International Journal of Hybrid Information Technology
Vol.7, No.3 (2014), pp.303-310
http://dx.doi.org/10.14257/ijhit.2014.7.3.28

Hybrid Iterative Algorithm of Asymptotically Non-expansive Mappings for Equilibrium Problems

Shanshan Yang[1] and Jingxin Zhang[2, *]

[1,2]*Mathematics and Applied Mathematics, Harbin University of Commerce, Harbin, 150028, China*

E-mail: yangshsh@hrbcu.edu.cn,
zhjx_19@163.com

Abstract

Optimization problems, variational inequalities, minimax problems can be formulated as equilibrium problems. The iterative algorithms of fixed points are often applied to finding the solution of equilibrium problems. In this paper, we introduce a new hybrid iterative algorithm for finding a common element of the set of fixed points of asymptotically nonexpansive mappings and the set of solutions of an equilibrium problem in Hilbert spaces. Besides, an example of variational inequality problem is given to illustrate the efficiency and performance of the newly algorithm.

Keywords: *Equilibrium problem; Hybrid algorithm; Strong convergence; Asymptotically nonexpansive mapping*

1. Introduction

The classical Variational Inequality Problem is to find a vector such that

$$\langle F(\hat{x}), y - \hat{x} \rangle \geq 0, \quad \forall y \in C \tag{1.1}$$

The problem (1.1) was first introduced by Hartman and Stampacchia [1] in 1966. The primary goal is to compute the stationary points for nonlinear programs. It is widely used in the study of optimization and equilibrium problems and finding the numerical solution for many practical problems. It has a wide range of applications in engineering, operations research, economics etc. Many practical problems process for seeking better or best alternative solution from a number of possible solutions. However, the analytical optimal solution is difficult to obtain even for relatively simple application problems. Researchers instead study the numerical optimization algorithm arises from almost every field, such as engineering design, systems operation, decision making, and computer science for example [2-4].

The equilibrium problem is to find $\hat{x} \in C$ such that

$$f(\hat{x}, y) \geq 0, \quad \forall y \in C \tag{1.2}$$

The set of solutions of the above inequality is denoted by $\mathrm{EP}(f)$. Let $f(x, y) = \langle F(x), y - x \rangle$, then (1.1) can be regarded as an equilibrium problem. The concept of equilibrium, which has long been connected with maximization or minimization, plays a central role and provides a valuable benchmark against which an existing state of such complex systems can be

[*] Corresponding author

ISSN: 1738-9968 IJHIT

compared. S. Dafermos [5] showed that a network equilibrium conditions were a finite-dimensional variational inequality and then utilized the theory to establish both existence and uniqueness results of the equilibrium problems as well as to propose an algorithm with convergence results.

The theoretical and practical challenge in solving equilibrium problem is due mainly to the fact that no natural objective is available and therefore monitoring the convergence of an iterative process to an equilibrium solution is difficult. For instance, iterative methods that proceed by solving a sequence of optimization problems rely for convergence on theoretical conditions difficult to verify in practice.

Asymptotically non-expansive mapping was first introduced and studied by W.A. Kirk [6] in 1972. From that moment on, many researchers further studied the properties of asymptotically non-expansive mappings.

In this paper, we adopt a different point of view and propose a new hybrid iterative algorithm for the fixed point of asymptotically non-expansive mapping and the solution of an equilibrium problem. The algorithm reduces the projection region at each iteration progress and monitors the convergence of an iterative process by the distance from an iterative element to the projection set which reduces gradually with the iterative progress. Besides, we give an example of variational inequality problem to illustrate the efficiency and performance of the newly algorithm.

2. Preliminaries

There have been many methods proposed in the literature to study the equilibrium problem, among of which we think the projection method is one of the best ways. We first present the projection ant its equivalent description.

Throughout this paper, let H be a real Hilbert space, $\langle \cdot\,, \cdot \rangle$ denote the inner product. Let C be a nonempty closed convex subset of H . Then for any $x \in H$, there exists a unique nearest point in C , denoted by $P_C(x)$, such that $\| x - P_C(x) \| \le \| x - y \|, \ \forall y \in C$. Such a mapping P_C is called the metric projection of H onto C . Furthermore [7], for $x \in H$ and $z \in C$,

$$z = P_C(x) \text{ if and only if } \langle x - z, z - y \rangle \ge 0, \ \forall y \in C .$$

A mapping $T : C \to C$ is said to be asymptotically nonexpansive if for each $n \in \mathbb{N}$, there exists a nonnegative real number k_n satisfying $\lim_{n\to\infty} k_n = 1$ such that

$$\| T^n x - T^n y \| \le k_n \| x - y \|, \ \forall x, y \in C .$$

We denote by $F(T) = \{ x \in H : Tx = x \}$ the set of fixed points of T . If $T : H \to H$ is asymptotically nonexpansive, the $F(T)$ is nonempty convex.

For solving the equilibrium problem, let us assume that a bifunction F satisfies the following conditions [8]:

(A1) $f(x, x) = 0$, for all $x \in C$;

(A2) f is monotone, i.e., $f(x, y) + f(y, x) \le 0$, for all $x, y \in C$;

(A3) for each $x, y, z \in C$, $\limsup_{t \to 0^+} f(tz + (1 - t)x, y) \le F(x, y)$.

(A4) for each $x \in C$, $f(x, \cdot)$ is convex and lower semi-continuous.

To prove the strong convergence of our algorithm later, the following two lemmas are presented here.

Lemma 1[9] Let C be a nonempty closed convex subset of H , and let $f : C \times C \to \mathbb{R}$ satisfying (A1)-(A4). And let $r > 0$, and $x \in H$. Then, there exists $z \in C$ such that

$$f(z, y) + \frac{1}{r} \langle y - z, z - x \rangle \ge 0, \ \forall y \in C .$$

Further, define a mapping $T_r : X \to C$ as follows:

$$T_r(x) = \left\{ z \in C : F(z, y) + \frac{1}{r}\langle y - z, Jz - Jx \rangle \geq 0, \quad \forall y \in C \right\},$$

for all $z \in H$. Then, the following hold:

1) T_r is single-valued;
2) T_r is firmly nonexpansive, i.e.,
   $\| T_r x - Ty \|^2 \leq \langle T_r x - Ty, x - y \rangle, \quad \forall x, y \in H$;
3) $F(T_r) = \mathrm{EP}(f)$;
4) $\mathrm{EP}(f)$ is closed and convex.

Lemma 2[9] Let C be a nonempty closed convex subset of H, and let $f : C \times C \to \mathrm{R}$ satisfying (A1)-(A4). Let $r > 0$, for $x \in H$ and $q \in F(T_r)$, then $\| q - T_r x \|^2 + \| T_r x - x \|^2 \leq \| q - x \|^2$.

3. Hybrid iterative algorithm for asymptotically nonexpansive mappings and equilibrium problems

In this section, we introduce a new hybrid iterative algorithm for the fixed point of asymptotically nonexpansive mapping and the solution of an equilibrium problem and analysis the strong convergence of the proposed method. In fact, we prove a strong convergence theorem for finding a common element of the set of zero points of asymptotically nonexpansive mapping and the set of solutions of an equilibrium problem in a Hilbert space.

Let C be a nonempty bounded closed convex subset of a real Hilbert space H, let $f : C \times C \to \mathrm{R}$ be a functional, satisfying (A1)-(A4). Let $T : C \to C$ be a asymptotically nonexpansive mapping with k_n, such that $F(T) \cap \mathrm{EP}(f) \neq \varnothing$.

Now, we introduce a new projection method for equilibrium problem as follows:

Hybrid Algorithm

1) *Given* $\varepsilon_0 > 0$ *(error bound),* $r_0 > 0$, $0 < a < 1$. *Let* $C_0 = C$ *, choose arbitrarily* $x_0 \in C_0$ *;*
2) Generate y_n by Mann's Iteration of T:
   $$y_n = \alpha_n x_n + (1 - \alpha_n) T^n x_n \quad ,$$
   where $0 \leq \alpha_n \leq a < 1$ for all $n \in \mathrm{N}$;
3) Solve the equilibrium problem
   $$f(u_n, y) + \frac{1}{r_n}\langle y - u_n, u_n - y_n \rangle \geq 0, \quad \forall y \in C$$
   and obtain the solution $u_n \in C$, where $\{r_n\} \subset (0, \infty)$ such that $\liminf_{n \to \infty} r_n = r_0 > 0$;
4) Reduce the projection region by dividing the distance equally:
   $$C_n = \left\{ z \in C : \| u_n - z \|^2 \leq \| x_n - z \|^2 + \theta_n \right\}$$
   where $\theta_n = (1 - \alpha_n)(k_n^2 - 1)(\mathrm{diam}(C))^2 \to 0$, as $n \to \infty$;
5) Reduce the projection region using Acute Angle Principle:
   $$Q_n = \left\{ z \in C : \langle x_n - z, x_0 - x_n \rangle \geq 0 \right\};$$
6) Take the projection on the object point-set as the next iteration point:
   $$x_{n+1} = P_{C_n \cap Q_n}(x_0);$$

If $\| x_{n+1} - x_n \| < \varepsilon_0$ then stop; otherwise, set $n := n + 1$ go to 2).

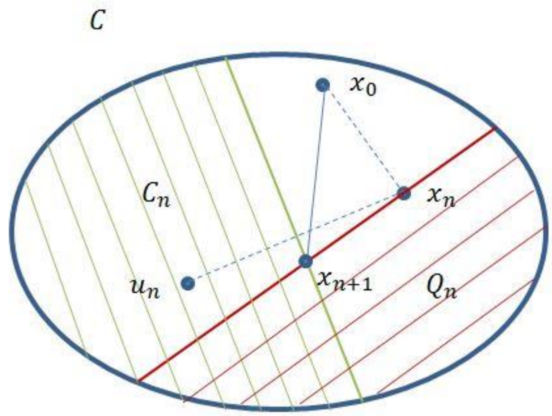

Figure 1. Hybrid algorithm diagram

Convergence analysis

In the following, we prove the strong convergence of the proposed method.

Theorem The sequence $\{x_n\}$ generated by the above algorithm converges strongly to $x^* = P_{F(T)\cap EP(f)}(x_0)$, which is a common element of the set of zero points of asymptotically nonexpansive mapping T and the set of solutions of Equilibrium Problem (1.2).

Proof. Firstly, C_n and Q_n are closed and convex for each $n \in \mathrm{N}$.

Secondly, $F(T)\cap \mathrm{EP}(f) \subset C_n \cap Q_n, \ \forall n \in \mathrm{N}$.

Let $p \in F(T)\cap \mathrm{EP}(f)$. Putting $u_n = T_{r_n} y_n, \ \forall n \in \mathrm{N}$, by 2) of Lemma 1, we have T_{r_n} is relatively nonexpansive hence nonexpansive, then for any $n \in \mathrm{N}$,

$$\| u_n - p \|^2 = \| T_{r_n} y_n - p \|^2 = \| T_{r_n} y_n - T_{r_n} p \|^2 \le \| y_n - p \|^2 .$$

Since

$$\begin{aligned} \| y_n - p \|^2 &\le \alpha_n \| x_n - p \|^2 + (1-\alpha_n)\left(T^n x_n - p\right)^2 \\ &\le \alpha_n \| x_n - p \|^2 + (1-\alpha_n) k_n^2 \| x_n - p \|^2 \\ &\le \| x_n - p \|^2 + \theta_n , \end{aligned}$$

we have $\| u_n - p \|^2 \le \| x_n - p \|^2 + \theta_n$, thus $p \in C_n$. Hence $F(T) \cap \mathrm{EP}(f) \subset C_n$. For $n = 0$, we have $F(T)\cap \mathrm{EP}(f) \subset C = Q_0$. Suppose that $F(T)\cap \mathrm{EP}(f) \subset Q_n$, then $\varnothing \ne F(T)\cap \mathrm{EP}(f) \subset C_n \cap Q_n$ and there exists a unique element $x_{n+1} \in C_n \cap Q_n$ such that $x_{n+1} \in P_{C_n \cap Q_n}(x_0)$. Then

$$\langle x_{n+1} - z, x_0 - x_{n+1} \rangle \ge 0, \ \ \forall z \in C_n \cap Q_n .$$

In particular,

$$\langle x_{n+1} - p, x_0 - x_{n+1} \rangle \ge 0, \ \ \forall p \in F(T)\cap \mathrm{EP}(f) .$$

It follows that $F(T)\cap \mathrm{EP}(f) \subset Q_{n+1}$. By induction, $F(T)\cap \mathrm{EP}(f) \subset Q_n, \ \forall n \in \mathrm{N}$. This means that $\{x_n\}$ is well-defined.

Thirdly, $\{x_n\}$ is bounded and $\lim_{n\to\infty} \| x_n - T x_n \| = 0$.

It follows from the definition of Q_n that $x_n = P_{Q_n}(x_0)$, thus

$$\| x_n - x_0 \| \le \| z - x_0 \|, \ \ \forall z \in Q_n, \ \forall n \in \mathrm{N} \tag{3.1}$$

$z \in F(T)\cap \mathrm{EP}(f) \subset Q_n, \ \forall n \in \mathrm{N}$, then $\| x_n - x_0 \| \le \| z - x_0 \|$.

On the other hand, from $x_{n+1} = P_{C_n \cap Q_n}(x_0) \in Q_n$, we have $\| x_n - x_0 \| \le \| x_{n+1} - x_0 \|, \ \forall n \in \mathrm{N}$ .So $\{\| x_n - x_0 \|\}$ is nondecreasing. Since C is bounded, we obtain that $\lim_{n\to\infty} \| x_n - x_0 \|$ exists. This implies that $\{x_n\}$ is bounded. Noticing again that $x_{n+1} = P_{C_n \cap Q_n}(x_0) \in Q_n$ and $x_n = P_{Q_n}(x_0)$, we have $\langle x_{n+1} - x_n, x_n - x_0 \rangle \geq 0$. Thus, for all $n \in \mathbb{N}$,

$$\begin{aligned} \| x_{n+1} - x_n \|^2 &= \| (x_{n+1} - x_0) - (x_n - x_0) \|^2 \\ &= \| x_{n+1} - x_0 \|^2 - \| x_n - x_0 \|^2 - 2\langle x_{n+1} - x_n, x_n - x_0 \rangle \\ &\leq \| x_{n+1} - x_0 \|^2 - \| x_n - x_0 \|^2 . \end{aligned} \tag{3.2}$$

This implies that

$$\lim_{n \to \infty} \| x_{n+1} - x_n \| = 0 \tag{3.3}$$

Since $x_{n+1} = P_{C_n \cap Q_n}(x_0) \in Q_n$, then $\| u_n - x_{n+1} \|^2 \leq \| x_n - x_{n+1} \|^2 + \theta_n \quad \to 0$. Hence

$$\lim_{n \to \infty} \| x_n - u_n \| \leq \lim_{n \to \infty} \| x_n - x_{n+1} \| + \lim_{n \to \infty} \| x_{n+1} - u_n \| \to 0 \tag{3.4}$$

For $p \in F(T) \cap \mathrm{EP}(f) \subset C_n$, we have $\| u_n - p \|^2 \leq \| x_n - p \|^2 + \theta_n$.

Since $u_n = T_{r_n} y_n$, by Lemma 2, we get that

$$\begin{aligned} \| u_n - y_n \|^2 &= \| T_{r_n} y_n - y_n \|^2 \\ &\leq \| y_n - p \|^2 - \| T_{r_n} y_n - p \|^2 \\ &\leq \| x_n - p \|^2 + \theta_n - \| u_n - p \|^2 \to 0 . \end{aligned} \tag{3.5}$$

Since $\alpha_n \leq a < 1$, $\forall n \in \mathbb{N}$, then by (3.4) and (3.5), we have

$$\| x_n - T^n x_n \| = \frac{1}{1 - \alpha_n} \| y_n - x_n \| \leq \frac{1}{1 - a} (\| y_n - u_n \| + \| u_n - x_n \|) \to 0 .$$

Put $k_\infty = \sup\{k_n : n = 1, 2, \cdots\} < +\infty$, we have

$$\begin{aligned} \| Tx_n - x_n \| &\leq \| Tx_n - T^{n+1} x_n \| + \| T^{n+1} x_n - T^{n+1} x_{n+1} \| + \| T^{n+1} x_{n+1} - x_{n+1} \| + \| x_{n+1} - x_n \| \\ &\leq k_\infty \| x_n - T^n x_n \| + (k_\infty + 1) \| x_{n+1} - x_n \| + \| T^{n+1} x_{n+1} - x_{n+1} \| \to 0 . \end{aligned}$$

Finally, $\{x_n\}$ convergence strongly to $P_{F(T) \cap EP(f)}(x_0)$.

Since $\{x_n\}$ is bounded, there exists a subsequence $\{x_{n_k}\}$ of $\{x_n\}$ such that $x_{n_k} \xrightarrow{w} w'$. By Demiclosed Principle, we have $w' \in F(T)$. Next we show $w' \in \mathrm{EP}(f)$.

From (3.4 and (3.5), we get that $u_{n_k} \xrightarrow{w} w'$, $y_{n_k} \xrightarrow{w} w'$. Since $u_n = T_{r_n} y_n$, replacing n by n_k, from Condition (A2),

$$\frac{1}{r_{n_k}} \langle y - u_{n_k}, u_{n_k} - y_{n_k} \rangle \geq -f(u_{n_k}, y) \geq f(y, u_{n_k}), \quad \forall y \in C .$$

Let $k \to \infty$, since $\liminf_{n \to \infty} r_n > 0$, by (3.5) and Condition (A4), we get that $f(y, w') \leq 0, \ \forall y \in C$.

For $t \in (0,1)$, $y \in C$, let $y_t = ty + (1-t)w'$, then $y_t \in C$, thus $f(y_t, w') \leq 0$. By Condition (A1), we get that

$$0 = f(y_t, y_t) \leq tf(y_t, y) + (1-t) f(y_t, w') \leq tf(y_t, y) .$$

Dividing by t, we have $f(y_t, y) \geq 0, \ \forall y \in C$. Let $t \to 0$, from Condition (A3), we obtain that $f(w', y) \geq 0, \ \forall y \in C$. Therefore, $w' \in \mathrm{EP}(f)$.

Denote $w = P_{F(T) \cap \mathrm{EP}(f)}(x_0)$. Since $x_{n+1} = P_{C_n \cap Q_n}(x_0)$, $w \in F(T) \cap \mathrm{EP}(f) \subset C_n \cap Q_n$, then

$$\| x_{n+1} - x_0 \| \leq \| w - x_0 \| .$$

Since the norm is weakly lower semi-continuous, we have

$$\| w - x_0 \| \leq \| w' - x_0 \| \leq \liminf_{k \to \infty} \| x_{n_k} - x_0 \| \leq \limsup_{k \to \infty} \| x_{n_k} - x_0 \| \leq \| w - x_0 \| .$$

Hence $\lim_{k \to \infty} \| x_{n_k} - x_0 \| = \| w' - x_0 \| = \| w - x_0 \|$. Using the Kadec-Klee property of H, we get $\lim_{k \to \infty} x_{n_k} = w' = w$. Since $\{x_{n_k}\}$ is an arbitrary subsequence of $\{x_n\}$, we can conclude that $\{x_n\}$ converges strongly to $P_{F(T) \cap EP(f)}(x_0)$. The proof is complete.

Remark The space $\mathbb{R}^n$ is a Hilbert space with the inner product defined by $\langle x, y\rangle = \sum_{i=1}^{n} \xi_i \eta_i$, where $x = (\xi_1, \cdots, \xi_n)$, $y = (\eta_1, \cdots, \eta_n)$, and the corresponding norm is $\| x \| = \langle x, x\rangle^{1/2} = (\xi_1^2 + \cdots + \xi_n^2)^{1/2}$. Hence, the above algorithm holds under the framework of $\mathbb{R}^n$.

Terminal condition

Inequality (3.3) shows that our algorithm is terminable. Let us estimate the terminal condition of our iterative scheme. By (3.1), we have

$$\| x_n - x_0 \|^2 \leq \operatorname{dist}(x_0, Q_n)^2,$$

where $\operatorname{dist}(x_0, Q_n) = \inf\{d(x_0, y) : y \in Q_n\}$. Since $\{\| x_n - x_0 \|\}$ is nondecreasing, by (3.2) we obtain

$$\| x_{n+1} - x_n \|^2 \leq \operatorname{dist}(x_0, Q_n)^2 - \| x_1 - x_0 \|^2.$$

So if n satisfies $\operatorname{dist}(x_0, Q_n)^2 \leq \varepsilon_0^2 + \| x_1 - x_0 \|^2$, then terminate the iterative progress.

4. Numerical Examples

In this section, we test the proposed iterative scheme by an example of variational inequality problem. All computations were done using the PC with DualCore Intel Core i5 430M, 2533 MHz and with 4GByte of RAM. All the programming is implemented in MATLAB R2010b.

Throughout the computational experiment, the parameters in Hybrid Algorithm were set as $\varepsilon_0 = 10^{-6}$, $a = 0.98$, $\{\alpha_n\}$ are uniformly distributed random numbers in $[0, a]$, and $r_n \equiv r \equiv 100$ for simplicity.

Example. The Kojshin problem was used by Pang and Gabriel [10]. Let

$$F(x) = \begin{pmatrix} 3x_1^2 + 2x_1x_2 + 2x_2^2 + x_3 + 3x_4 - 6 \\ 2x_1^2 + x_1 + x_2^2 + 10x_3 + 2x_4 - 2 \\ 3x_1^2 + x_1x_2 + 2x_2^2 + 2x_3 + 9x_4 - 9 \\ x_1^2 + 3x_2^2 + 2x_3 + 3x_4 - 3 \end{pmatrix}.$$

Consider variational inequality problem: find $\hat{x} \in C$ such that

$$\langle F(\hat{x}), x - \hat{x}\rangle \geq 0, \quad \forall x \in C.$$

This problem has one degenerate solution $(\sqrt{6}/2, 0, 0, 1/2)^T$ and one non-degenerate solution $(1, 0, 3, 0)^T$. The numerical results are listed in Table 1 using different initial points (SP). The asterisk (*) denotes that the limit point generated by the algorithm is the degenerate.

Table 1. Numerical results for Example 1

SP	Iter.	Error	CPU
$(0,0,0,0)^T$	176	8.54e–007	0.0208
$(1,1,1,1)^T$	184	9.47e–007	0.0213
$(2,2,2,2)^T$	79*	7.81e–007	0.0106
$(3,2,1,4)^T$	68*	8.32e–007	0.0098
$(4,1,3,6)^T$	191	8.72e–007	0.0208

5. Conclusions

A new iterative algorithm based on hybrid method is proposed in this paper. The algorithm not only reduces the projection region at each iteration progress by directional and distance relations, but also monitors the convergence of an iterative process by the distance from an iterative element to the projection set which reduces gradually with the iterative progress. This method overcomes the difficulty of monitoring the contraction argument for convergence. Besides, some examples are given to illustrate the efficiency and performance of the newly algorithm. Although the algorithm might not be competitive with other codes for solving optimization and variational inequality problems, it possesses several theoretical and practical advantages over current algorithms. There are still some imperfections and need to be improved further, such as how to select $\{\alpha_n\}$ to raise iterative efficiency, comparing with other algorithms, etc.

Acknowledgements

This work is supported by Research Fund for the Doctoral Program of Harbin University of Commerce (13DL002).

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Authors

Shanshan Yang
Female, Born in 1961
Current position: Professor, School of Basic Science, Harbin University of Commerce, Harbin, China
Education: M.S. in fundamental mathematics, Northeast Normal University, Changchun, China
Main Research Fields: Numerical Computation and Algorithm, Fixed Point Theory and Applications

Jingxin zhang

Male, Born in 1982

Current position: Lecturer, School of Basic Science, Harbin University of Commerce, Harbin, China

Education: Ph.D in fundamental mathematics, Harbin Institute Technology, Harbin, China

Main Research Fields: Iterative Algorithm, Fixed Point Theory and Applications