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Evolutionary Constrained Design of Seismically Excited Buildings, Part I: Actuators Placement

Alireza Rowhanimanesh
Department of Electrical Engineering
Ferdowsi University of Mashhad
rowhanimanesh@gmail.com

Abbas Khajekaramodin
Department of Civil Engineering
Ferdowsi University of Mashhad
karamodin@gmail.com

Mohammad-R. Akbarzadeh-T.
Department of Electrical Engineering
Ferdowsi University of Mashhad
akbarzadeh@ieee.org

Abstract: Optimal placement of actuators and sensors is an important problem in control of structures that is often selected without any systematic method. Appropriate placement strongly influences on the performance of control system. This study is presented in two parts In this paper as the first part, Actuators Placement is presented. In this way, a general method is suggested based on a proposed constrained genetic algorithm to determine the optimal placement of actuators in structures. The optimal placement scheme is general for passive, active and semi-active controls. It can handle linear and nonlinear constraints and it does not depend on strategy of control and dynamics of control system such as nonlinearities. The efficiency of proposed method is evaluated on the 20-story benchmark building. The optimal scheme is applied on the sample active LQG control system to place 25 and 5 actuators. The results show that the proposed method could find the optimal placement of actuators and improve the performance of control system. Generally, the proposed method is an approach to achieve the best utilization of available resources.

Keywords: Earthquake, Structural Control, Structural Design, Actuators Placement, Constrained GA.

1. Introduction

Civil structures might be excited by natural hazards such as earthquakes and strong winds. Since damages in some structures such as buildings and bridges might be dangerous for people and reconstruction of the damaged structures is very costly, designing a system that can protect and control structures against these dynamic loads is valuable. The first proactive researches on structural control were started by Yao in 1972 [1]. The initial methods are based on passive actuators such as dampers. Next, to reach higher levels of control, active control methods were proposed. In these methods, complex control algorithms can be programmed on a digital computer and suitable commands are sent to active actuators. The recent method is semi-active control that uses some actuators such as controllable dampers. This approach includes the advantages of both previous methods. A challenge that is common in all of these three methods is optimal placement of actuators and sensors that is often neglected and selected according to guess and experience without any systematic method. Appropriate placement strongly influences on the performance of control system. This problem is more necessary for actuators than sensors, because they're more expensive, have limited capacities, their installation is hard and only few numbers of them can be installed in each story. Thus, to achieve the best utilization, the optimal placement must be found before installation. In the following, some of the previous works are reviewed. Martin and Soong (1980) [2] considered the placement of active devices in structures for modal control. Lindberg and Longman (1984) [3] discussed the appropriate number and placement of devices based on modal control. Vander Velde and Carnignan (1984) [4] focused on structural failure modes to place the devices, and some other works performed by Ibidapo (1985) [5] and Cheng and Pantiledes (1988) [6]. Most of these methods are often problem specific. Takewaki (1997) [7] used a gradient-based approach to search for an optimal placement. Teng and Liu (1992) [8] and Xu and Teng (2002) [9] developed an incremental algorithm and Wu et al. (1997) [10] used both iterative and sequential approaches. Zhang and Soong (1992) [11] and Lopez and Soong (2002) [12] proposed sequential search methods for optimal damper placement. The main problem of these methods is converging to local optima. Simulated annealing as a guided random search was employed to place devices by Chen (1991) [13] and Liu (1997) [14]. Although these method could solve the problem of local optima, but they couldn't always provide general and efficient techniques. Finally, the most recent approaches focused on Evolutionary Algorithms such as Genetic Algorithms (GA). Simpson and Hansen (1996) [15] used GAs to optimize the placement of actuators for specific active control problem. Ponslet and Eldred (1996) [16] employed a GA approach to design an isolation system. Abdullah (2001) [17] combined genetic algorithms and a gradient-based optimization technique for optimal placement of controllers in a direct velocity feedback control system. Li (2001) [18] have developed a multilevel GA to solve a multitasking optimization problem. Singh and Moreschi (2002) [19] considered placement of passive devices in a multistory building. Wongprasert and Symans (2004) [20] employed GA for identifying the optimal damper distribution to control the nonlinear seismic response of a 20- story benchmark building. Tan (2005) [21] used GA to propose an integrated method for device placement and active controller design.

In this study, regarding the importance of the problem, both actuators and sensors placements are considered in two separate parts. The Second paper, Part II [27], proposes a general method for sensors placement that is based on constrained GA, and handles constraints using new preserved crossover and mutation.

In this paper, Part I, we propose a general method based on constrained GA for optimal placement of actuators. This problem is a constrained, nonlinear and discrete optimization problem that is difficult to solve. The proposed method is general for passive, active and semi-active controls. It can handle linear and nonlinear constraints and it is independent from control strategy and dynamics of control system such as nonlinearities. To indicate the efficiency of proposed method, simulations have been performed on 20-story benchmark building [22]. In the benchmark building definition paper, a sample LQG active control system was designed, but the placement of actuators is not optimal. The proposed method is applied on this control system to find the optimal configuration of 25 and 5 actuators. The results demonstrate the efficiency of the optimal placement scheme.

2. Optimal Placement of Actuators

2.1 Defining the Optimization Problem

As mentioned before, optimal placement of actuators is a difficult optimization problem. Some of these difficulties are mentioned in the following two paragraphs:

A. The problem is integer and constrained. The decision variables are the number of actuators on each floor and must be discrete. For example for a 20-story building, there are 20 decision variables. Also, only limited number of actuators can be installed in a given story and the total number of actuators is often fixed for economical reasons. In this paper, we suppose that the capacities of actuators are equal. Thus the decision variables must be integer. These constraints are the most common ones for actuators placement problem that are shown in Table1. Other linear or nonlinear constraints including equalities or inequalities could be added. In this paper, we focus on linear constraints.

B. The problem is nonlinear, discrete and not analytical. The analytical relation could not be extracted simply and precisely between the configuration of actuators as an input and a control objective as an output. The input space is discrete; the objective functions often use the operators such as maximum or absolute value that they are not analytical. The model of structure is a system of nonlinear differential equations that often must be solved numerically. Furthermore, because of complexity and nonlinearity of the problem, the method must be able to seek the global optima. For these reasons, derivative-based optimization methods could not be performed directly. Therefore global optimization techniques such as population-based natural optimization methods are suitable for solving this problem.

In this paper, Constrained Genetic Algorithms have been used to solve the problem. Handling constraints in GA is a big challenge. To deal with existing difficulties a specific constrained GA based on new interpretation function is propose.

1	***X_i : integer***
2	***$0 < X_i < N_{max}$***
3	***$X_1+X_2+\ldots+X_n = N_{tot}$***

Table 1.Constraints for Optimal Actuators Placement

2.2 Constrained GA

As mentioned in [23, 24 and 25], there are two major approaches for handling constraints in GA:

A. Direct constraint handling which contains four methods: 1.eliminating infeasible candidates, 2. repairing infeasible candidates, 3. preserving feasibility by special operators, 4. decoding such as transforming the search space. Direct constraint handling has two advantages. It might perform

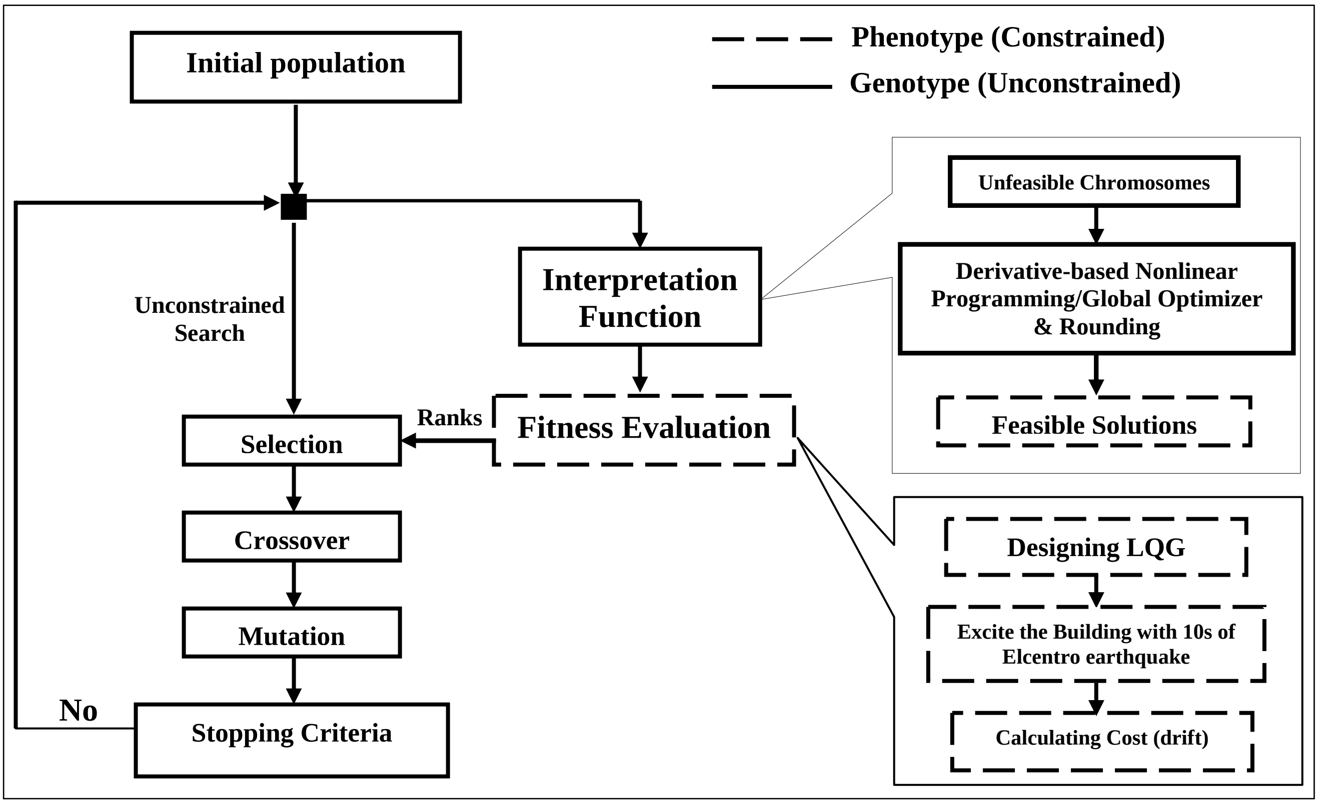


Figure1. Proposed Constrained GA

very well, and might naturally accommodate existing heuristics. Because the technique of direct constraint handling is usually problem dependent it has some disadvantages. Designing a method for a given problem may be difficult and using a given method might be computationally expensive.
B. Indirect constraint handling: Indirect constraint handling incorporates constraints into a fitness function. Advantages of indirect constraint handling are: generality (problem independent penalty functions), reducing problem to 'simple' optimization, and allowing user preferences by selecting suitable weights. One of disadvantages of indirect constraint handling is loss of information by packing everything in a single number and Generally in case of constrained optimization, it is reported to be weak.

2.3 Proposed Constrained GA

In this paper, a constrained GA based on new interpretation function is proposed which contains advantages of both direct and indirect methods for constraint handling. The structure of Proposed Constrained GA is presented in figure 1. Each gene is the number of actuators in a given floor. So, the length of a chromosome is equal to the number of stories of the building. In the proposed method, the operators of real-valued GA are used. Constraints are just considered in interpretation function when genotype must be converted to phenotype. The major operators of GA work on genotype; hence, in the viewpoint of GA, the problem is a usual unconstrained problem. The chromosomes in genotype are allowed to be unfeasible. Only when the fitness of population must be evaluated, interpretation function converts the unfeasible population in genotype to feasible solutions in phenotype. The fitness of each solution is calculated and the process is continued on genotype (unfeasible population).
The proposed interpretation function is based on finding a point in feasible space that has the least Euclidean distance to the given unfeasible solution. This point is called a feasible equivalent of that unfeasible chromosome. The process is performed in two levels: First, the discrete constraints such as the first in Table1 are ignored and for a given unfeasible solution, the nearest equivalent point in continuous feasible space is found. In the next level, the specific rounding is performed for handling discrete constraints. When constraints are linear such as Table1, finding the nearest Euclidean distance is a single modality problem, thus derivative-based nonlinear programming can be applied to solve it. Placement problems often

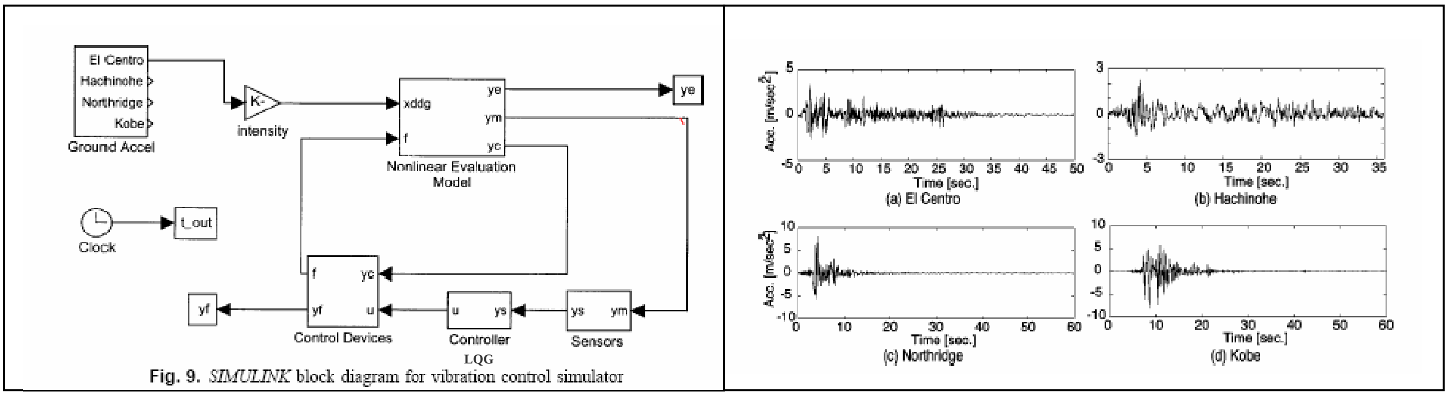


Figure 2.Benchmark nonlinear building and control system and Time histories of the far- and near-field historical earthquake records used in the benchmark

include linear constraints. But, even if there are some nonlinear constraints, the proposed method could deal with them by using a global optimizer in place of classical nonlinear programming.

The proposed method has the most of advantages of direct and indirect methods: It might perform very well and accommodate existing heuristics. It can use ordinary crossover and mutation operators. Moreover, it can perform linear or nonlinear constraints, reduce problem to simple optimization and allow the user to incorporate all experiences and methods of unconstrained GA. Disadvantage of proposed method is that several unfeasible solutions might have the same feasible equivalent. This can be little time consuming for high dimensional problems.

3. Benchmark Building

For evaluating the efficiency of the proposed method, a 20-story benchmark building introduced in 2004 for control of seismically excited nonlinear buildings, has been used [22]. The benchmark building definition paper has introduced three typical steel structures, 3-, 9-, and 20-story. The main purpose of introducing benchmark buildings is to provide a basis for evaluating the efficiency of various structural control strategies. Hence, numerical model of benchmark structures have been mentioned and discussed in the paper [22]. Also, 17 criteria with four historical earthquakes have been introduced for evaluation. Furthermore, practical constrains and conditions of control system have been stated such as sensor noise, sample rate, A/D and D/A characteristics, capacity of actuators and etc. Finally, a sample LQG Active control system has been designed based on acceleration feedbacks. The results of evaluation of sample control system have been shown and also the MatLab files of benchmark buildings can be achieved electronically.

3.1. Sample LQG Control System

In the benchmark paper, the LQG controller has been designed based on reduced-order linear model of 20-story nonlinear benchmark structure. The 25 active actuators and 5 acceleration sensors were placed at some various locations on the structure. The actuators are assumed to be ideal and the dynamics of them are neglected. In the sample control system of benchmark paper, the placements of sensors and actuators are not optimal. The optimal placement of sensors has been discussed in Part II [27]. The actuators are located on each story of the structure to provide forces to the building with specific configuration shown in Figure 4. As the proposed method demonstrates, the distribution of actuators in the benchmark building is not optimal. The other information about the benchmark paper and MatLab simulation files are available in [22].

In this paper, we apply the proposed method on the benchmark building sample control system to achieve optimal placement of actuators. The process is shown in figure1. Everything is as same as benchmark paper and only the placement of actuators is optimized. The results demonstrate that using proposed method, better performance of the sample control system could be achieved only with optimal configuration of actuators. This means achieving the best performance and highest efficiency of available devices.

4. Results

The following figures show the results of evaluation. The characteristics of real-valued GA are mentioned in Table 2. The proposed method used the first 10 seconds of Elcentro earthquake that is a far-field earthquake. The cost function is the MPA (Maximum of Peak of Absolute value) of drifts of 20 stories when the benchmark building is excited by the first 10s of Elcentro performed for both 25 and 5 actuators. As presented in figure4, the insight of benchmark paper is based on approximately uniform distribution of devices with more attention to the

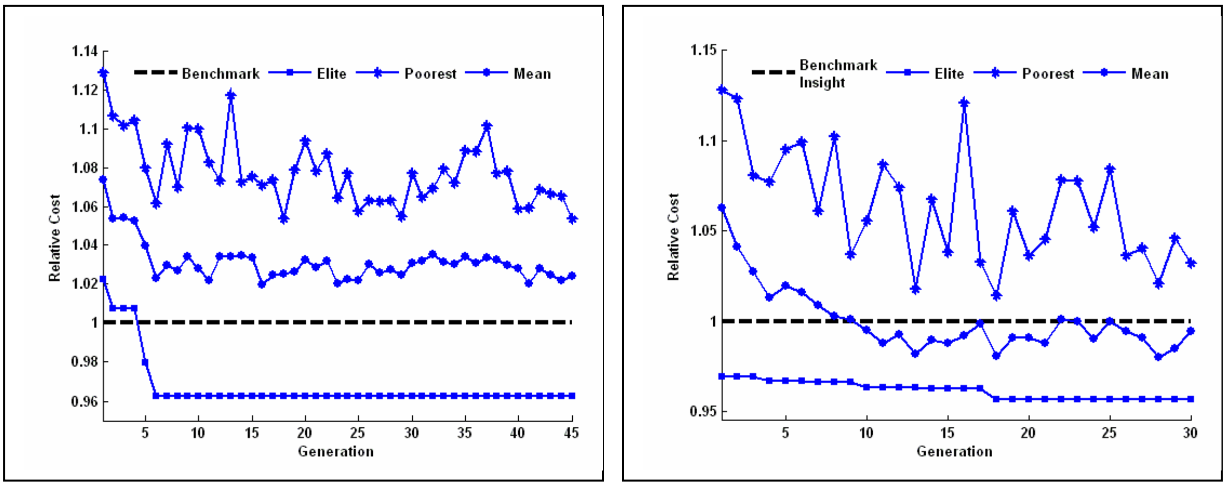
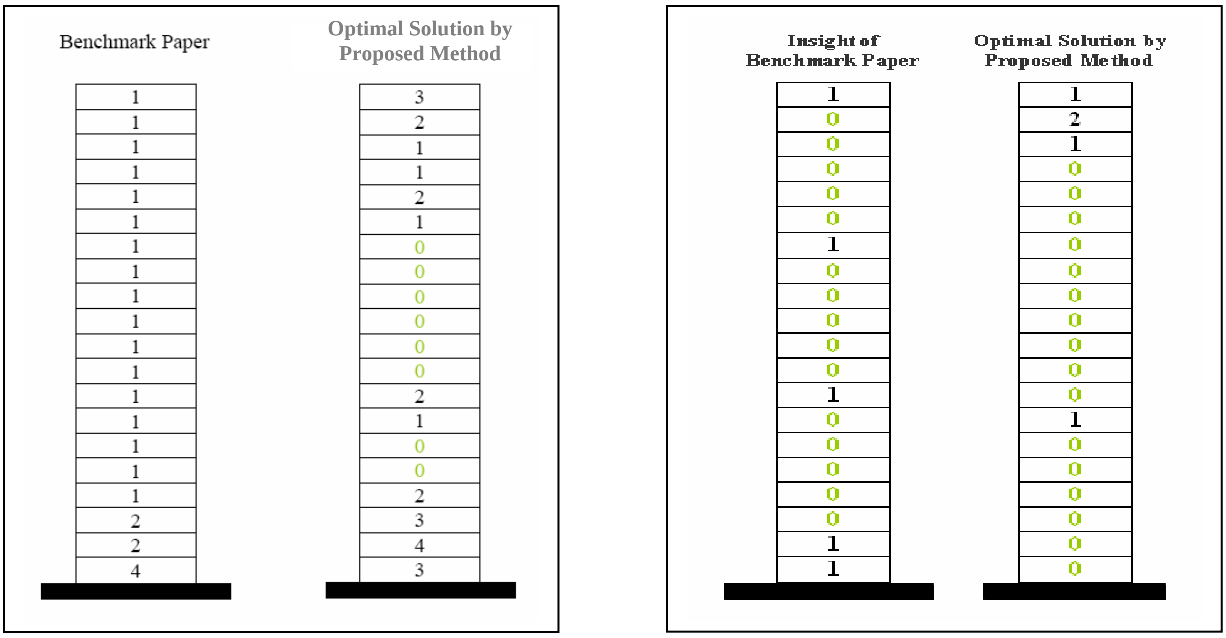


Figure3. Convergence of Proposed Constrained GA – *(Relative Cost = Proposed / Benchmark)*
25 Actuators *(Left)* (Optimal Cost: **0.9625**) - **5 Actuators** *(Right)* (Optimal Cost: **0.9567**)



Placement of 25 Actuators **Placement of 5 Actuators**

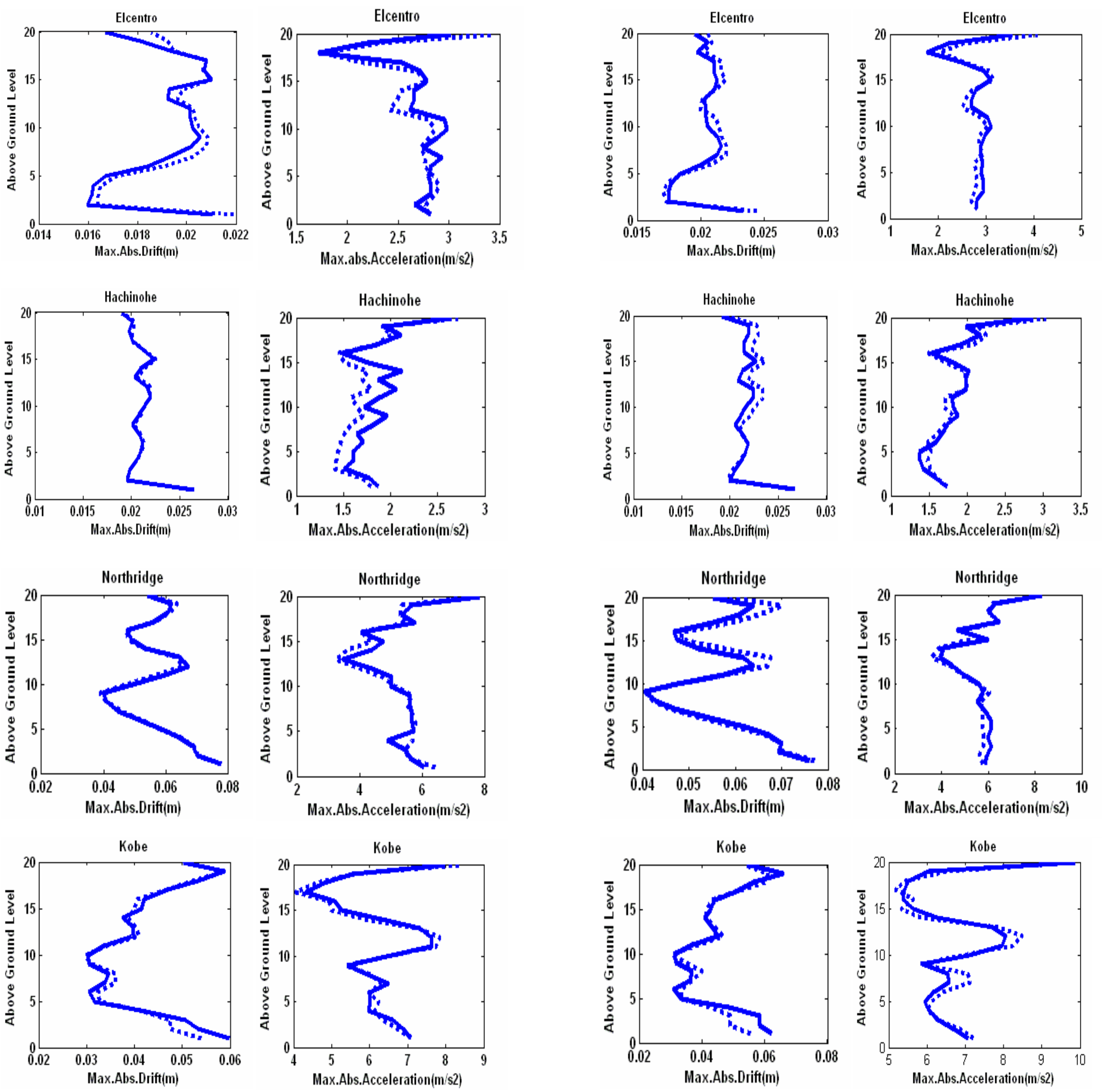
Figure4. Optimal Placement of Actuators, Proposed method vs. Benchmark Paper

earthquake. In this study, minimization of drifts has been used as an objective. The other objectives such as acceleration or hybrids can be used. It is also better to use both near-field (like Kobe) and far-field (like Elecentro) earthquakes. Figure 3 shows the convergence of the proposed evolutionary method. Next, the optimal solution was tested on 50s of two far-field (Elcentro, Hachinohe) and two near-field (Northridge, Kobe) historical earthquakes (figure2). The method was

1	***Type of GA***	***Real-valued , Single-objective***
2	***Mutation rate:***	***Fixed 0.3***
3	***Crossover***	***Single point crossover***
4	***Population size***	***20***
5	***Selection***	***Keep 50% , give high probability for better individuals***
6	***Elitism***	***1 elite***
7	***Initial Population***	***Random , unconstrained***
8	***Objective***	***Minimizing max of peak of Abs of Drifts***

Table2. Characteristics of GA

first floors. Thus, we use this insight to produce a benchmark for 5 actuators. The results that are shown in figure5, demonstrate that using proposed



25 Optimally Placed Actuators vs. Benchmark Paper

5 Optimally Placed Actuators vs. Benchmark Paper's Insight

Figure5. Benchmark Paper (dotted), Proposed Method (solid) – The results of evaluating the optimal placement scheme using 4 historical benchmark earthquakes

method higher degree of performance could be achieved from the existing actuators without adding any extra devices.

Conclusions

This study has been performed in two parts including actuators and sensors placements. In this paper, Part I, we proposed a general evolutionary method for optimal placement of actuators with handling the practical constraints. The method is general for passive, active and semi-active controls. The proposed method allows designer to consider linear and nonlinear constraints, all dynamics such as nonlinearities and various control objectives. The optimal placement scheme is simple, efficient and flexible for different applications. The method can be used for all control strategies including intelligent and conventional schemes. The results indicate the success of the method to improve the performance of Benchmark building control system. In this paper, we just considered minimization of drifts as the objective function and only a far-field earthquake, Elcentro, was used by the method. For real designs, the designer might consider both drifts and accelerations as objectives and the proposed method can be performed for both near-field and far-field earthquakes. As the results showed, using the proposed method the best performance and utilization of available actuators could be achieved without adding any extra device.

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