A_x=\phi$ and $U_x\subset \mathrm{Cl}(U_x) \subset A_x$. By $G_x\cap A_x=\phi$, we obtain $\mathrm{Cl}(G_x)\cap A_x=\phi$ and hence $\mathrm{Cl}(G_x)\cap \mathrm{Cl}(U_x)=\phi$. Let us put $B_x=X-\mathrm{Cl}(G_x)$, then $\mathrm{Cl}(U_x)\subset B_x$ and $B_x\in\mathcal{U}(\overline{\mathcal{U}}_x)$. The family $\{B_x \mid x\in A\}$ is a cover of A by open sets of X and $A\subset \cup\{\mathrm{Int}(\mathrm{Cl}(U_x)) \mid x\in A\}$. Therefore, there exists a finite number of points $x_1, x_2, \cdots, x_n$ in A such that $A\subset\cup\{\mathrm{Cl}(B_{x_i}) \mid i=1, 2, \cdots, n\}$. Therefore, we have

$$(*) \qquad \cap\{X-\mathrm{Cl}(B_{x_i}) \mid i=1, 2, \cdots, n\}\subset X-A.$$

For each $i=1, 2, \cdots, n$, $G_{x_i}\subset\mathrm{Int}(\mathrm{Cl}(G_{x_i}))$, hence we have

$$X-\mathrm{Cl}(B_{x_i})=\mathrm{Int}(X-B_{x_i})=\mathrm{Int}(\mathrm{Cl}(G_{x_i}))\in\mathcal{G}.$$

Therefore, by (*) we obtain $X-A\in\mathcal{G}$. This is a contradiction.

(2)$\Rightarrow$(3)$\Rightarrow$(4)$\Rightarrow$(5)$\Rightarrow$(6)$\Rightarrow$(4)$\Rightarrow$(7)$\Rightarrow$(1) : These implications are proved similarly to the proof of [2, Lemma 2.1].

(4)$\Rightarrow$(8) : Let $\Gamma(\nabla)$ be the family of all finite subsets of ∇. We suppose that

$$\cap\{\mathrm{Int}(C_\alpha)\mid\alpha\in\Delta\}\not\subset X-A \text{ for every } \Delta\in\Gamma(\nabla).$$

Then, $\mathcal{F}=\{\bigcap_{\alpha\in\Delta}\mathrm{Int}(C_\alpha)\mid\Delta\in\Gamma(\nabla)\}$ is an open filter base with $\mathrm{tr}_A\mathcal{F}\neq O$. Thus, $\mathcal{U}(\bar{\mathcal{F}})$ is a quasi-regular filter on X such that $\mathrm{tr}_A\mathcal{F}\neq O$. By (4), there exists a point $x\in A$ such that $\mathcal{U}(\bar{\mathcal{F}})\wedge\mathcal{U}_x\neq O$. Put

$$\mathcal{L}=\{\bigcap_{\alpha\in\Delta}A_\alpha\mid\Delta\in\Gamma(\nabla)\},$$

then it is an open filter base such that $\mathcal{U}(\bar{\mathcal{F}})\subset\mathcal{L}$. Therefore, $\mathcal{L}\wedge\mathcal{U}_x\neq O$ and hence $x\in\mathrm{Cl}(A_\alpha)$ for every $\alpha\in\nabla$. Thus, we obtain $x\in\cap\{\mathrm{Cl}(A_\alpha)\mid\alpha\in\nabla\}$. This is a contradiction because $\cap\{\mathrm{Cl}(A_\alpha)\mid\alpha\in\nabla\}\subset X-A$.

(8)$\Rightarrow$(1) : Let $\{A_\alpha\mid\alpha\in\nabla\}$ be an open cover of A with Property (P). For each $\alpha\in\nabla$, there exists a nonempty regular closed set C_α such that $C_\alpha\subset A_\alpha$ and $A\subset\cup\{\mathrm{Int}(C_\alpha)\mid\alpha\in\nabla\}$. We consider the family $\{X-A_\alpha\mid\alpha\in\nabla\}$ of closed sets. For each $\alpha\in\nabla$, $X-C_\alpha$ is open in X, $X-C_\alpha\subset X-A_\alpha$ and

$$\cap\{\mathrm{Cl}(X-C_\alpha)\mid\alpha\in\nabla\}=X-\cup\{\mathrm{Int}(C_\alpha)\mid\alpha\in\nabla\}\subset X-A.$$

By (8), there exists a finite subset ∇_0 of ∇ such that

$$\cap\{\mathrm{Int}(X-A_\alpha)\mid\alpha\in\nabla_0\}\subset X-A.$$

Therefore, we obtain $A\subset\cup\{\mathrm{Cl}(A_\alpha)\mid\alpha\in\nabla_0\}$. This shows that A is weakly compact relative to X.

4. *WC*-continuous functions

DEFINITION 4.1. A function $f: X\to Y$ is said to be *WC-continuous* if for each $x\in X$ and each open neighborhood V of $f(x)$ having the complement weakly compact relative to Y, there exists an open neighborhood U of x such that $f(U)\subset V$.

THEOREM 4.2. *For a function $f: X\to Y$ the following are equivalent:*

(1) *f is WC-continuous.*

(2) *If V is open in Y and $Y-V$ is weakly compact relative to Y, then $f^{-1}(V)$ is open in X.*

(3) *If F is closed in Y and weakly compact relative to Y, then $f^{-1}(F)$ is closed in X.*

Proof. (1)$\Rightarrow$(2) : Let V be an open set of Y such that $Y-V$ is weakly compact relative to Y. Let $x\in f^{-1}(V)$. Then $f(x)\in V$ and there exists an open neighborhood U of x such that $f(U)\subset V$. Therefore, we have $x\in U\subset f^{-1}(V)$. This shows that $f^{-1}(V)$ is open in X.

(2)$\Longleftrightarrow$(3) : This is obvious.

(3)$\Longrightarrow$(1) : Let $x\in X$ and V an open neighborhood of $f(x)$ such that $Y-V$ is weakly compact relative to Y. By (3), $f^{-1}(Y-V)$ is closed in X and hence $U=f^{-1}(V)$ is an open set containing x such that $f(U)\subset V$.

LEMMA 4.3. *If A_1 and A_2 are weakly compact relative to a space X, then $A_1\cup A_2$ is weakly compact relative to X.*

Proof. Let $\mathcal{V}=\{V_\alpha|\alpha\in\nabla\}$ be a cover of $A_1\cup A_2$ by open sets of X satisfying Property (P). Then $\mathcal{V}$ is a cover of A_1, A_2 satisfying (P) and hence for each $i=1,2$ there exists a finite subset ∇_i of ∇ such that $A_i\subset\cup\{\mathrm{Cl}(V_\alpha)\,|\alpha\in\nabla_i\}$. Therefore, we have

$$A_1\cup A_2\subset\cup\{\mathrm{Cl}(V_\alpha)\,|\alpha\in\nabla_1\cup\nabla_2\}.$$

This shows that $A_1\cup A_2$ is weakly compact relative to X.

Let (X,τ) be a topological space. It follows from Lemma 4.3 that the family of open sets having the complement weakly compact relative to (X,τ) may be used as a base for a topology τ_{WC}. It has been shown that the family of open sets having the compact (resp. quasi H-closed) complement may be used as a base to generate a topology τ_C (resp. τ_H) on X [5, 7].

REMARK 4.4. For a topological space (X,τ), we have $\tau_C\subset\tau_H\subset\tau_{WC}\subset\tau$.

THEOREM 4.5. *A function $f: X\rightarrow(Y,\sigma)$ is WC-continuous if and only if $f: X\rightarrow(Y,\sigma_{WC})$ is continuous.*

Proof. This is obvious from the definition of σ_{WC}.

REMARK 4.6. It is obvious that continuity implies WC-continuity and WC-continuity implies H-continuity. The following example shows that WC-continuity does not necessarily imply continuity.

EXAMPLE 4.7. Let X be the set of real numbers with the usual topology and $f: X\rightarrow X$ a function defined as follows: $f(x)=1/x$ if $x\neq 0$; $f(0)=1/2$. Then f is C-continuous [5, Example 2] and by Theorem

4. 17 (below) f is WC-continuous. However, f is not continuous.

For a function $f: X \to Y$, the set $\{(x, f(x)) \mid x \in X\}$ is called the *graph* of f and denoted by $G(f)$.

THEOREM 4. 8. *If $f: X \to Y$ is an open function and $G(f)$ is γ-closed in the product space $X \times Y$, then f is WC-continuous.*

Proof. We suppose that f is not WC-continuous at some point $x \in X$. Then there exists an open set V containing $f(x)$ and having the complement weakly compact relative to Y such that $f(U) \cap (Y - V) \neq \phi$ for every open set U containing x. Since f is open,

$$\mathcal{Q} = \{f(U) \mid x \in U \text{ and } U \text{ is open in } X\}$$

is an open filter base with $\mathrm{tr}_{Y-V}\mathcal{Q} \neq O$. Since $Y - V$ is weakly compact relative to Y, by (2) of Theorem 3. 4 $\mathcal{Q}$ has a γ-adherence point $y \in Y - V$. Therefore, $y \neq f(x)$ and (x, y) is a γ-adherence point of $G(f)$. However, we have $(x, y) \notin G(f)$. This is a contradiction.

The following three theorems are immediate consequences of Theorem 4. 5 and the proofs are omitted.

THEOREM 4. 9. *If $f: X \to Y$ is WC-continuous and A is a subset of X, then the restriction $f|A: A \to Y$ is WC-continuous.*

THEOREM 4. 10. *If $f: X \to Y$ continuous and $g: Y \to Z$ is WC-continuous then the composition $g \circ f: X \to Z$ is WC-continuous.*

THEOREM 4. 11. *Let X be a space and let $\{A_\alpha \mid \alpha \in \nabla\}$ be a cover of X such that*

(a) each $\alpha \in \nabla$, A_α is open in X or

(b) each $\alpha \in \nabla$, A_α is closed in X and the family $\{A_\alpha \mid \alpha \in \nabla\}$ forms a neighborhood finite family.

If $f: X \to Y$ is a function such that $f|A_\alpha: A_\alpha \to Y$ is WC-continuous for each $\alpha \in \nabla$, then f is WC-continuous.

THEOREM 4. 12. *If X is Urysohn and A is weakly compact relative to X, then A is closed.*

Proof. Let x_0 be a point of $X - A$. For each $x \in A$, there exist open sets U_x and V_x containing x_0 and x, respectively, such that $\mathrm{Cl}(U_x) \cap \mathrm{Cl}(V_x) = \phi$. For each $x \in A$, we have
$x \in \mathrm{Int}(\mathrm{Cl}(V_x)) \subset \mathrm{Cl}(V_x) \subset X - \mathrm{Cl}(U_x)$ and $A \subset \cup \{\mathrm{Int}(\mathrm{Cl}(V_x)) \mid x \in A\}$.

Therefore, the family $\{X\text{-}\mathrm{Cl}(U_x) \mid x \in A\}$ is a cover of A by open sets of X satisfying Property (P). Since A is weakly compact relative to X, there exist a finite number of points $x_1, x_2, \cdots, x_n$ in A such that

$$A \subset \bigcup_{i=1}^{n} \mathrm{Cl}(X - \mathrm{Cl}(U_{x_i})) = X - \bigcap_{i=1}^{n} \mathrm{Int}(\mathrm{Cl}(U_{x_i})).$$

Thus, we obtain $A \cap [\cap \{\mathrm{Int}(\mathrm{Cl}(U_{x_i})) \mid i=1, 2, \cdots, n\}] = \phi$, where $\cap \{\mathrm{Int}(\mathrm{Cl}(U_{x_i})) \mid i=1, 2, \cdots, n\}$ is a regular open set containing x_0. This shows that A is closed.

REMARK 4.13. The proof of Theorem 4.12 shows that A is a δ-closed set due to Veličko [13].

THEOREM 4.14. *Let Y be a Urysohn space. Then, a function $f: X \to Y$ is WC-continuous if and only if $f^{-1}(K)$ is closed in X for each set K of Y weakly compact relative to Y.*

Proof. This is an immediate consequence of Theorems 4.2 and 4.12.

A subset S of a space X is said to be *N-closed relative to X* [4] if every cover of S by regular open sets of X has a finite subcover.

THEOREM 4.15. *Let X be an almost-regular space and A a subset of X. If A is weakly compact relative to X, then it is N-closed relative to X.*

Proof. Let $\{V_\alpha \mid \alpha \in \nabla\}$ be a cover of A by regular open sets of X. For each $x \in A$, there exists an $\alpha(x) \in \nabla$ such that $x \in V_{\alpha(x)}$. Since X is almost-regular, there exist regular open sets $G_{\alpha(x)}$ and $W_{\alpha(x)}$ such that

$$x \in G_{\alpha(x)} \subset \mathrm{Cl}(G_{\alpha(x)}) \subset W_{\alpha(x)} \subset \mathrm{Cl}(W_{\alpha(x)}) \subset V_{\alpha(x)}.$$

The family $\{W_{\alpha(x)} \mid x \in A\}$ is a cover of A by open sets of X satisfying Property (P). There exists a finite subset A_0 of A such that

$$A \subset \cup \{\mathrm{Cl}(W_{\alpha(x)}) \mid x \in A_0\}.$$

Therefore, we have $A \subset \cup \{V_{\alpha(x)} \mid x \in A_0\}$. This shows that A is N-closed relative to X.

THEOREM 4.16. *Let Y be an almost-regular space. Then, a function $f: X \to Y$ is WC-continuous if and only if f is H-continuous.*

Proof. This is an immediate consequence of Theorem 4.15 and the fact that N-closed relative to Y implies quasi H-closed relative to Y.

THEOERM 4.17. *Let Y be a regular space. Then, for a function*

$f: X \to Y$ the following are equivalent:

(*a*) *WC-continuous.*

(*b*) *H-continuous.*

(*c*) *C-continuous.*

Proof. Since Y is regular, Y is almost-regular and hence by Theorem 4.15 every set weakly compact relative to Y is N-closed relative to Y. Moreover, every subset of a regular space is compact if it is N-closed relative to X [4, Theorem 4.1].

THEOREM 4.18. *Let Y be a compact space. Then, for a function $f: X \to Y$ the following are equivalent*:

(*a*) *continuous.*

(*b*) *WC-continuous.*

(*c*) *H-continuous.*

(*d*) *C-continuous.*

Proof. By Remark 4.6, it is only necessary to show that (d) implies (a). Let F be a closed set of Y. Since Y is compact, F is compact and hence $f^{-1}(F)$ is closed in X [5, Theorem 1]. Therefore, f is continuous.

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