Co-evolutionary Stability in the Alternating-Offer Negotiation

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***Abstract*—Co-evolution has been proved by experiments to be a promising technique to achieve the automatic acquisition of the optimal strategies in automated negotiations. However, little theoretical work can be found currently to verify its validity. In this paper, we will use evolutionary game theory and replicator dynamics as theoretical foundation and study the co-evolutionary stability of the sub-game perfect equilibrium in alternating-offer protocol, which is widely used in the e-commerce negotiations. We first propose a reasonable assumption, then prove the sub-game perfect equilibrium can repel any rare mutations occurred on its equilibrium and non-equilibrium paths, and finally draw a conclusion that the sub-game perfect strategy is co-evolutionary stable. In the end of this paper, we design an experiment with co-evolutionary genetic algorithm and validate the conclusion.**

***Keywords*—Evolutionary game; Alternating offer; Replicator dynamics; Sub-game perfect equilibrium.**

I. INTRODUCTION

Automated negotiation is the most intelligent and creative stage in the future agent-mediated e-commerce paradigm, and has been studied fruitfully from such domains as economics, computer science and social psychology. With the rapid development of machine learning and intelligent computation, recent years have witnessed the emergence of another research method, which simulates the negotiation by competitive co-evolution [1]. Its basic principle is to encode the negotiation strategy spaces as co-evolving populations, one for each competing agent. Co-evolution starts with randomly generated strategy populations, which compete with and adapt to each other in successive iterations to form a co-evolutionary arm race. As a result, each population will converge to its optimal strategies. This method is particularly promising because it can realize the automated acquisition of the optimal strategies in automated negotiations.

Great progress has been made since Oliver first put forward this idea [2]. For instance, Bragt presented a systematic validation of co-evolution technique in the field of automated negotiation, and investigated the dynamics and equilibrium selection behaviors of the adaptive negotiating agents [3]; Gerding simulated the multi-issue negotiation scenario with co-evolutionary algorithm, and discussed the influence of social and cultural norms on decision-making [4]. Tu improved Oliver's original model with co-evolution encoded by finite state machine, and proved that its performance is better than linear genome [5]. These literatures come to a same conclusion that co-evolution will produce game-theoretically optimal strategies. However, they are all experimental research, and no theoretical research has so far been seen on this topic. Therefore, in order to successfully integrate the co-evolution technique within the agent-mediated e-commerce systems, its validity must be proved theoretically.

This paper uses the evolutionary game theory (EGT) as a theoretical foundation to verify the stability of co-evolution in the alternating-offer protocol, which is widely used in current e-commerce negotiations. This protocol can be modeled as an asymmetric two-player dynamic game with continuous strategy spaces. Our aim is to check the stability of its unique sub-game perfect equilibrium (SPE) using the concept of evolutionary stable strategy (ESS). The remainder of this paper is organized as follows. Section II introduces two key concepts in EGT, namely the ESS and replicator dynamics; Section III proposes the co-evolutionary model of the alternating-offer negotiation (AON); Section IV analyzes the co-evolutionary stability of the SPE in AON game; Section V presents the experimental validation; Finally, section VI concludes.

II. Background Knowledge

A. ESS

ESS was first presented by Maynard Smith and Price [6], and defined as a strategy such that, if most of the members in the population adopt it, no mutant strategy could invade the population under the influence of natural selection. Therefore, ESS is a stable attractor so that any small perturbation will be followed by a dynamic selection process which will lead to a restoration to the ESS. On the other hand, ESS can also be considered as a refinement of Nash equilibrium (NE), and can be used to describe the local dynamics of an evolutionary system. In this paper, we focus mainly on the ESS concept in multiple populations.

Following traditional notations, if $I = \{ag_1, ..., ag_n\}$ is the set of negotiating agents and $S_i = \{s_i^1, s_i^2, ...\}$ stands for the strategy population of $ag_i \in I$, then we can define an n-population ESS as follows:

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Definition: Strategy profile $s^* = \{s_1^*, ..., s_n^* \mid s_i^* \in S_i\}$ is an n-population ESS, if and only if for any mutated strategy profile $s = \{s_1, ..., s_n \mid s_i \in S_i\}$ and $s \neq s^*$, there exists a positive invasion barrier $\varepsilon_s \in (0,1)$ so that for all $\varepsilon \in (0, \varepsilon_s)$ and $w = \varepsilon s + (1-\varepsilon)s^*$, we have

$$u_i(s_i^*, w_{-i}) > u_i(s_i, w_{-i}) \text{ for } \forall i \in [1..n]$$

Here $w = \{w_1, ..., w_n\}$, and $w_i = \varepsilon s_i + (1-\varepsilon)s_i^*$ is the mixed population of ag_i after invasion. Accordingly, w_{-i} stands for all the opponent populations of ag_i with the subscript $-i$ denoting the opponents. $u_i(s_i^*, w_{-i})$ and $u_i(s_i, w_{-i})$ are the payoffs of strategies s_i^* and s_i when confronted with w_{-i}.

B. Replicator Dynamics

Replicator dynamics is the most widespread dynamics in EGT [7], and an explicit model of the natural selection process. It can be used to interpret and predict how populations playing specific strategies evolve. Generally speaking, there are discrete and continuous time versions of replicator dynamics. We consider the latter one in this paper. Formally, let ε_i^j denote the proportion of individuals adopting strategy s_i^j in population S_i, then the n-population replicator equation can be described as:

$$\dot{\varepsilon}_i^j = [u_i(s_i^j, w_{-i}) - \sum_{k=1}^{|S_i|} \varepsilon_i^k u_i(s_i^k, w_{-i})] \cdot \varepsilon_i^j \qquad (1)$$

As is shown in equation (1), $\dot{\varepsilon}_i^j / \varepsilon_i^j$ equals to the difference between s_i^j' payoff and the average payoff of the entire population, and represents the per capita growth rate of s_i^j in population S_i. Obviously, all strategies whose payoffs are higher than average will have positive growth rates, and otherwise negative. Therefore, once a population stabilized in ESS, all the rare mutated strategies will get a payoff below the average, and will die out in the long run under the influence of replicator dynamics.

III. Co-evolutionary Model of the AON Game

A. AON Game

AON is one of the most popular games in the non-cooperative game theory [8]. In this game, the agent set $I = \{ag_1, ag_2\}$, and their time preferences can be measured by discount factors $\delta_1, \delta_2 \in (0,1)$. Both agents offer alternately in discrete periods $t = 1, 2, 3...$ until an agreement is reached. Without loss of generality, assume ag_1 offers first.

An AON strategy is an ordered sequence of offers and acceptance thresholds. The former specifies a value for an agent whenever it is its turn to make an offer, and the latter is a threshold below which it will not accept the opponent offer. If we denote the offer and acceptance threshold of ag_i in period t by o_i^t and τ_i^t, then the strategies can be represented as $s_1 = \{o_1^1, \tau_1^2, o_1^3, \tau_1^4, ...\}$ and $s_2 = \{\tau_2^1, o_2^2, \tau_2^3, o_2^4, ...\}$ for each agent respectively. For simplicity, here we assume the amount of the negotiation surplus is equal to unity, so $o_i^t, \tau_i^t \in [0,1]$. The agreement will be reached in the minimum period t satisfying $o_i^t + \tau_{-i}^t \le 1$, with the offering agent receiving o_i^t and its opponent receiving $1 - o_i^t$. It has been proved [8] that AON game has such a unique SPE profile $s^* = \{s_1^*, s_2^*\}$: 1) In each odd period t, $o_1^t = (1-\delta_2)/(1-\delta_1\delta_2)$ and $\tau_2^t = 1 - o_1^t$; 2) In each even period t, $o_2^t = (1-\delta_1)/(1-\delta_1\delta_2)$ and $\tau_1^t = 1 - o_2^t$; 3) The agreement will be reached in the first period to o_1^1 and τ_2^1.

B. Co-evolutionary Model

The model consists of two co-evolving infinite populations S_1 and S_2. Each individual of S_i is encoded to play a certain strategy on behalf of ag_i, $i = 1, 2$. In each period, two individuals, one from each population, are drawn randomly and repeatedly to form a strategy profile and play the AON game.

The main goal of this model is to validate the co-evolutionary stability of the SPE strategy profile in the AON game. Put differently, we must prove that SPE can repel the invasion of any rare mutants. Therefore, we assume now both populations have stabilized at the SPE profile $s^* = \{s_1^*, s_2^*\}$, and then the populations are perturbed by a small group of strategies with proportions of ε_1 and ε_2 mutated randomly to s_1 and s_2, so $w_1 = \varepsilon_1 s_1 + (1-\varepsilon_1)s_1^*$ and $w_2 = \varepsilon_2 s_2 + (1-\varepsilon_2)s_2^*$. If such a system will stabilize at $\varepsilon_1 = \varepsilon_2 = 0$ again under the natural selection process, then we can conclude that the SPE profile s^* is a two-population ESS.

In order to simplify the model, we assume mutation occurs singly and orderly. This can be interpreted as follows: On the one hand, not all the offers and acceptance thresholds of a strategy, but only one of them in a certain period will have the opportunity to change in each mutation; On the other hand, mutation is a very rare event and selection acts much faster, so that there is enough time between mutations for the population to stabilize before the next mutation.

IV. The Co-evolutionary Stability of the SPE Profile

This section will analyse the stable point of $(\varepsilon_1, \varepsilon_2)$ in the above model using replicator dynamics. The analysis is based on a reasonable assumption as follows.

Assumption: For $\forall s_i, s_i' \in S_i$ and $\forall s_{-i} \in S_{-i}$, if equation $u_i(s_i, s_{-i}) = u_i(s_i', s_{-i})$ holds and one of the following two conditions is satisfied: ① s_i reaches an agreement earlier than s_i'; or ② s_i, s_i' reach agreements in a same period in which the offer or acceptance threshold of s_i is higher than that of s_i', an extra payoff ξ will be given to s_i so that $u_i(s_i, s_{-i}) = u_i(s_i', s_{-i}) + \xi$. Here $\xi > 0$ and $\xi \to 0$.

The aim of this assumption is to eliminate the weakly dominated strategies in the AON game during co-evolution. It can be interpreted as: In case that two strategies have an equal payoff, ①agent prefers the strategy with an earlier agreement, or ②agent prefers the strategy with higher offer or acceptance threshold if they reach agreements in the same period.

Now we analyse the co-evolutionary stability of the SPE profile s^* in two cases, in which mutation occurs on the equilibrium and non-equilibrium paths respectively.

A. Mutation on the Equilibrium Path

The equilibrium path of s^* is the first period of the AON game, so mutation will occur on o_1^1 and τ_2^1. It has been proved [9] that all mutants which do not lead to an NE will be eliminated by replicator dynamics, so we can assume o_1^1 and τ_2^1 will be mutated to x and $1-x$ respectively, $x \in [0,1]$. Table I shows the mixed populations after mutation.

TABLE I. POPULATIONS AFTER MUTATIONS ON EQUILIBRIUM PATH

Mixed Population	*SPE profile* s^*	*Proportion*	*Mutation profile* s	*Proportion*
w_1	$s_1^* = \{o_1^1, \tau_1^2, \ldots\}$	$1-\varepsilon_1$	$s_1 = \{x, \tau_1^2, \ldots\}$	ε_1
w_2	$s_2^* = \{\tau_2^1, o_2^2, \ldots\}$	$1-\varepsilon_2$	$s_2 = \{1-x, o_2^2, \ldots\}$	ε_2

Firstly, consider the case $x > o_1^1$.

In mixed population w_1, we have $u_1(s_1^*, s_2^*) = o_1^1$ and $u_1(s_1^*, s_2) = o_1^1$, so the SPE strategy s_1^* will get a payoff $u_1(s_1^*, w_2) = o_1^1$; On the other hand, we can deduce from $u_1(s_1, s_2^*) = \delta_1\tau_1^2$ and $u_1(s_1, s_2) = x$ that the payoff of mutated strategy s_1 is $u_1(s_1, w_2) = (1-\varepsilon_2)\delta_1\tau_1^2 + \varepsilon_2 x$. According to equation (1), $\dot{\varepsilon}_1 = \varepsilon_1(1-\varepsilon_1)[\varepsilon_2(x-\delta_1\tau_1^2) - (o_1^1 - \delta_1\tau_1^2)]$. The mutated strategy s_1 will die out from w_1 if and only if $\dot{\varepsilon}_1/\varepsilon_1 < 0$, from which the invasion barrier can be calculated to be $\max\varepsilon_2 = (o_1^1 - \delta_1\tau_1^2)/(x-\delta_1\tau_1^2)$.

Similarly in population w_2, we have $u_2(s_2^*, s_1^*) = \tau_2^1$ and $u_2(s_2^*, s_1) = \delta_2 o_2^2$, so $u_2(s_2^*, w_1) = (1-\varepsilon_1)\tau_2^1 + \varepsilon_1\delta_2 o_2^2$; Besides, $u_2(s_2, s_1^*) = \tau_2^1$ and $u_2(s_2, s_1) = 1-x$ will lead to $u_2(s_2, w_1) = (1-\varepsilon_1)\tau_2^1 + \varepsilon_1(1-x)$. It is worth noting that the condition ② of the assumption is satisfied here because $u_2(s_2^*, s_1^*) = u_2(s_2, s_1^*) = \tau_2^1$ and both s_2^* and s_2 reach agreements in the first period with acceptance thresholds $\tau_2^1 > 1-x$. From assumption, we have $u_2(s_2^*, s_1^*) = \tau_2^1 + \xi$. So we can rephrase the payoff of the SPE strategy s_2^* as $u_2(s_2^*, w_1) = (1-\varepsilon_1)\tau_2^1 + \varepsilon_1\delta_2 o_2^2 + \xi$. According to equation (1), $\dot{\varepsilon}_2 = \varepsilon_2(1-\varepsilon_2)[\varepsilon_1(1-x-\delta_2 o_2^2) - \xi]$. We can prove from calculation that the growth rate $\dot{\varepsilon}_2/\varepsilon_2$ of strategy s_2 is negative for $\forall\varepsilon_1 \in [0,1]$, so the invasion barrier is $\max\varepsilon_1 = 1$.

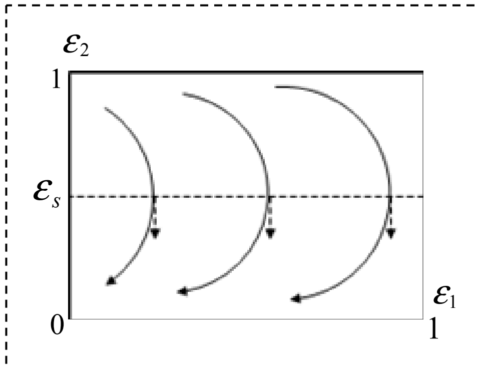

Figure 1. The Phase Graph of the Co-evolutionary System

Let $\dot{\varepsilon}_1 = 0$ and $\dot{\varepsilon}_2 = 0$, we can get four possible stable points for $(\varepsilon_1, \varepsilon_2)$: $(0,0)$, $(0,1)$, $(1,0)$ and $(1,1)$, among which only $(0,0)$ makes the second derivatives $\ddot{\varepsilon}_1 < 0$ and $\ddot{\varepsilon}_2 < 0$. Therefore, we can come to a conclusion that this co-evolutionary system will stabilize at $\varepsilon_1 = \varepsilon_2 = 0$, and all mutated strategies will be repelled. Figure 1 shows the phase graph, in which the tangent direction of each point stands for the changing trends of ε_1 and ε_2. The uniform invasion barrier of w_1 and w_2 is $\varepsilon_s = \min\{\max\varepsilon_1, \max\varepsilon_2\}$, that is, $\varepsilon_s = \max\varepsilon_2 = (o_1^1 - \delta_1\tau_1^2)/(x-\delta_1\tau_1^2)$.

Secondly, consider the case $x < o_1^1$.

In w_1, $u_1(s_1^*, s_2^*) = o_1^1$ and $u_1(s_1^*, s_2) = \delta_1\tau_1^2$, so s_1^*'s payoff is $u_1(s_1^*, w_2) = (1-\varepsilon_2)o_1^1 + \varepsilon_2\delta_1\tau_1^2$; In addition, the equation $u_1(s_1, s_2^*) = u_1(s_1, s_2) = x$ results in s_1's payoff $u_1(s_1, w_2) = x$; According to equation (1), we have $\dot{\varepsilon}_1 = \varepsilon_1(1-\varepsilon_1)[\varepsilon_2(o_1^1 - \delta_1\tau_1^2) - (o_1^1 - x)]$. In order for w_1 to repel the mutant s_1, the growth rate $\dot{\varepsilon}_1/\varepsilon_1 < 0$ must be satisfied. So the invasion barrier is $\max\varepsilon_2 = (o_1^1 - x)/(o_1^1 - \delta_1\tau_1^2)$.

In w_2, $u_2(s_2^*, s_1^*) = \tau_2^1$ and $u_2(s_2^*, s_1) = 1-x$, so s_2^*'s payoff is $u_2(s_2^*, w_1) = (1-\varepsilon_1)\tau_2^1 + \varepsilon_1(1-x)$; Furthermore, $u_2(s_2, s_1^*) = \delta_2 o_2^2$ and $u_2(s_2, s_1) = 1-x$, so s_2's payoff is

$u_2(s_2,w_1)=(1-\varepsilon_1)\delta_2 o_2^2+\varepsilon_1(1-x)$. Here conditions ① and ② of the assumption are all satisfied. For one thing, it can be proved by calculation that $u_2(s_2^*,s_1^*)=u_2(s_2,s_1^*)$, s_2^* and s_2 reach agreements in the first and second period respectively, so condition ① holds and $u_2(s_2^*,s_1^*)=\tau_2^1+\xi$; For another, $u_2(s_2^*,s_1)=u_2(s_2,s_1)$, both s_2^* and s_2 reach agreements in the first period with acceptance threshold $1-x>\tau_2^1$, so condition ② holds and $u_2(s_2,s_1)=(1-x)+\xi$. To sum up, s_2^*'s payoff will be $u_2(s_2^*,w_1)=(1-\varepsilon_1)(\tau_2^1+\xi)+\varepsilon_1(1-x)$, and s_2's payoff is $u_2(s_2,w_1)=(1-\varepsilon_1)\delta_2 o_2^2+\varepsilon_1(1-x+\xi)$. Because ε_1 is a relatively small value, we believe here that $u_2(s_2^*,w_1)-u_2(s_2,w_1)=(1-2\varepsilon_1)\xi>0$. In other words, SPE strategy s_2^* is better than the mutant s_2. So, for simplicity, we rephrase s_2^*'s payoff as $u_2(s_2^*,w_1)=(1-\varepsilon_1)\tau_2^1+\varepsilon_1(1-x)+\xi$, and keep s_2's payoff $u_2(s_2,w_1)=(1-\varepsilon_1)\delta_2 o_2^2+\varepsilon_1(1-x)$ unchanged. According to equation (1), we can get $\dot{\varepsilon}_2=-\xi\varepsilon_2(1-\varepsilon_2)$. Obviously, the growth rate of mutated strategy s_2 is negative for $\forall\varepsilon_1\in[0,1]$, so the invasion barrier is $\max\varepsilon_1=1$.

Let $\dot{\varepsilon}_1=0$ and $\dot{\varepsilon}_2=0$. As before, we can get four possible stable points $(0,0)$, $(0,1)$, $(1,0)$ and $(1,1)$. Only $(0,0)$ satisfies $\ddot{\varepsilon}_1<0$ and $\ddot{\varepsilon}_2<0$. Therefore, in this case, the co-evolutionary system will also stabilize at $\varepsilon_1=\varepsilon_2=0$, and have a similar phase graph as figure 1 with the only difference in that the uniform invasion barrier in this case is $\varepsilon_s=\max\varepsilon_2=(o_1^1-x)/(o_1^1-\delta_1\tau_1^2)$.

B. Mutation on the Non-Equilibrium Path

All sub-games beginning after the first period of the SPE are on the non-equilibrium path. Without loss of generality, assume the mutations in strategies s_1 and s_2 occur in the t_1 and t_2 period respectively, and the offer or acceptance threshold after mutation are x and y. Table II shows the mixed populations.

TABEL II
POPULATIONS AFTER MUTATIONS ON NON-EQUILIBRIUM PATH

Mixed Population	*SPE profile* S^*	*Proportion*	*Mutation profile* S	*Proportion*
w_1	$s_1^*=\{o_1^1,\tau_1^2,...\}$	$1-\varepsilon_1$	$s_1=\{o_1^1,...,x,...\}$	ε_1
w_2	$s_2^*=\{\tau_2^1,o_2^2,...\}$	$1-\varepsilon_2$	$s_2=\{\tau_2^1,...,y,...\}$	ε_2

Obviously, all strategy profiles between w_1 and w_2 will reach agreements in the first period, and $u_1(s_1^*,w_2)=u_1(s_1,w_2)=o_1^1$, $u_2(s_2^*,w_1)=u_2(s_2,w_1)=\tau_2^1$. In other words, the mutated strategies receive the same payoff as the SPE strategies. According to replicator dynamics, the mutated strategies will neither die out nor spread out, but co-exist with the SPE strategies to form a dimorphic population.

However, the mutated strategies s_1 and s_2 do not satisfy the sequential rationality, although they constitute an NE. Put differently, they are weakly dominated strategies compared with the SPE ones. Taking s_1 as an example, if the mutation rate is μ, then there must exist a positive possibility $f(\mu)$ that the AON game will proceed until the t_1 period, so that the sub-game beginning at this period will be on the equilibrium path. According to conclusions in section IV.A, mutated strategies will gradually die out and SPE strategies will be the outcome of co-evolution. As a result, we can come to a conclusion that the weakly dominated mutants occurred on the non-equilibrium path cannot invade the SPE strategies in the long run.

V. The Experimental Validation

In order to validate the co-evolutionary stability of the SPE profile, we use co-evolutionary genetic algorithm here to simulate the AON game. We will simulate a finite-horizon AON game for simplicity, since the dynamics are similar between the finite and infinite horizon versions [10].

Assume the discount factors are $\delta_1=0.8$ and $\delta_2=0.6$, and the deadline period $T=3$. We can deduce from backward induction that the SPE profile is $s_1^*=\{0.88,0.8,1\}$ and $s_2^*=\{0.12,0.2,0\}$, and an agreement will be reached in the first period to $o_1^1=0.88$ and $\tau_2^1=0.12$.

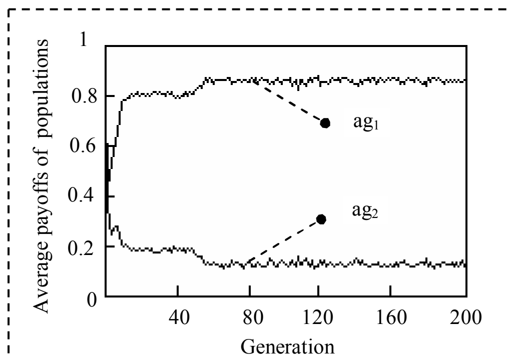

Figure 2. The Simulation Result

The simulation result is shown in figure 2. We can see clearly that both populations begin to stabilize from about the 60th generation, after which all mutants caused by the mutation operator of genetic algorithm will be repelled; The average payoffs stabilize at 0.88 and 0.12 after co-evolution, and the agreement must be reached in the first period (otherwise the sum of the payoffs will be less than one because of being discounted); Furthermore, we can see from the populations of the last generation that all strategy individuals have converged to s_1^* or s_2^*. These observations validate that the SPE profile is the eventual outcome of the co-evolution process.

VI. Conclusion and Future Work

To theoretically prove the validity of co-evolution in automated negotiations is a very important and interesting topic. In this paper, we analysed the co-evolutionary stability of the SPE profile in the AON game based on the EGT and replicator dynamics, and draw a conclusion that the SPE profile will be the eventual outcome of co-evolution process. This conclusion lays a solid foundation for the idea of using co-evolution to simulate the AON game and acquire its SPE strategies automatically. The research method in this paper is also suitable for other negotiation scenarios or protocols, in which the dynamics might of course be more complicated.

It is worth noting that we focus here only on the uninvadability analysis of the SPE profiles, of which the dynamic attainability is not concerned. For example, in figure 2, we have only proved that the populations will be locked in the SPE profile after about 60 generations, but not considered how the SPE is achieved before that. Therefore, we will emphasize on the dynamic attainability in our future work.

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