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Research Article

On the Strong Convergence of an Algorithm about Firmly Pseudo-Demicontractive Mappings for the Split Common Fixed-Point Problem

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Based on the recent work by Censor and Segal (2009 J. Convex Anal.16), and inspired by Moudafi (2010 Inverse Problems 26), we modify the algorithm of demicontractive operators proposed by Moudafi and study the modified algorithm for the class of firmly pseudodemicontractive operators to solve the split common fixed-point problem in a Hilbert space. We also give the strong convergence theorem under some appropriate conditions. Our work improves and/or develops the work of Moudafi, Censor and Segal, and other results.

1. Introduction

Throughout, let H_1 and H_2 be real Hilbert spaces, and let $A : H_1 \to H_2$ be a bounded linear operator. The split feasibility problem (SFP) [1–4] is to find a point

$$x \in C \text{ such that } Ax \in Q, \tag{1.1}$$

where C is a closed convex subset of a Hilbert space H_1 and Q is a closed convex subset of a Hilbert space H_2. If the two closed convex subsets C and Q are fixed point sets of U and T, respectively, where $U : H_1 \to H_1$ and $T : H_2 \to H_2$ are nonlinear operators, we obtain the two-set split common fixed-point problem (SCFP).

The split common fixed-point problem [5–8] requires to find a common fixed point of a family of operators in one space such that its image under a linear transformation is a common fixed point of another family of operators in the image space. This generalizes the split feasibility problem (SFP) and the convex feasibility problem (CFP).

In 2008, Censor and Segal proposed the split common fixed-point problem (SCFP) in [5] for directed operators in finite-dimensional Hilbert spaces. They invented an algorithm for the two-set SCFP which generated a sequence $\{x_n\}$ according to the iterative procedure

$$x_{k+1} = U\left(x_k + \gamma A^*(T - I)Ax_k\right), \quad k \in N, \tag{1.2}$$

where $\gamma \in (0, 2/\lambda)$ with λ being the spectral radius of the operator A^*A. Let $x_0 \in R^n$ be arbitrary.

They proved the convergence of the algorithm in finite-dimension spaces. Inspired by the work of Censor and Segal, Moudafi [6] introduced the following algorithm for μ-demicontractive operators in Hilbert spaces:

$$u_k = x_k + \gamma A^*(T - I)Ax_k, \tag{1.3}$$

and let

$$x_{k+1} = (1 - t_k)u_k + t_k U(u_k), \quad k \in N, \tag{1.4}$$

where $\gamma \in (0, (1 - \mu)/\lambda)$ with λ being the spectral radius of the operator A^*A, $t_k \in (0, 1)$. Let $x_0 \in H_1$ be arbitrary. Using *Féjer*-monotone and the demiclosed properties of $U - I$ and $T - I$ at the origin, Moudafi proved the convergence theorem. Based on the work of Censor, Segal, and Moudafi, Sheng and Chen gave their results of pseudo-demicontractive operators for the split common fixed-point problem recently.

Furthermore, we modify the algorithm (1.4) proposed by Moudafi and extend the operators to the class of firmly pseudo-demicontractive operators [9] in this paper. The firmly pseudo-demicontractive operators are more general class, which properly includes the class of demicontractive operators, pseudo-demicontractive operators, and quasi-nonexpansive mappings and is more desirable, for example, in fixed-point methods in image recovery where, in many cases, it is possible to map the set of images possessing a certain property to the fixed-point set of a nonlinear quasi-nonexpansive operator. Also for the hybrid steepest descent method, see [10], which is an algorithmic solution to the variational inequality problem over the fixed-point set of certain quasi-nonexpansive mappings and applicable to a broad range of convexly constrained nonlinear inverse problems in real Hilbert spaces. Our work is related to significant real-world applications, see, for instance, [2–4, 11], where such methods were applied to the inverse problem of intensity-modulated radiation therapy (IMRT) and to the dynamic emission tomographic image reconstruction. Based on the very recent work in this field, we give an extension of their unified framework to firmly pseudo-demicontractive operators and obtain convergence results of a modified algorithm in the context of general Hilbert spaces.

Our paper is organized as follows. Section 2 reviews some preliminaries. Section 3 gives a modified algorithm and shows its strong convergence under some appropriate conditions. Section 4 gives some conclusions briefly.

2. Preliminaries

To begin with, let us recall that the split common fixed point problem [5] proposed by Censor and Segal in finite spaces.

Given operators $U_i : R^n \to R^n$, $i = 1,2,\ldots,p$, and $T_j : R^m \to R^m$, $j = 1,2,\ldots,r$, with nonempty fixed points sets C_i, $i = 1,2,\ldots,p$ and Q_j, $j = 1,2,\ldots,r$, respectively. The split common fixed point problem (SCFP) is to find a vector

$$x^* \in C := \bigcap_{i=1}^{p} C_i \text{ such that } Ax^* \in Q := \bigcap_{j=1}^{r} Q_j \ . \tag{2.1}$$

In the sequel, we concentrate on the study of the two-set split common fixed-point problem, which is to find that

$$x^* \in C \text{ such that } Ax^* \in Q, \tag{2.2}$$

where H_1 and H_2 are two Hilbert spaces, C and Q are two nonempty closed convex subsets, $A : H_1 \to H_2$ is a bounded linear operator, $U : H_1 \to H_1, T : H_2 \to H_2$ are two firmly pseudo-demicontractive operators with $\mathrm{Fix}(U) = C$ and $\mathrm{Fix}(T) = Q$. α, β, and μ, θ are coefficients of U, T, respectively.

Definition 2.1. We say that T is demicontractive [6] means that there exists constant $\beta < 1$ such that

$$\|Tx - q\|^2 \leq \|x - q\|^2 + \beta\|x - Tx\|^2, \quad \forall (x,q) \in H \times \mathrm{Fix}(T), \tag{2.3}$$

T is pseudo-demicontractive [9] means that there exists constant $\alpha > 1$ such that

$$\|Tx - q\|^2 \leq \alpha\|x - q\|^2 + \|x - Tx\|^2, \quad \forall (x,q) \in H \times \mathrm{Fix}(T). \tag{2.4}$$

Definition 2.2. We say that T is firmly pseudo-demicontractive means that there exist constants $\alpha > 1$, $\beta > 1$ such that

$$\|Tx - q\|^2 \leq \alpha\|x - q\|^2 + \beta\|x - Tx\|^2, \quad \forall (x,q) \in H \times \mathrm{Fix}(T). \tag{2.5}$$

The inequality (2.5) is equivalent to

$$\langle x - Tx, x - q\rangle \geq \frac{1-\alpha}{2}\|x - q\|^2 + \frac{1-\beta}{2}\|Tx - x\|^2, \quad \forall (x,q) \in H \times \mathrm{Fix}(T), \tag{2.6}$$

An operator satisfying (2.5) will be referred to as a α, β firmly pseudo-demicontractive mapping. It is worth noting that the class of firmly pseudo-demicontractive maps contains important operators such as the demicontractive maps, quasi-nonexpansive maps, and the strictly pseudo-contractive maps with fixed points.

Next, let us recall several concepts:

(1) a mapping $T : H \to H$ is said to be nonexpansive if

$$\|Tx - Ty\| \leq \|x - y\|, \quad \forall(x, y) \in H \times H; \tag{2.7}$$

(2) a mapping $T : H \to H$ is said to be quasi-nonexpansive if

$$\|Tx - q\| \leq \|x - q\|, \quad \forall(x, q) \in H \times \text{Fix}(T); \tag{2.8}$$

(3) a mapping $T : H \to H$ is said to be strictly pseudo-contractive if

$$\|Tx - Ty\|^2 \leq \|x - y\|^2 + \beta\|x - y - (Tx - Ty)\|^2, \quad \forall(x, y) \in H \times H \ (\beta \in [0, 1)). \tag{2.9}$$

Obviously, the nonexpansive operators are both quasi-nonexpansive and strictly pseudo-contractive maps and are well known for being demiclosed.

Lemma 2.3 (see [5]). *An operator T is said to be closed at a point $y \in R^n$ if for every $x \in R^n$ and every sequence x_k in R^n, such that, $x_k \to x$ $(k \to \infty)$ and $T(x_k) \to y$, we have $Tx = y$.*

In what follows, only the particular case of closed at zero will be used, which is the particular case when $y = 0$.

Lemma 2.4 (see [12]). *Let $\{a_n\}$,$\{b_n\}$ and $\{\delta_n\}$ be sequences of nonnegative real numbers satisfying the inequality*

$$a_{n+1} \leq (1 + \delta_n)a_n + b_n, \quad n \geq 1, \tag{2.10}$$

where $\{\delta_n\} \subset l^1$, $\{b_n\} \subset l^1$, then $\lim_{n\to\infty} a_n$ exists.

Motivated by the former works in [5–9], we modify the algorithm proposed by Moudafi in [6] for solving SCFP in the more general case when the operators are firmly pseudo-demicontractive, defined on a general Hilbert space and also change several conditions. Then, we prove a strong convergence theorem of the modified algorithm about firmly pseudo-demicontractive operators, which improves and/or develops several corresponding results in this field. We present in this paper only theoretical results of algorithmic developments and convergence theorems. Experimental computational work in other literatures [4, 10] shows the practical viability of this class of algorithms.

3. Main Results

Let us consider now the two operators split common fixed-point problem (SCFP) [5, 6]

$$\text{find } x^* \in C \text{ such that } Ax^* \in Q, \tag{3.1}$$

where $A : H_1 \rightarrow H_2$ is a bounded linear operator, $U : H_1 \rightarrow H_1$, $T : H_2 \rightarrow H_2$ are two firmly pseudo-demicontractive operators with $\mathrm{Fix}(U) = C$ and $\mathrm{Fix}(T) = Q$,

$$\begin{aligned} \|Tx - q\|^2 &\le \alpha\|x - q\|^2 + \beta\|x - Tx\|^2, \quad \forall (x, q) \in H_2 \times \mathrm{Fix}(T), \\ \|Ux - q\|^2 &\le \mu\|x - q\|^2 + \theta\|x - Ux\|^2, \quad \forall (x, q) \in H_1 \times \mathrm{Fix}(U), \end{aligned} \tag{3.2}$$

where α, β and μ, θ are two firmly pseudo-demicontractive coefficients of U, T, respectively. $\alpha > 1,\ \beta > 1,\ \mu > 1,\ \theta > 1,\ H_1,\ H_2$ are two Hilbert spaces.

In what follows we always assume that the solution set of the two-operator SCFP is not empty, which denotes by

$$\Gamma = \{y \in C \mid Ay \in Q\}. \tag{3.3}$$

Based on the algorithm of [5, 6], we develop the following modified algorithm to solve (3.1).

Algorithm 3.1. Initialization: let $x_0 \in H_1$ be arbitrary.

Iterative step: for $k \in N$ set $u_k = x_k + \gamma A^*(T - I)Ax_k$ and let

$$x_{k+1} = (1 - t_k)u_k + t_k U(u_k), \quad k \in N, \tag{3.4}$$

where $(1 - \beta)/\lambda < \gamma < 0$ with λ being the spectral radius of the operator A^*A, $t_k > 0$.

Theorem 3.2. *Let H_1, H_2 are two Hilbert spaces, A is a bounded linear operator, $U : H_1 \rightarrow H_1$, $T : H_2 \rightarrow H_2$ are two firmly pseudo-demicontractive operators with $\mathrm{Fix}(U) = C$ and $\mathrm{Fix}(T) = Q, \alpha, \beta$, and μ, θ are two firmly pseudo-demicontractive coefficients of U, T, respectively. Let $b_k = t_k(\theta + t_k - 1)$ $\|U(u_k) - u_k\|^2$, $\delta_k = t_k(\mu - 1)$ and $\{b_k\} \subset l^1$, $\{\delta_k\} \subset l^1$. $T - I$ is closed at the origin, λ the spectral radius of the operator A^*A, then the sequence generated by the modified algorithm* (3.4) *converges strongly to the solution of* (3.1).

Proof. Taking $y \in \Gamma$, that is, $y \in \mathrm{Fix}(U)$, $Ay \in \mathrm{Fix}(T)$, and using (2.6), we obtain that

$$\begin{aligned} \|x_{k+1} - y\|^2 &= \|(1 - t_k)u_k + t_k U(u_k) - y\|^2 \\ &= \|u_k - y\|^2 - 2t_k\langle u_k - y, u_k - U(u_k)\rangle + t_k^2\|U(u_k) - u_k\|^2 \\ &\le \|u_k - y\|^2 - 2t_k\left(\frac{1-\mu}{2}\|u_k - y\|^2 + \frac{1-\theta}{2}\|U(u_k) - u_k\|^2\right) + t_k^2\|U(u_k) - u_k\|^2 \\ &\le (1 - t_k(1 - \mu))\|u_k - y\|^2 - t_k(1 - \theta - t_k)\|U(u_k) - u_k\|^2. \end{aligned} \tag{3.5}$$

Using the expression of u_k in Algorithm 3.1, we also have

$$\begin{aligned}\|u_k - y\|^2 &= \|x_k + \gamma A^*(T-I)Ax_k - y\|^2 \\ &= \|x_k - y\|^2 + \gamma^2\|A^*(T-I)Ax_k\|^2 + 2\gamma\langle x_k - y, A^*(T-I)Ax_k\rangle \\ &= \|x_k - y\|^2 + \gamma^2\langle (T-I)Ax_k, AA^*(T-I)Ax_k\rangle \\ &\quad + 2\gamma\langle Ax_k - Ay, (T-I)Ax_k\rangle.\end{aligned} \tag{3.6}$$

From the definition of λ, it follows that

$$\gamma^2\langle (T-I)Ax_k, AA^*(T-I)Ax_k\rangle \leq \lambda\gamma^2\|(T-I)Ax_k\|^2. \tag{3.7}$$

Now, by setting $\theta = 2\gamma\langle x_k - y, A^*(T-I)Ax_k\rangle$ and using the fact (2.5) and its equivalent form (2.6), we infer that

$$\begin{aligned}\theta &= 2\gamma\langle Ax_k - \mathrm{A}y, T(Ax_k) - Ax_k\rangle \\ &\leq 2\gamma\left(\frac{\alpha-1}{2}\|Ax_k - Ay\|^2 + \frac{\beta-1}{2}\|T(Ax_k) - Ax_k\|^2\right) \\ &= \gamma(\alpha-1)\|Ax_k - Ay\|^2 + \gamma(\beta-1)\|T(Ax_k) - Ax_k\|^2.\end{aligned} \tag{3.8}$$

Substituting (3.8), (3.7), and (3.6) into (3.5), we get the following inequality:

$$\begin{aligned}\|x_{k+1} - y\|^2 &\leq (1 - t_k(1-\mu))\|u_k - y\|^2 - t_k(1-\theta-t_k)\|U(u_k) - u_k\|^2 \\ &\leq (1 - t_k(1-\mu))\left(\|x_k - y\|^2 + \gamma(\alpha-1)\|Ax_k - Ay\|^2\right. \\ &\quad \left.+\gamma(\beta - 1 + \gamma\lambda)\|(T-I)(Ax_k)\|^2\right) - t_k(1-\theta-t_k)\|U(u_k) - u_k\|^2 \\ &= (1 + t_k(\mu-1))\|x_k - y\|^2 + (1 - t_k(1-\mu))\gamma(\alpha-1)\|Ax_k - Ay\|^2 \\ &\quad + (1 - t_k(1-\mu))\gamma(\beta - 1 + \gamma\lambda)\|(T-I)(Ax_k)\|^2 + t_k(\theta + t_k - 1)\|U(u_k) - u_k\|^2.\end{aligned} \tag{3.9}$$

Since $((1-\beta)/\lambda) < \gamma < 0$, $t_k > 0$ and $\alpha > 1, \beta > 1, \mu > 1, \theta > 1$, we obtain that $-t_k(1-\mu) > 0$, $(1 - t_k(1-\mu))\gamma(\alpha-1) < 0$, $(1 - t_k(1-\mu))\gamma(\beta - 1 + \gamma\lambda) < 0$, and $t_k(\theta + t_k - 1) > 0$, thus,

$$\|x_{k+1} - y\|^2 \leq (1 + t_k(\mu-1))\|x_k - y\|^2 + t_k(\theta + t_k - 1)\|U(u_k) - u_k\|^2. \tag{3.10}$$

Setting $b_k = t_k(\theta + t_k - 1)\|U(u_k) - u_k\|^2$ and $\delta_k = t_k(\mu - 1)$, (3.10) can be formulated as

$$\|x_{k+1} - y\|^2 \leq (1 + \delta_k)\|x_k - y\|^2 + b_k. \tag{3.11}$$

We also can denote that $a_{k+1} = \|x_{k+1} - y\|^2$, $a_k = \|x_k - y\|^2$, thus (3.11) can be rewritten as

$$a_{k+1} \le (1 + \delta_k) a_k + b_k. \tag{3.12}$$

Obviously, $\{a_k\}$, $\{b_k\}$, and $\{\delta_k\}$ are sequences of nonnegative real numbers. Since $\{b_k\} \subset l^1$, $\{\delta_k\} \subset l^1$, that is, $\sum_{k=1}^{\infty} \delta_k < \infty$, $\sum_{k=1}^{\infty} b_k < \infty$ from Lemma 2.4, $\lim_{k\to\infty}\|x_k - y\|^2$ exists.

Since λ being the spectral radius of the operator A^*A, (3.9) also can be reformulated as the following:

$$\begin{aligned}
\|x_{k+1} - y\|^2 \le{}& (1 + t_k(\mu - 1))\|x_k - y\|^2 + (1 - t_k(1 - \mu))\gamma(\alpha - 1)\|Ax_k - Ay\|^2 \\
&+ (1 - t_k(1 - \mu))\gamma(\beta - 1 + \gamma\lambda)\|(T - I)(Ax_k)\|^2 + t_k(\theta + t_k - 1)\|U(u_k) - u_k\|^2 \\
={}& (1 + t_k(\mu - 1))\|x_k - y\|^2 + (1 - t_k(1 - \mu))\gamma(\alpha - 1)\langle x_k - y, A^*A(x_k - y)\rangle \\
&+ (1 - t_k(1 - \mu))\gamma(\beta - 1 + \gamma\lambda)\|(T - I)(Ax_k)\|^2 + t_k(\theta + t_k - 1)\|U(u_k) - u_k\|^2 \\
\le{}& (1 + t_k(\mu - 1))\|x_k - y\|^2 + (1 - t_k(1 - \mu))\gamma(\alpha - 1)\lambda\|x_k - y\|^2 \\
&+ (1 - t_k(1 - \mu))\gamma(\beta - 1 + \gamma\lambda)\|(T - I)(Ax_k)\|^2 + t_k(\theta + t_k - 1)\|U(u_k) - u_k\|^2.
\end{aligned} \tag{3.13}$$

Taking limits from both side of (3.13), $(1 - t_k(1 - \mu))\gamma(\alpha - 1)\lambda < 0$, $t_k(\mu - 1) \to 0$, $(1 - t_k(1 - \mu))\gamma(\beta - 1 + \gamma\lambda) < 0$, $t_k(\theta + t_k - 1)\|U(u_k) - u_k\|^2 \to 0$, we obtain that

$$\lim_{k\to\infty}\|x_k - y\|^2 \longrightarrow 0, \quad \text{that is, } x_k \longrightarrow y(k \longrightarrow \infty). \tag{3.14}$$

If we take limits from both sides of (3.9), we can get the following:

$$\lim_{k\to\infty}\|Ax_k - Ay\|^2 \longrightarrow 0, \quad \text{that is, } Ax_k \longrightarrow Ay(k \longrightarrow \infty), \tag{3.15}$$

$$\lim_{k\to\infty}\|(T - I)(Ax_k)\|^2 \longrightarrow 0, \quad \text{that is, } (T - I)(Ax_k) \longrightarrow 0(k \longrightarrow \infty). \tag{3.16}$$

Because $T - I$ is closed at the origin, from (3.15) and (3.16), using Lemma 2.3, we have

$$(T - I)(Ay) = 0, \quad \text{that is, } T(Ay) = Ay. \tag{3.17}$$

The sequence generated by modified algorithm (3.1) converges strongly to the solution of SCFP. The proof is completed. □

Under the same conditions as in Thereom 3.2, if we take $\beta = \theta = 1$ (i.e., U, T are pseudo-demicontractive operators), the strong convergence also holds, so we get the following corollary.

Corollary 3.3. *Let H_1, H_2 are two Hilbert spaces, A is a bounded linear operator, $U : H_1 \to H_1$, $T : H_2 \to H_2$ are two pseudo-demicontractive operators with* $\mathrm{Fix}(U) = C$ *and* $\mathrm{Fix}(T) = Q$, *α and μ are two pseudo-demicontractive coefficients of U, T, respectively. Let $b_k = (1 - t_k(1-\mu))\gamma^2\lambda\|(T-I)(Ax_k)\|^2 + t_k^2\|U(u_k) - u_k\|^2$, $\delta_k = t_k(\mu - 1)$, and $\{b_k\} \subset l^1, \{\delta_k\} \subset l^1$. $T - I$ is closed at the origin, and λ is the spectral radius of the operator A^*A, then the sequence generated by the modified algorithm* (3.4) *converges strongly to the solution of* (3.1).

Proof. Taking $\beta = \theta = 1$, here (3.9) as the following:

$$\begin{aligned}\|x_{k+1} - y\|^2 \le (1 + t_k(\mu - 1))\|x_k - y\|^2 + (1 - t_k(1-\mu))\gamma(\alpha - 1)\|Ax_k - Ay\|^2 \\ + (1 - t_k(1-\mu))\gamma^2\lambda\|(T-I)(Ax_k)\|^2 + t_k^2\|U(u_k) - u_k\|^2.\end{aligned} \tag{3.18}$$

Because

$$b_k = (1 - t_k(1-\mu))\gamma^2\lambda\|(T-I)(Ax_k)\|^2 + t_k^2\|U(u_k) - u_k\|^2, \quad \delta_k = t_k(\mu - 1), \tag{3.19}$$

from (3.18), we get

$$a_{k+1} \le (1 + \delta_k)a_k + b_k. \tag{3.20}$$

The same lines as the proof of Thereom 3.2, we obtain the desired result. □

At last, we want to say that the condition $\{b_k\} \subset l^1, \{\delta_k\} \subset l^1$ actually controls the distance between independent variable and dependent variable of the related operators. Provided that the distance may not fluctuate too severely, the condition can always be satisfied with some appropriate coefficients, for example, taking $t_k = 1/k^2$.

4. Conclusion

In this paper, we generalize the algorithm proposed by Moudafi for demicontractive operators to firmly pseudo-demicontractive operators for SCFP and use some beautiful lemmas to prove the strong convergence of the modified algorithm. Our results improve and/or develop Moudafi, Censor, and some other people's work.

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