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On the effectiveness of immune inspired mutation operators in some discrete optimization problems

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ABSTRACT

Artificial immune systems have been widely applied to a variety of complex real-world problems. However, theoretical studies on artificial immune system are still limited and there is a strong need for building a rigorous theoretical foundation to better understand these heuristics. This paper contributes to a theoretical runtime analysis of immune inspired hypermutations on some discrete optimization problems. In particular, we are interested in the performance comparison among somatic contiguous hypermutations (CHM), standard bit mutations (SBM) and local mutation. We reveal that the immune inspired hypermutations can significantly outperform the standard bit mutation most often used in evolutionary algorithms on some well-known pseudo-Boolean functions including Trap and Hierarchical-if-and-only-if functions and instances of two combinatorial optimization problems, namely the Max-Cut problem and the Minimum s-t-cut problem. The proofs give some insights into the relationships between the problem characteristics and algorithmic features. The results of the analysis help strengthen the usefulness of Artificial immune systems.

1. Introduction

Over the past decades, a lot of randomized search heuristics (RSHs) have been proposed, analyzed, and applied to different discrete optimization problems. Artificial immune systems (AIS) are a special class of nature-inspired algorithms, which are based on the natural immune system of vertebrates [7,11]. AIS are new emerging fields of research in Computational Intelligence, and they have been widely applied to anomaly detection, classification and function optimization [7,11]. The B-Cell Algorithm (BCA) is one of the clonal selection algorithms based on the clonal selection principle [2], which was introduced by Kelsey and Timmis [31]. Evolutionary Algorithms (EAs) and AIS both are RSHs, and there are many similarities between EAs and AIS. However, AIS are derived from various immunological theories, i.e., the clonal selection principle, negative selection, immune networks, and the danger theory, while the EAs are based on the process of natural evolution and work on a population of candidate solutions and include selection, crossover and mutation [9].

Theoretical research of RSHs including rigorous runtime analysis is a modern and important research area in theoretical computer science and probabilistic analysis of randomized algorithms. Since RSHs have gradually been developed in recent years, they have attracted a great deal of attention. Many different theoretical research results on the performance analysis

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of RSHs have been obtained, including results for Simulated Annealing, Evolutionary Algorithms (EAs), Estimation of Distribution Algorithms (EDA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Memetic Algorithms (MA) and Random Local Search (RLS) on different kinds of pseudo-Boolean functions and many classical combinatorial optimization problems [1,20,35].

There is a significant amount of work on the applications and empirical studies of AIS [8]. Also the theoretical study has received more attention from many researchers in the past couple of years. There is a common belief that a rigorous theoretical foundation of RSHs can help us better understand the working principles, and how and why they perform well [1]. Some early theoretical work of AIS was concerned mainly on the limit behavior [41]. Since 2008, theoretical results about the runtime analysis of these heuristics have been obtained to some extent.

Initially, the theoretical research was carried out on a simple immune algorithm for some artificial pseudo-Boolean functions such as OneMax, LeadingOnes, etc. Zarges [44] analyzed the runtime of different inversely fitness proportional mutation operators often used in AIS on the OneMax function. She proved that these mutation operators are inefficient for the OneMax function. However, the performance of these operators improves drastically when considering a large population [45]. Furthermore, Jansen and Zarges [21] investigated the performance of a mutation operator with somatic contiguous hypermutation (CHM) that is positionally biased. They showed that the immune inspired CHM is slightly inferior to the (1+1) EA with standard bit mutations (SBM) on OneMax and LeadingOnes. Moreover, it is proven that CHM can beat SBM drastically even by an exponential performance gap on a function called $\text{CLOB}_{b,k}$. While the operator CHM in [21] suffers from a positional bias, later, Jansen and Zarges [22] considered another variant CHM wrapping around which has no positional bias at all.

Recently, a novel performance evaluation by using the fixed budget perspective has been introduced [25]. This perspective considers the expected performance within a specific computational budget instead of analyzing the expected time needed for optimization. This new performance measure is closer to practical optimization problems when the optimal value is unknown. Based on this perspective of fixed budget computations, Jansen and Zarges analyzed the performance of some CHMs on the well-known example functions OneMax [26] and H-IFF [27]. Moreover, they presented the first theoretical results of standard evolutionary algorithms and artificial immune systems in dynamic optimization environments [24].

In the case of combinatorial optimization problems, some different theoretical results on the runtime analysis of AIS have been obtained. One of the first performance analyses of the BCA for NP-hard problems is by Jansen, Oliveto and Zarges [28], who analyzed the runtime of the BCA on the vertex cover problem. They showed that the BCA can beat EAs with only mutation on a bipartite graph instance of the vertex cover problem. It is also proved that there is another vertex cover instance where the BCA outperforms a crossover-based EA. Afterwards, Jansen and Zarges [23] analyzed the performance of the BCA on some instances of the longest common subsequence problem. They revealed that the BCA performs better than EAs on these instances.

However, one cannot hope that there exists an algorithm that performs better than all other algorithms across all possible problems. This implies that no algorithm can be always efficient for all specific problems. Wolpert and Macready [43] presented the No Free Lunch Theorem (NFL) to show the limitations of stochastic search algorithms when considering the optimization of all possible functions. Furthermore, Igel and Toussaint [19] gave a more general NFL theorem for the non uniform distributions of fitness. Qian et al. [40] proved that the OneMax and Trap problem are the easiest and the hardest cases for the (1+1) EA with mutation probability less that $\frac{1}{2}$, respectively. Recently, He et al. [14] also presented the easiest and hardest fitness functions for RSHs, and revealed that the unimodal functions are the easiest and deceptive functions are the hardest in terms of the time-fitness landscape. This further explains that RSHs are not always efficient for all problems.

Although the above results reveal the effectiveness of the immune inspired hypermutations in some specific instances. These results, however, do not describe any impact of different algorithmic features on the runtime. They do not compare the runtime with the standard bit mutation and local mutation operators. We aim to know the effectiveness of different mutation operators in discrete optimization problems.

In this paper, we further contribute to theoretically investigating the performance of the immune inspired hypermutations on some other optimization problems. Moreover, we compare the performance of the immune inspired hypermutations with the performance of local search operators and standard bit mutations used in the (1+1) EA. More precisely, we prove that the immune inspired hypermutations perform better than the standard mutation-based (1+1) EA on some instances in both pseudo-Boolean functions and combinatorial optimization problems. It is shown that the immune inspired hypermutations can optimize some well-known pseudo-Boolean functions in expected polynomial runtime, i.e., TRAP and Hierarchical-if-and-only-if (H-IFF) function, while standard bit mutations most often used in evolutionary algorithms need exponential expected runtime. Furthermore, we extend such analyses to problems from combinatorial optimization, namely the Max-Cut problem and the Minimum s-t-cut problem. We will see that immune inspired hypermutations are efficient on some instances of these two problems while other RSHs like the (1+1) EA and local search algorithms fail to find a global optimum, as they need an exponential or infinite number of steps.

The remainder of the paper is organized as follows. Section 2 introduces some basic definitions, notations, and the algorithms considered in this paper. Section 3 analyzes the runtime of the immune inspired hypermutations for artificial functions. Sections 4 and 5 investigate some instances of Max-Cut, and Minimum s-t-cut, respectively, and compare the performance of different mutation operators on these instances. Finally, Section 6 presents conclusions and future work.