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Feedback-control operators for improved Pareto-set description: Application to a polymer extrusion process

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ABSTRACT

This paper presents a new class of operators for multiobjective evolutionary algorithms that are inspired on feedback-control techniques. The proposed operators, the *archive-set reduction* and the *surface-filling crossover*, have the purpose of enhancing the quality of the description of the Pareto-set in multi-objective optimization problems. They act on the Pareto-estimate sample set, performing operations that eliminate archive points in the most crowded regions, and generate new points in the less populated regions, leading to a dynamic equilibrium that tends to generate a uniform sampling of the efficient solution set. The internal parameters of those operators are coordinated by feedback-control inspired techniques, which ensure that the desired equilibrium is attained. Numerical experiments in some benchmark problems and in a real problem of optimization of a single screw extrusion system for polymer processing show that the proposed methodology is able to generate more detailed descriptions of Pareto-optimal fronts than the ones produced by usual algorithms.

1. Introduction

One of the main concerns in the design of multi-objective evolutionary algorithms (MOEAs) has been to ensure the quality of the sample set of Pareto-optimal estimates that is generated by the algorithm. The quality measure is, by itself, multi-dimensional, and there are not, up to now, any definitive standards that represent it (Zitzler et al., 2003; Auger et al., 2012). A high-quality solution set can be defined as a set of samples that reach, as long as possible, the exact Pareto-set, and is representative of the whole extension of the Pareto-set (Silva et al., 2007; Zitzler et al., 2010). It should be noticed that a MOEA can be built with the purpose of describing a subset of the Pareto set, in the cases in which some *a priori* or *online* decision information is available (Kim et al., 2012; Sinha et al., 2013). In those cases, the quality measures should refer to the representation of such subsets (Auger et al., 2012).

This paper introduces new operators that can be used to enhance the ability of a MOEA to represent the Pareto set in detail, with a uniform spread of the samples: the *sphere-control operators*. Such operators are based on the information about the distances between every pair of solution samples in a set – this motivates the denomination of "sphere" operators. The key idea is the usage of a *feedback-control* inspired scheme (Ogata, 2001) in order to establish a dynamic equilibrium along the algorithm iterations, associated to the high-quality description of the Pareto-set. While such a high-quality description is not reached, some measured variables do not reach an equilibrium, causing a control action that will enhance a quality metric.

The proposed methodology is applied to an optimization problem of the operational and screw geometrical parameters of a single screw polymer extrusion system. In this problem, a modeling routine describing properly the complex process developed is necessary. This involves the mathematical description of the different phases suffered by the polymer inside the machine (Gaspar-Cunha, 2009). This practical problem of strong industrial relevance concerns the employment of multiobjective optimization on a simulation model for the purpose of gaining knowledge about possible efficient operating modes to be implemented in a real machine. The main purpose of such a multiobjective optimization study is to obtain

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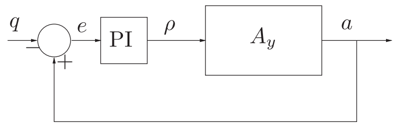

Fig. 1. Diagram of a mechanism, inspired on a PI feedback control loop, that controls the number of points stored in the archive set.

different optimal solutions that will help the polymer engineers in selecting the best operating conditions and/or screw geometry. Further discussions about the application of evolutionary computation methods for problems in materials science and engineering are reported in Paszkowicz (2013).

An instance of application of a feedback-control inspired scheme, as proposed here, is represented in Fig. 1. In this figure, the measured variable is the error $e = q - a$, which feeds a mechanism that is inspired in the proportional-integral (PI) controller, which in turn determines the value of the control variable ρ. ρ, which represents the radius of the spheres associated to the points in the archive file, plays the role of the control input variable, while the variable a, which represents the number of points in the archive file, plays the role of the controlled variable. The pre-established reference number of points in the archive, denoted by q, will be attained in an equilibrium[1] situation that will be reached due to the feedback mechanism.

In the equilibrium, $e = 0$ (which means the desired result of $a = q$). As in other contexts of application of feedback-control techniques, the role of the feedback-control inspired scheme here is to induce an overall system behavior that presents low sensitivity to variations in the initial conditions and in the algorithm parameter values, delivering stable results, with repeatability in the reach of high-quality solution sets (Ogata, 2001). The error variables are defined here such that the feedback loop reaches an equilibrium only when a good description of the Pareto-set is attained.

Specifically, two sphere-control operators are presented here: an *archive-set reduction* operator, which controls the number of non-dominated solutions that are stored, and a crossover operator that is applied in the archive set, the *surface-filling crossover*. The archive-set reduction plays the role of solution density reduction in the most crowded regions of the Pareto-set. The surface-filling crossover is to be applied in the less crowded regions of the Pareto-set, in order to fill eventual gaps in its description. The equilibrium between the opposite actions of surface-filling and archive-reduction, attained by a feedback-control inspired scheme, leads to an ultimate description of the Pareto-set that is composed of samples that are evenly distributed in the space of objectives.

Feedback-control inspired mechanisms, based on the principles of a switched controller and of a proportional-integral (PI) controller, are employed in the surface-filling operators and in the archive-set reduction operator, in order to enhance the distribution of solutions along the Pareto surface. This motivates the denomination of "sphere-control" operators. These operators are to be employed together, since their effects are complementary, and their dynamic interaction is necessary in order to achieve the desired behavior.

It should be noticed here that the idea of feedback-control inspiration constitutes a further step beyond some studies that have considered the theme of *parameter adaptation* in evolutionary computation. Examples of those studies can be found for instance in Vasconcellos et al. (2001), McGinley et al. (2011), Lin and Chen (2013), and Jebari et al. (2013). The introduction of feedback control concepts in order to state the parameter adaptation procedures allows the recovery, within the field of evolutionary computation, of some well-established results from control theory concerning closed-loop system dynamics and stability. Some preliminary studies concerning the proposed feedback-control scheme have been presented by the authors in Takahashi et al. (2009). The ideas presented here also have connection with the ones presented in Takahashi et al. (2004) and Silva et al. (2007) which employ "sphere" operations which are similar to the archive-set reduction operator presented here, yet without any feedback adaptation scheme.

The basic idea, both in that references and here, is that a "sphere" means roughly a domain in which the information gained by a solution point in its center would be representative – with no need of further function evaluations inside such a sphere. Bui et al. (2008, 2009) also employ the concept of "spheres" for construction of an MOEA (multi-objective evolutionary algorithm), with a dual meaning: in that cases, the "sphere" is the domain in which a local search is conducted, with sub-populations assigned to perform searches inside each sphere.

In the specific formulation that is presented here, the proposed operators are structured for continuous-variable spaces. However, the adaptation for discrete-variable problems can be performed directly, provided that some distance metric becomes defined in the discrete-variable space. This can be performed according to the guidelines presented by Carrano et al. (2010).

It should be noticed that the proposed methodology may be supplemented by the usage of local search operators, that can enhance the precision of solutions if applied along the algorithm iterations (Wanner et al., 2008), or even provide a certificate of optimality in some cases (Takahashi et al., 2011). Those hybridizations are not discussed further, in order to privilege the presentation of the main aspects of the methodology proposed here.

This paper is structured as follows. A discussion about multi-objective evolutionary algorithms is provided in Section 2. The proposed feedback-control inspired operators are presented in Section 4. Section 3 presents a modified version of the classical NSGA-II algorithm, in which the proposed sphere-control operators are included. The results of numerical tests on some benchmark problems are presented in Section 5. The numerical tests show that the proposed methodology leads to a significant enhancement of the ability of the algorithm for reaching a fine-grained description of the Pareto-optimal set. Finally, in Section 7, the proposed algorithm is employed in the problem of polymer extrusion process design. The results are compared with the ones obtained using the basic NSGA-II and with another algorithm, the RPSGA, that was employed formerly for dealing with the same problem. The results support the conclusion that the proposed methodology is able to significantly enhance the description of the efficient solution set in this practical problem too.

2. Multiobjective evolutionary algorithms

Consider $f(\cdot) : \mathbb{R}^n \mapsto \mathbb{R}^m$ a vector-valued real function. Let $f_i(\cdot)$ denote the i-th coordinate of the function in the image space. The multiobjective problems appear from the partial ordering induced by the relation of *dominance*:

$$u \prec v \Leftrightarrow \begin{cases} f_i(u) \le f_i(v) \quad \forall i = 1, \dots, m \\ \text{and} \\ \exists i \in \{1, \dots, m\} \text{ such that } f_i(u) < f_i(v) \end{cases} \tag{1}$$

[1] According to the analogy employed here, the *equilibrium* refers to the situation in which the algorithm variables converge to values that remain fixed along the algorithm iterations.