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A modified Imperialist Competitive Algorithm for multi-robot stick-carrying application

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HIGHLIGHTS

- Multi-robot stick-carrying problem is solved by the proposed ICFA.
- ICFA is fusion of motion dynamics of Firefly and Imperialist Competitive Algorithm.
- Modified random-walk strategy is proposed to balance exploration/exploitation.
- Simulation results confirm efficiency of the proposed ICFA in the state-of-art.
- Experiment with twin Khepera-II mobile robots is done amidst static obstacles.

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ABSTRACT

The paper proposes a novel evolutionary optimization approach of solving a multi-robot stick-carrying problem. The problem refers to determine the time-optimal trajectory of a stick, being carried by two robots, from a given starting position to a predefined goal position amidst static obstacles in a robot world-map. The problem has been solved using a new hybrid evolutionary algorithm. Hybridization, in the context of evolutionary optimization framework, refers to developing new algorithms by synergistically combining the composite benefits of global exploration and local exploitation capabilities of different ancestor algorithms. The paper proposes a novel approach to embed the motion dynamics of fireflies of the Firefly Algorithm (FA) into a socio-political evolution-based meta-heuristic search algorithm, known as the Imperialist Competitive Algorithm (ICA). The proposed algorithm also uses a modified random-walk strategy based on the position of the candidate solutions in the search space to effectually balance the trade-off between exploration and exploitation. Thirteen other state-of-art techniques have been used here to study the relative performance of the proposed Imperialist Competitive Firefly Algorithm (ICFA) with respect to run-time and accuracy (offset in objective function from the theoretical optimum after termination of the algorithm). Computer simulations undertaken on a well-known set of 25 benchmark functions reveal that the incorporation of the proposed strategies into the traditional ICA makes it more efficient in both run-time and accuracy. The performance of the proposed algorithm has then finally been studied on the real-time multi-robot stick-carrying problem. Experimental results obtained for both simulation and real frameworks indicate that the proposed algorithm based stick-carrying scheme outperforms other state-of-art techniques with respect to two standard metrics defined in the literature. The application justifies the importance of the proposed hybridization and parameter adaptation strategies in practical systems.

1. Introduction

Multi-robot co-ordination has emerged as an important part of robotics research since late 1980s [1]. The problem of co-ordination of multiple robots arises in numerous applications, for example, in factory environment (to transfer materials and products between workstations), in patient-carrying systems in hospitals/airports and in defense and security systems. Co-ordination in multi-agent robotics aims at synchronizing and harmonizing the simultaneous actions of multiple robotic agents in pursuit of a specific goal. One of the crucial challenges for multi-agent co-ordination systems is to design appropriate coordination strategies between the robotic agents that enable them to perform

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effectively and time optimally in complex workspace. There exists extensive literature on multi-robot co-ordination employing different approaches including graphs [2], Voronoi diagrams [3], potential field [4], adaptive action selection [5], intention inference [6], cooperative conveyance [7], and perceptual cues [8]. The traditional mathematical model of a multi-robot co-ordination system can be recast in the settings of an optimization problem [9] with an aim to efficiently utilize the system resources. The objective of optimization here is to determine optimal robotic actions based on the sensory readings collected from the environment by the robots to meet one or more desired objectives of the problem. Thus optimization of the objective functions, characterizing the functionality of a multi-robot co-ordination system, provides the feasible solutions for the qualitative system performance.

The paper proposes a novel formulation of a multi-robot stick-carrying system as an optimization problem. The stick-carrying problem [10] includes two robots to jointly carry a stick from an assigned initial position to a specified final position in a given environment, without collision with the given obstacles near the robots and the stick, constrained by the constant distance (equal to the stick length) between the robots. The sensory data of the robots, offering the range measurements of the stick from the nearby obstacles and the workspace boundary, are the input variables of the optimization problem while the output variables being the necessary amount of rotation and translation of the stick (by the robots) to transfer it in small step towards the goal. The primary objective function of the stick-carrying optimization problem in this context is concerned with the minimization of the time consumed by the robots (i.e., the length of the path to be traversed by the robots) for complete traversal of the planned trajectory. In other words, we expect the robots to plan the local trajectory, so that the stick is shifted from a given position to the next position (sub-goal) in a time-optimal sense avoiding collision with the obstacles or the boundary of the world-map in the robots' workspace. The optimization algorithm is executed for each local planning step to carry the stick by a small distance. A sequence of local planning ultimately transports the stick to the desired goal position.

In the past decades, a plethora of computing algorithms has been proposed in the domain of numerical function optimization. Traditional derivative-based optimization techniques, such as Newton–Raphson method, quasi-Newton strategy, steepest descent leaning algorithm and the like completely rely on the derivative information of the objective function guiding the direction of search in the fitness landscape. These methods perform satisfactorily when the objective function to be optimized is globally concave over the search space. However, in real world scenario, the objective functions are sometimes found to be irregular and multi-modal comprising multiple local optima, saddle points and discontinuities. Traditional gradient-based optimization algorithms are, therefore, ineffective to capture the global optima of these non-differentiable functions.

Since early 1990s, Evolutionary Algorithms (EAs) have emerged as a derivative-free stochastic global optimizer with capability of providing promising results to optimize the non-differentiable functions of the real world problems. EAs with the real-valued vector representation of the potential solutions of a complex physical system have earned wide popularity due to its flexibility and simple search strategy in the high-dimensional hyper-space and robust performance in the dynamic environment. They commence with a population of trial solutions, symbolizing the potential solutions of the problem. The relative integrity of a solution can be assessed by evaluating its associated objective function value (often called fitness). New solutions are then generated by population-based evolutionary procedure. Finally, a greedy selection step is employed being inspired by Darwinian principle of the survival of the fittest. The selection step is responsible for filtering and promoting better candidate solutions from the candidate pool to the next evolutionary generation.

The radical reduction in the computational time in the recent past coupled with the increasing demand to solve complex real world problems has enhanced the quest for more proficient nature-inspired metaheuristics. It is to be noted that two fundamental processes drive the evolution of an EA population—the diversification process, which enables exploring different regions of the search space and the intensification process, which ensures the exploitation of previous knowledge about the fitness landscape. The effects of such exploration and exploitation processes need to be competently balanced by an EA for its qualitative performance both w.r.t. computational accuracy and run-time complexity over different fitness landscapes.

However, the superiority of an EA in optimizing different objective functions is subjected to the No Free Lunch Theorem (NFLT) [11]. According to NFLT the expected effectiveness of any two traditional EAs across all possible optimization problems is identical. A self-evident implication of NFLT is that the elevated performance of one EA, say A, over other EA, say B, for one class of optimization problems is counterbalanced by their respective performances over another class. It is therefore practically difficult to devise a universal EA that would solve all the problems. This apparently paves the way for hybridization of EAs with other optimization strategies, machine learning techniques, and heuristics. In evolutionary computation paradigm, hybridization [12] refers to the process of integrating the attractive features of two or more EAs synergistically to develop a new hybrid EA. The hybrid EA is expected to outperform its ancestors w.r.t. both accuracy and complexity over application-specific or general benchmark problems. The fusion of EAs through hybridization hence can be regarded as the key to overcome their individual limitations.

In this paper, we propose a simple yet very powerful hybrid EA by collegially coalescing the attributes of two global optimizers—the traditional Imperialist Competitive Algorithm (ICA) [13,14] and the traditional Firefly Algorithm (FA) [15]. ICA is a novel socio-politically motivated population-based meta-heuristic which has revealed remarkable performance in variant fields of optimization problems. The population individuals of ICA, resembling the countries in the world, are categorized as imperialist (best countries) and colonies (rest of the population) based on their associated objective function values. The entire population is subsequently divided into a number of sub-populations, known as empires, each consisting of an imperialist and a number of colonies (randomly selected based on the ruling power of the respective imperialist). The foundation of ICA is rooted in three elementary operations—(1) assimilation, which allows the possible movement of the colonies to their respective imperialist (strengthening exploitation), (2) revolution, which brings out sudden change in the countries' socio-political views (preventing premature convergence of ICA) and (3) the imperialistic competition, which reinforces the powerful empires with an attempt to collapse the weakest one. There exists a vast literature on the modification and application of ICA. Among these the following contributions need special mentioning.

A new EA has been proposed in [16] by combining ICA, Differential Evolution (DE) [17] and K-means clustering algorithm. ICA is also successfully hybridized with EA [18] and Genetic Algorithm (GA) [19]. ICA is treated as a local search strategy to develop a new memetic algorithm in [20]. A new variant of ICA has been introduced in [21] by strengthening the interaction among the imperialists of all the empires. A modified version of ICA is proposed in [22] based on the attraction and repulsion profiles between countries in an empire and is applied to solve a brushless direct current wheel motor design problem. A hybrid ICA, along