非劣个体,均用一对一方式替换父代个体中受支配的劣于个体;在模型II中,每次迭代获得的所有非劣个体,仅从中随机选取一个非劣个体用于替换父代个体中任意一个被支配个体;在模型III中,采用可行性法则进行替换操作.同时,算法根据种群中可行解与不可行解的比例以及解的目标函数值与约束违约度,适应性地从3种模型中选择一种模型进行父代与子代间的替换.另外,该算法还引入一种不可行解的存档和替换机制,其旨在于引导种群向可行域靠近.

在2010年的约束优化的国际竞赛中,Tasgetiren和Suganthan等人[65]提出了eDE(ensemble of differential evolution algorithms)算法.在该算法中,种群中每个个体采用不同的差分进化策略(比如DE/*best*/1/*bin*,VPS).在算法的不同过程中采用不同的约束处理技术,比如可行性准则,用于选出种群中最好的个体.当产生一个新的个体后,ε水平比较用于判断父代个体和子代个体的优劣,在VPS(variable parameter search)操作产生的子代个体和父代个体间之根据自适应惩罚适应度进行比较.

Mani和Patvardhan[66]通过实验和理论分析发现适应性罚函数法和可行性法则之间存在性能互补的关系(存在优势和劣势互补),设计了一种双种群的自适应协同法,该方法使用了两个同等规模的种群.在进化的过程中,第1个种群中个体采用自适应罚函数法来计算个体的适应度值,第2个种群中个体采用可行法则计算个体的适应度值.同时,第2个种群的个体与第1个种群进行个体交换(信息交流)来自适应地调整惩罚系数.

Gan和Peng等人[67]提出了一种自适应决策者(adaptive decision maker,简称ADM),该ADM以自适应惩罚函数的形式决定候选解(子代群体中的非劣个体)是否取代其父代个体.在每一代开始时,先从种群中随机选取u个个体组成一个群体,对群体中个体进行单形交叉(simplex crossover,简称SPX)操作后产生新的子代群体;然后,采用Pareto占优的选择准则从子代群体中找出所有的非劣个体;最后,根据转换后的自适应惩罚函数公式(31)来计算个体的适应度值,再从种群中选择一个最优的非劣个体(惩罚适应度最好的个体),并将此非劣个体与种群中最差的劣于个体(惩罚适应度最差的个体)进行比较,如果非劣个体具有更小的目标函数值,则立即用新的非劣个体取代父代个体:

$$F(x)=f(x)+10^{\alpha(1-\rho)}\cdot v(x) \tag{31}$$

其中,$f(x)$为目标函数,$v(x)$为个体总的约束违反程度,ρ为当前种群中可行解的百分比,α满足区间[1,15].该方法存在的主要限制在于,需要反复实验来进行参数的调优.

Deb和Datta[68]提出一种多目标优化和惩罚函数方法相结合的方法来处理约束优化问题.在方法中,约束优化问题被转变成无约束优化问题.在每一次迭代,首先用双目标优化法找到非支配前沿,若满足条件(隔一定代数t),根据当前非支配前沿与惩罚函数之间存在的关系(在二维坐标系(f-v)里,非支配前沿中位于约束违约度等于零处的点斜率来估计惩罚函数中惩罚系数)确定优良惩罚系数的估计值,然后利用罚函数法将约束问题转变成无约束优化问题,并用局部搜索模型来求解转换后的无约束优化问题,直到终止条件满足(解在局部搜索前后所对应的目标函数值之间的差值小于0.000 1),最终得到约束问题的最优解.在文献[68]的基础上,他们加入了一种自适应的约束标准化技术[69].近年来,他们再次提出一种基于个体惩罚的约束处理方法[70],与之前提出的方法不同之处在于,该方法利用双目标优化法来确定每个约束条件的惩罚系数的优良估计.

3 亟待解决的问题

虽然约束优化进化算法已经取得了一定的成果,但是仍有很多问题需要解决,主要是:

(1) 等式约束处理

目前,约束优化进化算法对于等式约束优化问题的约束效果并不令人满意,难以收敛算法最优解.目前主要采用动态缩小δ值来提高算法的收敛性能,但面对非线性等式约束、离散等式约束等问题,依然具有较大的挑战.

(2) 离散约束优化问题

在该类约束优化问题中,问题的可行区域是离散的,这使得算法容易陷入某个可行区域中的最优解,难以获得全局最优解.如何使得搜索能穿梭于各个可行区域间,是该问题的主要挑战.多种群、分布估计可能是解决该问题的可行方案之一.

(3) 约束条件与优化目标之间的不平衡

约束优化不仅要求所得解的质量,同时要求满足约束条件.对于有些情况,如过分强调满足约束条件,将有可能导致搜索偏离性能好的区域;相反,如果过分强调解的质量,则有可能导致搜索空间偏离可行域.因此,如何根据问题的先验信息和从搜索过程中得到的知识来有效协调约束与目标之间的不平衡非常重要.

(4) 可行解与不可行解的分别对待

约束优化问题相对于普通约束优化问题,其本质区别在于如何对待不可行解携带的信息.在早期的研究中,对该问题的研究取得了较大的进展,但近年来对该基本问题并没有取得实质性的进展.这主要是由于近年来进化算法的搜索效率得到了快速的发展,弥补了约束处理的不足.模糊理论、粗糙理论、ε约束处理等技术可能是该问题的研究方向.

(5) 普适的约束处理技术

目前,不同的约束处理技术对应不同的随机搜索技术有着不同的搜索效率.无免费的午餐定理告诉我们,没有任何算法能对所有问题都高效.但我们能不能设计一种对大多数类别算法都高效的约束处理机制?这将会是未来研究的方向之一.

(6) 自适应约束处理技术

正如前面所说,不同的约束处理技术对应不同的随机搜索技术有着不同的搜索效率.设计一种针对不同的搜索状态而采用不同的约束处理机制,自适应地选择不同的约束处理技术可能是可行的方案之一.另外,超启发式框架也具有一定的可行性.

4 结束语

约束优化进化算法是智能优化算法研究领域研究的重要课题之一.虽然经过多年的研究,但依然存在较多的问题亟待解决.本文对现有进化算法中的约束处理技术进行了系统的分析,并将其根据处理约束的方式不同划分为 6 大类,同时,对各方法的研究现状和主要不足进行了逐一分析,最后给出了进化算法中的约束处理技术研究亟待解决的问题与拟解决方案.由于问题所涉及的方面过多,不可能面面俱到,希望与研究者们广泛交流共同促进该领域的发展.

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