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Parameter tuning of PID controller with reactive nature-inspired algorithms

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HIGHLIGHTS

- PSO is the most reactive nature-inspired algorithm among BA, HBA, GA, DE, CS and PSO.
- Population based nature-inspired algorithms (e.g., PSO, BA, HBA, DE and CS) can be used for online implementation of PID parameter tuning.
- Low population sizes in nature-inspired algorithms are sufficient for PID tuning to obtain reactive response of SCARA robot.

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ABSTRACT

A PID controller is an electrical element for reducing the error value between a desired setpoint and an actual measured process variable. The PID controller operates according to its input parameters, which need to be set before its run. The optimal values of these parameters must be found during the so-called tuning process. Today, this process can be automatized using stochastic, nature-inspired, population-based algorithms, such as evolutionary and swarm intelligence-based algorithms. Unfortunately, these algorithms are too time consuming, and so the reactive, nature-inspired algorithms using a limited number of fitness function evaluations are proposed in this paper. Two reactive evolutionary algorithms (differential evolution and genetic algorithm), and four reactive, swarm intelligence-based algorithms (bat, hybrid bat, particle swarm optimization and cuckoo search), were used to tune the PID controller in our comparative study. Only ten individuals and ten iterations (generations) were used in order to select the most appropriate optimization algorithm for fast tuning of controller parameters. The results were compared using statistical analysis and showed that particle swarm optimization is the best option for such a task.

1. Introduction

A PID controller is an electrical element for reducing an error value between a desired setpoint and an actual process variable. The desired setpoint can be set by a function generator, while the actual process variable is measured by a sensor. A set of input parameters is required for proper controller service. Therefore, the optimal input parameters need to be searched for in a so-called tuning process. Only tuned parameters ensure correct behavior of the electrical and mechanical systems, long-term service, and damage prevention. The PID controller can be described as a closed-loop system, i.e., a system in which the actual process variable has to be controlled. There are many examples of closed-loop systems, such as:

- robot mechanism control,
- temperature control,
- level control,
- direction control, etc.

In this paper, we propose parameter tuning of the PID controller controlling the robot arm mechanism. This arm simulates the movement of a human arm and consists of two joints powered by two motors. This type of robot arm is also referred to as a Selective Compliance Assembly Robot Arm (SCARA) and was designed by Hiroshi Makino in 1980. The structure of the robot arm enables precise positioning in industrial robotics and electronics. Usually, SCARA is accompanied by another motor or hydraulic piston for vertical movement of the robot's top. The main task of the SCARA is to capture objects, manipulate them in 3-D space, and then put

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them into another position. We should note that only the positional part of the robot without vertical manipulator was used in our laboratory experiments.

The task of optimization is to search for the optimal input variables by known model and output variables [1]. There are numerous optimization problems that can be divided into many classes, e.g., continuous, numeric, discrete (also combinatorial), multi-objective, constrained, etc. Not all algorithms achieve the same results for all classes of optimization problems. This is in accordance with the No-Free Lunch theorem (NFL) [2], which states that the results of two optimization algorithms are equal when compared to the all classes of problems. In our case, it handles about the relatively simple problem belonging to a class of discrete/numerical problems being solved in four dimensional search space.

Recently, the problem of parameter tuning of the PID controller has been solved using a different stochastic, nature-inspired, population-based algorithms and even computational intelligence algorithms, including fuzzy systems, artificial neural networks, and artificial immune systems [3]. A survey of these algorithms can be found in [4–6]. We propose reactive algorithms, e.g. algorithms that use only little time to converge to the final result. Ten individuals and ten iterations were used to realize, how well reactive algorithms can perform, if they would be applied even for online tuning of controller parameters.

In general, the stochastic, nature-inspired, population-based algorithms are inspired by two aspects of the natural world. The first is Darwinian evolutionary theory [7], whereby only the more adapted individuals can survive in the unforgiving struggle for existence. This inspiration led to the emergence of evolutionary algorithms (EA), where the better solutions, generated by using operators crossover and mutation, can survive and transfer their values in the next generation in the simulated evolution. Alan Turing was the first engineer to incorporate the principles of the natural selection into an algorithm [8] and his first work in artificial intelligence was the *Intelligent Machinery*. Based on Turing's results, John Holland implemented a genetic algorithm (GA) in 1988 which even today remains the most widely-used evolutionary algorithm [9]. Differential evolution (DE), developed by Storn and Price in 1995 [10], was one of the youngest EAs especially suited to continuous global optimization.

The second inspiration for the development of the optimization algorithms emerged in 1995, when a Particle Swarm Optimization (PSO) was developed by Russel Eberhart and James Kennedy [11]. It was based on social relations among individuals in swarm. Many types of biological species have been mimicked since then, including birds, fish, ants, bees, cuckoos, bats, and termites. They all rely on a randomly generated population of particles which are continuously being moved around a search space using variation operators. The velocity of a single particle is calculated for every dimension of the problem and is later added to the appropriate position, thus exploring the problem search space. In 2009, an optimization algorithm called cuckoo search (CS) was developed by Yang and Deb [12] based on the behavior of the cuckoo, which dumps its eggs into random nests. A year later, the bat algorithm (BA), which mimics the phenomenon of echolocation in micro bats, was proposed in 2010 by Yang [13].

It is well known that the stochastic, nature-inspired, population-based algorithms are extremely time consuming for finding near-optimal solutions. The number of fitness function evaluations is the main factor responsible for the time complexity of these algorithms. Typically, it is expressed as a product of population size multiplied by the maximum number of generations. However, for the robot arm operating in an environment, it is important how rapidly a reaction to environmental change is performed. In order to make these kinds of algorithms more reactive, the number of fitness function evaluations needs to be limited. Therefore, these algorithms are used as reactive, nature-inspired algorithms in the study.

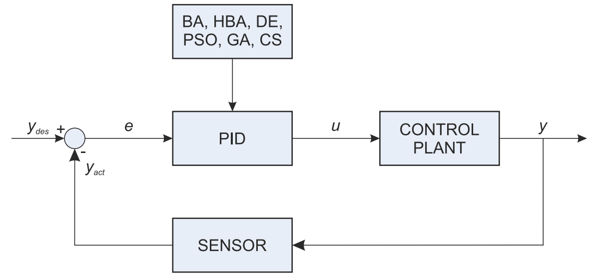

Fig. 1. SCARA robot arm mechanism.

The purpose of this paper is to compare different reactive, nature-inspired algorithms for tuning parameters of the PID controller in order to discover the most suitable algorithm for use in solving this class of problem. The reactive, nature-inspired algorithms such as BA, HBA, PSO, DE, GA, and CS are compared in order to show which of them is most useful in working with small population sizes and small generation numbers.

The remainder of the paper is organized as follows. Section 2 describes the system equipment of a highly nonlinear SCARA robot mechanism, i.e., the computer control hardware and simple PID position controller used during the development and testing of the optimization algorithms. In Section 3, we discuss stochastic, nature-inspired, population-based algorithms. Section 4 deals with a description of the experiments and the results of the nature-inspired algorithms used in the comparative study. The paper concludes with a summary of the work and the suggestions for further development.

2. Description of the 2-DOF SCARA robot arm

Robotics arose from the human desire to supplant human labor with machines for long-running, boring, and even dangerous tasks. Especially in Japan, robots already do housework, while their work on conveyor belts is indispensable in industry. Today, we cannot imagine painting cars without robots. Thus, a robotic arm successfully replaces the human arm and even outdoes it when needed. However, some form of feedback is necessary in order to move the arm in a specific environment. The PID controller is the most common device for using feedback in natural and man-made systems.

In engineering applications, this controller appears in many different forms, i.e., as a stand-alone controller, as a part of distributed systems, or built into embedded systems [14]. A lot of technological changes influenced the development of the controller, in particular the introduction of microprocessors. These provide additional features, such as automatic parameter tuning, gain scheduling, and continuous adaptation. A robotic arm is moved and positioned using a closed-control loop that consists of a PID controller, a control plant, and a sensor. The PID controller is part of a system that controls the electro-mechanical part of the SCARA robotic arm (control plant). The control plant consists of electrical motors to lift and lower the arm. The mechanical part obeys the mechanical laws. The sensor obtains feedback from the control plant (Fig. 1). The input of the PID controller is an error value e, which is transformed into the output signal u, according to Eq. (1), as follows

$$u(t) = K_P \cdot e(t) + \frac{1}{T_i} \cdot \int e(t)\,dt + T_d \cdot \frac{de(t)}{dt}, \tag{1}$$

where $e(t)$ means

$$e(t) = y_{des}(t) - y_{act}(t). \tag{2}$$