

Multiobjective Cascade Control System Design with an application to Level Control in Liquid Level process

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Abstract: This paper proposes a Multi-Objective Cascade Control approach to tune the various controllers employed in the cascade control loop. Most of the modern cascade loops require simultaneous tuning of primary and secondary controllers and hence the design task becomes complicated. Non-Dominated Sorting Genetic Algorithm (NSGA-II) and Non-Dominated Sorting Particle Swarm Optimization algorithm (NSPSO) based multiobjective approaches are employed in the design to fine tune the controller parameters of both primary and secondary loop. Inner loop comprises of flow process and the outer loop comprises of level process. The process considered in this paper is highly non-linear with varying time delay and provides a challenging test bed for most of the modern control problems. Experimental results confirm that a multi-objective, Pareto based NSPSO search gives a better performance for regulatory process when compared to NSGA-II. Finally, multiobjective optimization using NSPSO for the level process are compared with NSGA-II and the former exhibit good disturbance rejection capability which is a primary factor considered in cascade control.

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1. Introduction

Control Engineering problems are characterized by several multiple conflicting objectives, which have to be satisfied simultaneously which in turn yields Pareto-optimal solutions. Lot of Researchers have employed various techniques for cascade control of various processes. To improve overall control system performance, where multiple loops are involved cascade control becomes important. Cascade loops are employed where disturbances acting on the secondary process have major impact on the primary process. The system can lower the effect of the disturbances entering the secondary variable on the primary output. The task of regulating the level in an process control system is a challenging problem. Disturbances arising in the secondary loop further complicate the dynamics of the control problem. Due to these reasons, level control is viewed as an benchmark for control of highly non linear processes. Earlier level Control was performed using linear conventional controllers by employing cascade and feed forward controllers as proposed by Mcmillan. They suffer from the problems of robustness and load disturbances. Cascade control has two objectives. First is to suppress the effects of disturbances on the primary process output via the action of a secondary or inner control loop around a secondary process measurement. The second is to reduce the sensitivity of a primary process variable to gain variations of the

part of the process in the inner control loop. A robust fuzzy cascade control strategy is used with minimum number of rules for any number of inputs [1]. In main steam temperature of a boiler cascade control is used which improves the static and dynamic performances [16]. Cascade schemes of PI torque and speed controllers are presented to enhance the objectives of speed control in the system [14].

Cascade control is used to reduce the effect of load disturbances to overcome the failure of traditional PID control [15]. Cascade control uses PID and Fuzzy control logic to improve the dynamic characteristics of level control in horizontal tank [10]. Simple relay feedback test is applied to the outer loop of the cascade control to identify both loop parameters [5]. An improvement is achieved over an existing feedback cascade temperature control system using new hybrid control approach [9]. Using offline PID selection methods, cascade control methods has been designed and simulation done on Matlab/Simulink [18]. Cascade control is designed to ensure enhanced robustness by minimizing the mutual influence among loops [1].

Effect of hydro viscous drive speed regulating start depends on control strategy, present control has many problems, the problem is resolved by fuzzy PID cascade control system, the fuzzy PID cascade control was simulated by Matlab/Simulink [19]. Cascade control inner loop used for sliding control, outer loop uses PI control are designed and analyzed

for a boost converter [20]. Cascade control configuration used in Two degree of freedom design approach guarantees smooth control [11].

The multiobjective PID control problems are characterized in terms of Eigen value problem and it can be efficiently solved by the LMI toolbox in Matlab [3]. In cascade control arrangement, the inner loop consists of multivariable control of three compressors which gives high performance compared to SISO scheme [2]. NSPSO combines the operation of both NSGA-II and multiobjective PSO with a single particle swarm optimizer (PSO) and the obtained results are better than the two compared algorithms [12].

The multiobjective optimization problems are solved by evolutionary algorithm NSGA and its performance is compared with other algorithms [4]. A new multiobjective optimization algorithm is introduced to design optimal PID controller by tissue P systems to satisfy objectives synchronously [13].

By minimizing overshoot, settling time and by smoothening of output curve, the optimal fuzzy controller designed using GA [6]. GA are used in order to find the fittest solutions because of their ability to discover solutions quickly for complex searching and optimization problems [6]. A research on Multiobjective problems can be found on [7].

This study aims at designing a cascade control scheme for liquid level process based on multiobjective optimization technique. Multiobjective Optimization based on NSGA-II and NSPSO are presented. Comparative Analysis of NSGA-II and NSPSO are performed and simulation results are analysed.

2. Material and Methods

In Industries, Cascade control is employed in drum level boilers, distillation columns, evaporators and batch reactors. Cascade control is most advantageous on applications where the secondary closed loop can include the major disturbance and second order lag and the major lag is included in only the primary loop. The secondary loop should be established in an area where the major disturbance occurs. It is also important that the secondary variable respond to the disturbance.

Figure 1 shows the block diagram of cascade control system employed.

The primary loop monitors the control variable and uses deviation from its set point to provide an output to secondary loop. The secondary loop receives its set point from primary loop and controls the reference variable accordingly. Multiobjective Evolutionary algorithms NSGA-II and NSPSO are used. The two objectives considered are Overshoot and Settling time.

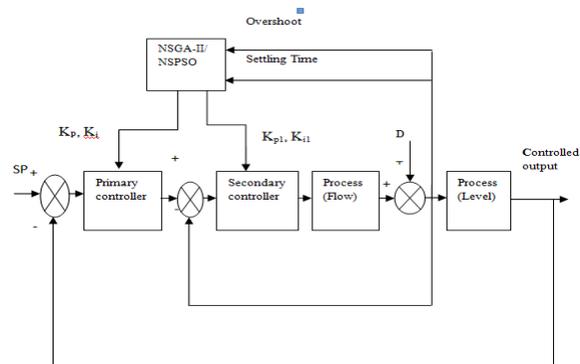


Fig.1 Multiobjective Cascade Control of Liquid Level Control System

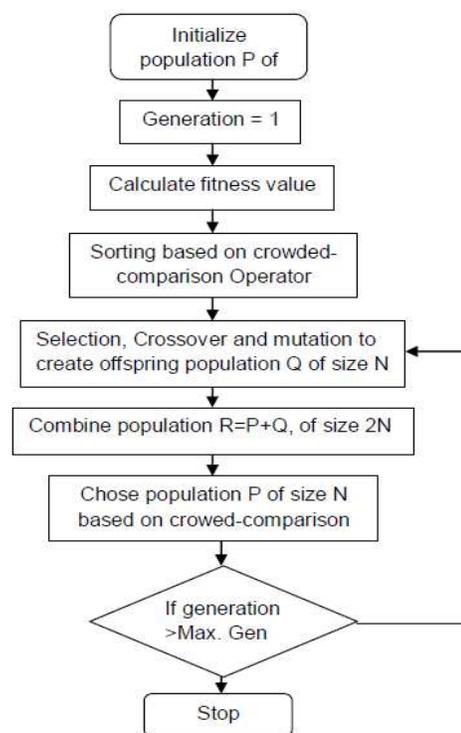


Fig. 2: Flow Chart of NSGA-II

Non Dominated Sorting Genetic Algorithm –II (NSGA – II): The primary reason for choosing EA is their ability to find multiple pareto-optimal solutions in a single run. The main criticism in NSGA was the high computational complexity of non-dominated sorting, lack of elitism and need for specifying the shared parameter. To overcome these, NSGA-II, a slight modification in NSGA approach is being used, which has a better sorting algorithm.

The population is initialized and sorted based on non-domination into each front. The first front being completely non-dominant set in the current population when compared to other higher

fronts. Each individual in each front are assigned a rank (fitness value) based on front in which they belong to. The crowding distance is calculated for each individual, which is based on how close an individual is to its neighbors. Large average crowding distance will result in better diversity in the population. An individual is selected in the rank is lesser than the other or if the crowding distance is greater than the other. The selected population generates offspring's from crossover and mutation operators. This algorithm is same as adopted in [12].

Multi-Objective Non Dominated Sorting Particle Swarm Optimization (NSPSO): NSPSO is a modified form of PSO which is highly competitive with other evolutionary and multiobjective algorithms. In the entire population NSPSO compares the personal bests of all particles and their offspring's instead of comparison between single particle and its offspring. This approach yields more non-dominated solutions through dominant comparisons and sorts the entire population into different non-dominated levels as used in NSGA-II. This NSPSO based on PSO and NSGA-II thereby it combines the features of other algorithms such as crowding distance ranking, elitist strategy, and selection and mutation operations with single objective PSO as adopted in [12].

- Step 1: Generate an initial population P (Population size = N) and velocity for each individual (agent or particle) in a feasible space; Set the maximum speed $v_i \max$ ($v_i \max$ = its upper bound minus lower bound) for a variable.
- Step 2: Sort the population based on the non-domination and crowding distance ranking.
- Step 3: Do rank-based selection operator (Carlos and Peter, Fleming, 1993).
- Step 4: Assign each individual a fitness (or rank) equal to its non-domination level (minimization of fitness is assumed).
- Step 5: Randomly choose one individual as gbest for N times from the nondominated solutions and modify each searching point using previous PSO formula and the gbest:

$$v_i(k+1) = k [v_i^k + c_1 \times \text{rand}() \times (pbest_i - s_i^k) + c_2 \times \text{rand}() \times (g)]$$

$$K = \frac{2}{2 - \phi - \sqrt{\phi^2 - 4\phi}} \quad \text{where } \phi = c_1 + c_2, \phi > 4$$

$$S_i^{k+1} = s_i^k + v_i^{k+1}$$

where, $\text{rand}()$ is a random number between (0, 1). The constriction factor approach can generate higher quality solutions than the conventional PSO approach. If current position outside the boundaries, then it takes the upper bound or lower bound and its velocity is generated randomly ($0 \leq v_i^{k+1} \leq v_i^{\max}$) and multiplied by -1 so that it searches in the opposite direction.

- Step 6: Do mutation operator (David, 1985).
- Step 7: Combine the offspring and parent population to form extended population of size 2N.
- Step 8: Sort the extended population based on nondomination and fill the new population of size N with individuals from the sorting fronts starting to the best.
- Step 9: Modify the pbesti of each searching point: If current rank of the new individual (offspring) P_i^{k+1} is smaller than or equal to the previous one (parent) in R, replace the pbest_i with current individual; otherwise keep the previous pbest_i.
- Step 10: Perform steps (2-9) until the stopping criterion is met.

Mathematical Modeling of Flow and Level Process:

Transfer function of level process is given by

$$G_1(s) = \frac{1.03e^{-0.5s}}{49.5s + 1}$$

Transfer function of flow process is given by

$$G_2(s) = \frac{17.6336}{s}$$

Objective Functions Employed in the Design

i. Overshoot:

$$f_1(K_p, K_i, K_d) = \max\left(\frac{1}{1 + OS}\right)$$

where OS refers to Overshoot.

ii. Settling Time:

$$f_2(K_p, K_i, K_d) = \max\left(\frac{1}{1 + T_s}\right)$$

where T_s refers to Settling Time.

3. Results

System Requirements:

PC : Intel Pentium, Dual core
Software used : MATLAB 7.10.0(R2010a)

Multi-objective optimal level control of cascade control system tuned using NSGA-II and NSPSO to be implemented in MATLAB/SIMULINK is shown in Fig.3.

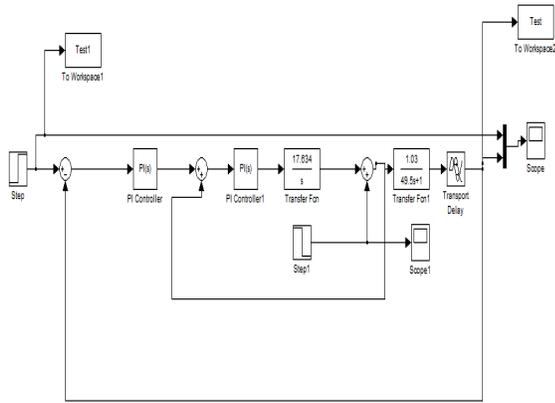


Fig. 3: Simulink Diagram of Cascade Control System

Basic Parameters employed in the system are listed in Table 1.

Table 1: Basic parameters of NSGA-II Algorithm

| ALGORITHM PARAMETER | VALUE |
|-----------------------|-------|
| Population, N | 20 |
| Generations, G | 20 |
| Pool size, N/2 | 10 |
| Tour size | 2 |
| Crossover probability | 0.9 |
| Mutation probability | 0.33 |

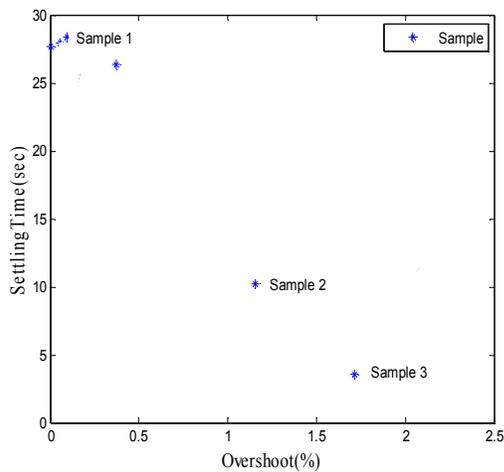


Fig.4: Pareto optimal front with Overshoot and Settling time as objectives with NSGA-II

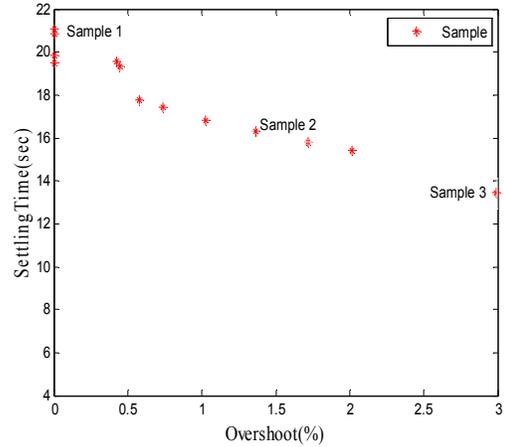


Fig.5: Pareto optimal front with Overshoot and Settling time as objectives with NSPSO

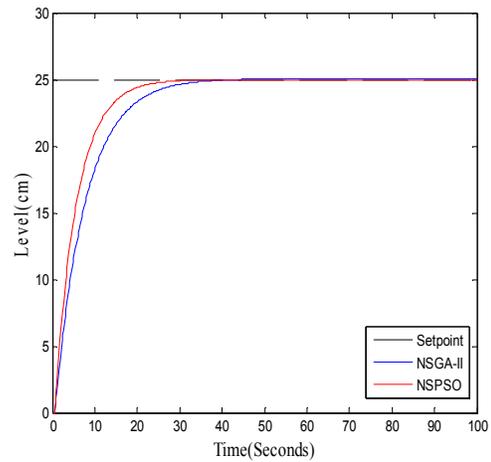


Fig. 6: Comparative Output level response with NSGA-II and NSPSO (Sample 1)

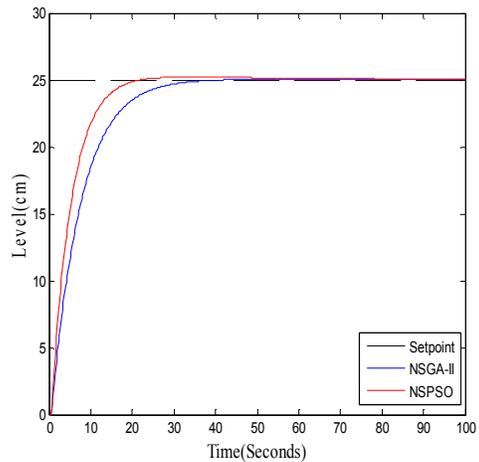


Fig. 7: Comparative Output level response with NSGA-II and NSPSO (Sample 2)

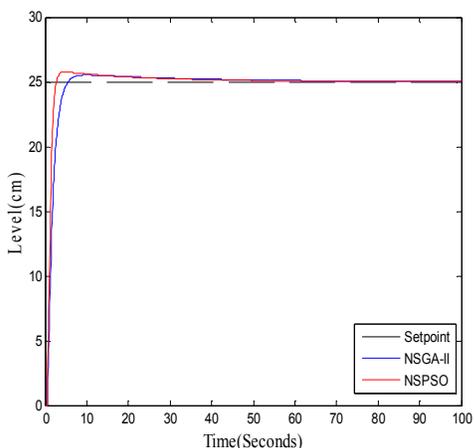


Fig. 8: Comparative Output level response with NSGA-II and NSPSO (Sample 3)

Basic Parameters employed in NSPSO are listed in Table 2.

Table 2: Basic parameters of NSPSO Algorithm

| ALGORITHM PARAMETER | VALUE |
|-----------------------|-------|
| Particle size, N | 20 |
| Generations, G | 20 |
| Pool size, N/2 | 10 |
| Tour size | 2 |
| Crossover probability | 0.9 |
| Mutation probability | 0.33 |

The Pareto optimal front with overshoot and settling time as objective functions obtained with NSGA-II and NSPSO are shown in Fig.4 and Fig.5. From the Pareto optimal front, samples are taken and from these samples, corresponding optimum Kp, Ki values are obtained as per the requirements of the user. Three samples are taken from the Pareto front for analysis.

Comparative analysis of output level responses in the absence of disturbances is shown in Fig. 6, 7 and 8 for Samples 1, 2 and 3 respectively and the results are tabulated in Table 3.

From Table 3, it is inferred that NSPSO provides less overshoot, short settling time and quick disturbance rejection compared to NSGA-II.

Comparative analysis of output level responses in the presence of disturbances introduced at t = 70 seconds with intermediate values of overshoot and settling time is shown in Fig. 9 and the results are tabulated in Table 4.

Table 3: Performance comparisons of NSGA-II and NSPSO Algorithm in absence of disturbances

| Set Point | Algorithm | Over shoot (%) | Settling Time (sec) | Rise Time (sec) | Steady state error (%) | Dist. Rej Time | Peak Time (sec) | ISE | IAE | ITAE |
|-----------|-----------|----------------|---------------------|-----------------|------------------------|----------------|-----------------|------|-------|------|
| 25 cm | NSGA-II | 0.01 | 28.38 | 15.82 | 0.00 | 40.6 | 0.01 | 0.63 | 13.98 | 0.01 |
| | NSPSO | 0.00 | 21.41 | 10.16 | 0.00 | 30.6 | 0.00 | 0.51 | 11.95 | 0.00 |
| Sample 1 | NSGA-II | 1.34 | 12.97 | 15.34 | 0.00 | 42 | 0.01 | 0.61 | 9.05 | 1.34 |
| | NSPSO | 1.23 | 10.67 | 10.16 | 0.00 | 22 | 0.00 | 0.56 | 8.27 | 1.23 |
| Sample 2 | NSGA-II | 2.04 | 11.34 | 2.64 | 0.00 | 11.2 | 0.01 | 0.35 | 3.83 | 2.04 |
| | NSPSO | 1.98 | 10.56 | 1.30 | 0.00 | 5.86 | 0.00 | 1.08 | 9.54 | 1.98 |

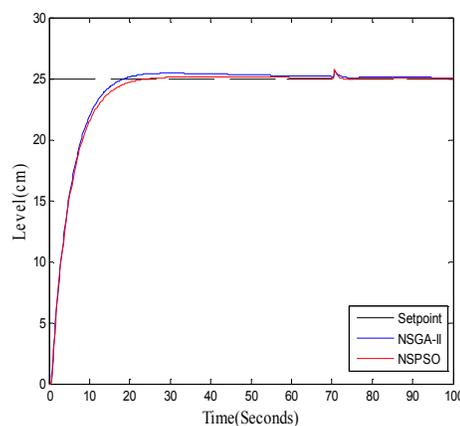


Fig. 9: Comparative Output level response with NSGA-II and NSPSO with disturbance.

Table 4: Performance comparisons of NSGA-II and NSPSO algorithm in the presence of disturbances

| Set Point | Algorithm | Over shoot (%) | Settling Time (sec) | Rise Time (sec) | Steady state error (%) | Dist. Rej Time | Peak Time (sec) | ISE | IAE | ITAE |
|-----------|-----------|----------------|---------------------|-----------------|------------------------|----------------|-----------------|------|------|-------|
| 25 cm | NSGA-II | 0.2 | 44 | 22.6 | 0.00 | 3.1 | 70.75 | 0.03 | 2.04 | 110.9 |
| | NSPSO | 0.0 | 22.53 | 11.6 | 0.00 | 2.1 | 40.34 | 0.01 | 1.68 | 64.58 |
| Sample 1 | NSGA-II | 2.24 | 14.8 | 9.85 | 0.00 | 3.5 | 32.6 | 0.00 | 0.08 | 5.52 |
| | NSPSO | 1.75 | 13.23 | 8.74 | 0.00 | 2.5 | 20.3 | 0.00 | 0.05 | 3.78 |
| Sample 2 | NSGA-II | 8.98 | 21.4 | 0.94 | 0.00 | 0.02 | 2.43 | 0.61 | 6.24 | 44.6 |
| | NSPSO | 3.45 | 5.76 | 1.13 | 0.00 | 0.01 | 1.97 | 0.01 | 1.20 | 30.4 |

From Table 4, it is inferred that NSPSO provides less overshoot, short settling time and quick disturbance rejection compared to NSGA-II.

4. Discussions

Multiobjective evolutionary algorithms NSGA-II and NSPSO are successfully implemented in cascade control loops with time domain specifications namely overshoot and settling time as objective functions. PI controllers are used for building the cascade controller in order to control the level in the cylindrical tank. Mathematical modeling of cylindrical tank for level and flow process is developed. Simulation results show that NSPSO gives accurate Pareto front values and good diversity as compared to NSGA-II. Simulation results of both the evolutionary algorithms NSGA-II and NSPSO are compared in absence and presence of disturbances. The comparative results prove that NSPSO provides better disturbance rejection and less overshoot than NSGA-II. Thus NSPSO outperforms NSGA-II in cascade control of level process.

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