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Invited/Review Article

Placement of control devices for passive, semi-active, and active vibration control of structures

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Abstract. An important subject in vibration control of large structures is the placement of control devices. The goal should be to achieve the best performance with minimum cost. A good number of papers have been published on the distribution of control devices in recent years. The purpose of this article is to present a review of the papers published on the placement of passive, semi-active, active, and hybrid devices for vibration control of structures subjected to various dynamic loading, such as earthquakes and winds. Significant additional research is needed, especially in the areas of semi-active and hybrid vibration control of large structures with hundreds or thousands of members, to make the adaptive/smart structure technology cost effective.

1. Introduction

Fisco and Adeli [1] presented a state-of-the-art review of journal articles on active control of structures, including Active Tuned Mass Dampers (ATMD) up to 2010. Fisco and Adeli [2] presented a review of journal articles on hybrid vibration control of structures and the improved or new control strategies developed for civil structures. Gutierrez Soto and Adeli [3] present a review of a representative research on Tuned Massed Dampers (TMD) reported in recent years, divided into four categories: conventional TMDs, Pendulum TMDs (PTMDs), Bi-directional TMDs (BTMDs), and Tuned Liquid Column Dampers (TLCDs).

An important subject in vibration control of large structures is the placement of control and sensor devices. The goal should be to achieve the best performance with minimum cost. In active and semi-active vibration control of structures [4,5], both the number of sensors used to collect measurement data and the number of actuators to apply internal forces must be limited for economic reasons, equipment access and maintenance issues. A good number of papers have been published on the distribution of control devices in recent years. Figure 1 shows an example space truss structure with actuators and sensors along various members subjected to seismic excitations. The purpose of this article is to present a review of recent papers published on the placement of passive, semi-active, active and hybrid devices for vibration control of structures subjected to various dynamic loadings, such as earthquakes and winds. Papers reviewed in this paper were published in twenty three different research journals.

2. Passive control

Singh and Moreschi [6] study the problem of optimum size and location of frequency-dependent and frequency-independent passive viscous and viscoelastic dampers for the vibration control of linearly behaving

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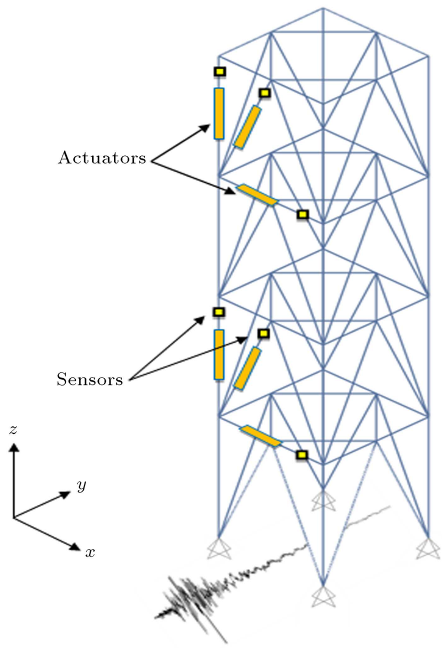


Figure 1. An example space truss structure with actuators and sensors along various members subjected to seismic excitations.

building structures under seismic loading, using a genetic algorithm [7,8]. They present examples of 6- and 24-story buildings with 3 Degrees-Of-Freedom (DOF) per floor, including a rotational DOF modeled for torsion. They conclude that for the 6-story example, 36 devices distributed on the top 4 floors result in a 49% response reduction, and for the 24-story example, 72 devices distributed mainly on the top 10 floors result in 60% response reduction.

Lopez Garcia and Soong [9] study damper allocation distribution using a Simplified Sequential Search Algorithm (SSSA). The authors analyzed the performance of regular building models, with variance in height up to 20 stories, a natural period varying from 0.4 to 2.0 seconds, and various damping levels subjected to various seismic excitations. Additionally, they compared damper locations obtained from the same seismic events with varying distances from the fault. Bishop and Striz [10] use the genetic algorithm [11,12] to obtain the minimum number of passive viscous dampers necessary to suppress structural vibrations in a space truss subjected to symmetric and asymmetric loadings. Their examples include 72- and 78-bar trusses, where four dampers are found to be sufficient to yield the desired response.

Bhaskararao and Jangid [13] study the structural response of two 10- and 20-story 2D frames rigidly connected by nonslip and slip mode friction dampers subjected to seismic loading. They conclude that using 5 dampers located on floors 6-10 yields responses similar to when dampers are placed on all floors. Kokil and Shrikhande [14] use a pattern search algorithm to study the placement of viscous dampers for a single-bay, 3D, 10-story rigid-floor building by varying soil conditions, including symmetric and asymmetric examples, with eccentricity varying from 0.15 m to 0.225 m from the center of mass. The authors conclude that the efficacy of passive viscous dampers decreases as the plan irregularity increases.

Aydin et al. [15] study the placement of viscous dampers on a 2D 10-story, three-span planar steel frame subjected to seismic loading, using the steepest gradient search optimization method [16] and various objective functions. They conclude that using a top floor displacement as an objective function decreases story displacements and inter-story drift but increases the base shear force. Lavan et al. [17] also use a steepest descent optimization technique that involves structural weakening and passive damping for an inelastic, shear-type, 8-story 2D frame subjected to 100 ground motion records. The method reduced the inter-story drift and absolute acceleration by 70% and 60%, respectively, when compared with the uncontrolled case. Ameduri et al. [18] use a multi-objective genetic algorithm [19] to determine the number, placement and orientation of Shape Memory Alloy (SMA) wires embedded in a rectangular composite panel subjected to noise excitations. The optimal configuration resulted in 5 SMA wires distributed over the panel.

Apostolakis and Dargush [20] discuss the topological optimal distribution and size of hysteretic passive devices, such as yielding metallic Buckling Restrained Braces (BRB) and/or friction dampers, in 2D, 3- and 6-story, steel Moment-Resisting Frames (MRFs), based on the nonlinear time history analysis of 4 synthetic ground motions representing the west coast of the U.S. with a probability of 5% exceedance over 50 years. They use a genetic algorithm [21] to solve the resulting discrete optimization problem [22]. Optimization parameters are the position of the device, the device type, the yield/slip load, and the bracing stiffness. To evaluate the performance of each structure, a relative performance/fitness function is defined as the weighted function of the maximum inter-story drift, Root Mean Squared (RMS) floor acceleration, and the maximum floor acceleration.

Estekanchi and Basim [23] use a so-called Endurance Time Method (ETM) and genetic algorithm [24] to obtain optimal viscous damper coefficients and placement on 3-story and 3-bay, 8-story, regular shear frames, and a 3-story steel frame with vertical irregularity subjected to earthquake ground motions. The ETM approach is intended to decrease the number of time-history analyses required. Aydin [25] uses the steepest descent optimization to obtain the location and size of passive viscous dampers in a 10-story steel frame, with soft first three stories subjected to earthquake loading. The author uses base moment as the objective function instead of displacement, acceleration, and/or base shear commonly used by other researchers. The results show that optimal location is on the first 3 floors, which corresponds to soft stories with varying damper damping coefficients.

Whittle et al. [26] study implementation of passive linear viscous dampers in two, 10-story, steel moment resisting, regular and vertically irregular frames, subjected to seismic loading through five different damper placement methods: Uniform damping and stiffness proportional damping, the Simplified Sequential Search Algorithm (SSSA), the Takewaki transfer function [27], Lavan fully-stressed analysis, and the redesign (LAR) method. Various methods resulted in different optimal damper distribution schemes. LAR, Takewaki and SSSA methods obtained comparable drift reductions that outperformed the other methods.

Hejazi et al. [28] use a multi-objective GA to find the optimum values of viscous damper properties with the following objectives: minimum number of plastic hinges and minimum floor displacements. They present an example of a 3D, 5-story, Reinforced Concrete (RC) regular building subjected to seismic loading. Their results indicate a displacement reduction in the range 64.2%-95.9% and a plastic hinge reduction of over 80% after 850 generations and 83.3 hours of computational time, with varying damping coefficients distributed along the 5 floors.

Kanno [29] proposes a mixed-integer cone programming method to obtain the optimum placement of viscous dampers for 3-story and 6-story uniform shear frames, and a 6-story shear frame with varying story stiffness subjected to seismic loading. For the 6-story example, with a uniform stiffness, the optimum placement of dampers is on the first 3 floors, while for the structure with varying stiffness, the optimum placement is on the top 4 floors.

Sonmez et al. [30] use the artificial bee colony optimization algorithm [31,32] to obtain the optimal size and placement of viscous dampers in three, 9-story, steel shear frames, with varying stiffness along the height of the structure, subjected to seismic loading. Their conclusion is: Vibration control devices should be placed mostly in more flexible stories to achieve optimal control.

Martinez et al. [33] use GA to obtain optimal placement of viscous dampers, as well optimal damping coefficients, for 15-story and 6-story 2D and 3D steel frames subjected to seismic excitations and modeled as a stationary stochastic process defined by a design spectrum compatible power density function. They conclude that "for building structures with different stiffness distribution over the height, the devices should be placed where the greatest interstory drifts occur (usually on the first stories)" and the optimum placement of dampers corrects the stiffness eccentricity by minimizing both the translational and torsional responses.

Amini and Ghaderi [34] use a combination of harmony search and ant colony optimization algorithms [35,36] to obtain optimal placement of passive dampers in three 2D structures: a 16-story shear frame, a truss, and a 10-story steel frame subjected to seismic excitations. Adachi et al. [37] propose an approximate ad-hoc, two-step optimization method consisting of a sensitivity analysis using nonlinear time-history response analyses [38] and iterative modification of a set of relief forces applied by nonlinear viscous dampers for their optimal placement in a 10-story 2D frame subjected to seismic ground motions. They minimize the maximum interstory drift or maximum acceleration of the top-story.

Christopoulos and Montgomery [39] introduced a viscoelastic coupling damper (VCD) consisting of viscoelastic dampers sandwiched between layers of steel plates, and study their optimal placement in reinforced concrete coupled wall buildings. Their examples include an 85-story, 2D, RC irregular structure and a 51-story, 3D, RC slender irregular building subjected to wind and seismic loadings. They determine optimal placement of 44 dampers in stories 7 to 28 for the 85-story example, and 128 dampers (4 per story) in stories 6 to 37 for the 51-story example.

3. Active control

Amini and Tavassoli [40] use the conventional nonlinear programming technique called the Sequential Unconstrained Minimization Technique (SUMT) and the artificial neural network [41-43] to determine the number, placement and force in actuators in 3-, 12- and 15-story shear frames subjected to six earthquake excitations. Tan et al. [44] use GA with a LQG control algorithm [45,46] to obtain control gain and optimum actuator placement for vibration control of two benchmark structures: a 40-story, 2D shear frame subjected to simulated earthquakes and a 9-story, irregular benchmark building subjected to El Centro and Northridge earthquakes.

Agranovich and Ribakov [47] propose a method for actuator placement on an 8-story reinforced concrete plane frame with stiff beams based on total energy dissipation characteristics. They use a heuristic solution and the LQG control algorithm for active control of structures subjected to seismic loading. Ribakov and Agranovich [48] study placement of actuators using the LQR control algorithm to minimize the required active force in 10-story reinforced concrete and 20-story steel shear frames subjected to white-noise excitation and 3 earthquake accelerograms. The optimum locations of the active dampers in the 10-story example are floors

3, 5, 7, 8 and 9, while in the 20-story example are at floors 1, 5, 6, 7, 8, 14, 15 and 16.

Bruant et al. [49] use GA to obtain optimum number, placement and orientation of piezoelectric sensors and actuators on a thin 38 cm by 30 cm 2D elastic plate subjected to sinusoidal loading. Out of 10 possible actuators, 2 or 3 sensors and 400 possible locations, they determine that 3 sensors and 5 actuators yield the desired response distributed over the plate. Mehrabian and Yousefi-Koma [50] study optimal placement of piezoelectric actuators for vibration control of a flexible aluminum scaled model of the vertical tail fin of an F/A-18 fighter jet, approximating the first two vibration modes of the full-scale fin. They use neural networks [51-53] to approximate the 3D surface for the frequency response function and GA [54] to find the optimal placement of a pair of actuators. Out of 47 possible placement configurations, they determine the optimal location of the actuator pair considering bending and torsional modes.

Ambrosio et al. [55] use H2 norm optimization in conjunction with GA to obtain the optimal design and placement of acceleration sensors and piezoelectric patch actuators on a 1 m by 1 m, 2D, square thin carbon fiber plate fixed on three sides, subjected to harmonic excitations. Chakraborty et al. [56] also use GA to determine the location and number of piezoelectric dampers in a smart fiber reinforced shell structure.

Li et al. [57] use a fuzzy control scheme based on fuzzy logic [58-62] and GA [63,64] to obtain the optimum size and placement of sensors and piezoelectric actuators simultaneously on a 68-node aluminum truss system located in space. Their results show the size and locations of 5 actuators and 5 sensors distributed along the truss height.

Raich and Liszkai [65] present multi-objective optimization of sensor and actuator layouts for frequency response, function-based, structural damage identification [66] using GA. Araujo et al. [67] present optimal placement of a piezoelectric sensor and patch actuators in a 3D composite sandwich plate with laminated face layers and a viscoelastic core subjected to varying impulse excitations, using a Direct Multi-Search Method that does not require the use of function derivatives.

Cha et al. [68] use a multi-objective GA to obtain placement of sensors and actuators in 2D and 3D, 20-story, steel frame structures subjected to seismic loading. They use the LQG control strategy for active control and a gene manipulation technique that reduces the number of generations by 40% without affecting the results negatively. Their main conclusion is that the optimum number and location of actuators depend strongly on the desired maximum drift.

Thin shell structures are a popular choice in architecture and structural engineering for covering long spans without intrusive intermediate vertical supports. Such structures, however, are susceptible to vibrations during high winds. Active controllers can be used to stabilize such structures and create an oscillation-dependent response during dynamic loading events. Sensors are needed to measure the current response of the structure in real time so that actuators can apply appropriate forces. Weickgenannt et al. [69] present a method for optimal sensor placement for the vibration response estimation of flexible thin shell structures so that model-based methods can be used for active vibration damping. They use a multi-objective simulated annealing algorithm for optimization with two objectives: the number of sensors as a proxy for implementation cost and an observability measure based observability gramian (a gramian used in optimal control theory to determine whether or not a linear system is observable), and considering average observation energy. The method is verified experimentally on a thin shell structure with a square base plan of 10 m×10 m shown in Figure 2. Their optimization results show that preferred locations for sensors are at the edges of the structure and near the support locations. They also note "while one sensor location is theoretically sufficient, increasing the number of sensors lowers the

Figure 2. Adaptive thin shell structure with sensor and actuators under construction (top photo) and after completion (bottom photo) (Courtesy of Michael Heidingsfeld of Bosch Rexroth Company).

observation cost and results in a better signal to noise ratio."

4. Semi-active control

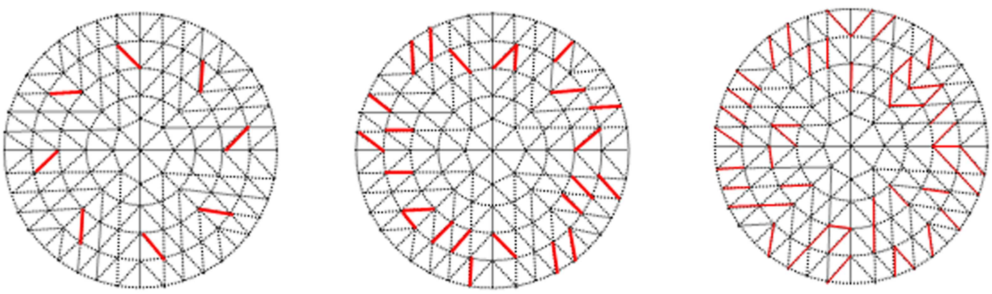
Semi-active control systems need a small amount of power, usually a battery. Magnetorheological (MR) dampers are a common example (see [70] for other examples of semi-active control systems). Bao et al. [71] combine GA with a gradient descent algorithm to obtain the optimal force and placement of MR dampers in reticulated space dome steel structures consisting of steel tubes subjected to dynamic excitations using a clipped-optimal control algorithm. They study semi-active velocity control of a spherical K-8 type space shell structure with 121 nodes and 320 tubular members, as shown in Figure 3. The results of the optimal placements for three cases of 8, 24, and 48 MR dampers considering 40 modes are shown in Figure 3(a) to (c), respectively. In all three cases, the optimal placements of MR dampers are distributed in the outer three circles of the structures.

Li et al. [72] present a two-step methodology for optimal placement of semi-active MR dampers in a 20-story, 3D, benchmark building structure subjected to seismic loading. They employ a multi-objective GA with three objective functions: inter-story drift, peak control force, and an evaluation index that accounts for the effect of active control in the structure. First, the optimum values of the semi-active control forces are determined. Next, the optimum placement of semi-active MR dampers is determined to yield the optimal control forces obtained in the first step. They conclude the bottom three and the top four stories to be the choice for the optimum placement of MR dampers, and the optimal distribution of dampers can reduce the total number of dampers required to provide a desired inter-story drift.

Patil and Jangid [73] study different arrangements of Linear Viscous Dampers (LVD) and Semi-Active Variable Friction Dampers (SAVFD) for vibration control of a 76-story, 306-m benchmark, Reinforced Concrete (RC) building subjected to wind excitations [74]. They modeled the structure as a simple vertical cantilever Bernoulli-Euler beam discretized as a 76-DOF (degree-of-freedom) system, with one DOF per floor, and considered three arrangements for dampers: a diagonal in every story (a total of 76 dampers), a diagonal in every story but connecting two stories (a total of 75 dampers), and a diagonal connecting every two stories (a total of 38 dampers). They report the latter two arrangements to be more effective than the first, and the last to be the most economical. When only one LVD is used, the authors conclude that a diagonal connection from the 74th to 76th floor is the optimum location for the damper.

5. Hybrid control

Li et al. [75] use a fuzzy logic-based [76-78] control algorithm for nonlinear vibration suppression of a 20-story regular three-dimensional benchmark steel moment-resisting frame with a rectangular plan (measuring 30.48-m by 36.58 m in plan and 80.77-m in height) and equipped with an Active Mass Damper (AMD) on the roof with a mass equal to 5% of the total weight of the structure, and passive viscous dampers on each floor (20 viscous dampers total). The authors note that in tall buildings, controlled at the top floor by an AMD, the inter-story drift can be amplified; an unintended and undesirable consequence. Use of a viscous damper on each floor will reduce the inter-story amplification phenomenon. They considered material nonlinearity only using a bilinear hysteresis model and the resulting plastic hinges. Using El Centro and Northridge earthquake records, the authors report that a Tuned Mass Damper (TMD) [79,80] does not control the vibrations effectively because it is effective only in a very limited range frequency, and a linear model-based LQR controller is not effective in reducing the inter-story drift. This point was noted earlier by Adeli and Kim, where the authors presented a novel wavelet-based control algorithm [81,82].



(a) Total 8 MR dampers (b) Total 24 MR dampers (c) Total 48 MR dampers

Figure 3. Optimal damper placements on spherical shell space truss structure after using GA (adapted from Bao et al. 2009 [71]).

Table 1. Summary of papers on vibration control device placement in chronological order.

Author	Year	Control type	Device type	Forces	Structural characteristics		Method
					Type	MDOF	
Adachi	2013	Passive	Viscous	Seismic	2D steel frame	10	Ad-hoc 2-step optimization
Amini and Ghaderi	2013	Passive	Viscous	Seismic	2D shear, truss, steel frames	16, 10	Harmonic search and ant colony
Araujo et al.	2013	Active	Sensor/ actuator	Harmonic	3D composite plate	–	Direct multisearch
Kanno	2013	Passive	Viscous	Seismic	2D shear frame varying stiffness	3, 6	Mix cone programming
Martinez	2013	Passive	Viscous	Seismic	2D shear frame	15	GA
Christopoulos and Montgomery	2013	Passive	Viscoelastic	Wind/ seismic	2D and 3D RC slender structures	85, 51	Equivalent viscous damping
Sonmez et al.	2013	Passive	Viscous	Seismic	2D steel shear frame	9	Artificial bee colony
Cha et al.	2013	Active	Actuator/ sensor	Seismic	3D steel building	20	GA
Hejazi	2013	Passive	Viscous	Seismic	2D and 3D reinforced concrete	5	GA
Weickgenannt et al.	2013	Active	Actuator/ sensor	Wind	3D thin shell wood	–	Multi-objective simulated annealing algorithm
Ambrosio et al.	2012	Active	Sensor/ actuator	Harmonic	2D plate	–	H2 norm, GA
Aydin	2012	Passive	Viscous	Seismic	2D steel shear frame	10	Steepest descent
Chakraborty et al.	2012	Active	Piezoelectric	Seismic	Composite plane	N/A	GA
Li et al.	2012	Active	Piezoelectric	Impulse/ harmonic	68-node truss system	7	Fuzzy control and GA
Whittle et al.	2012	Passive	Viscous	Seismic	2D shear frame	6	5 different methods
Mehrabian and Yousefi-Koma	2011	Passive	Piezoelectric	Wind dynamic vibration	Aircraft tail	N/A	Neural network, invasive weed optimization
Ribakov and Agranovich	2011	Active	Actuator	Seismic	RC and steel frame	10, 20	Optimization algorithm
Estekanchi and Basim	2011	Passive	Viscous	Seismic	Regular and irregular shear frames	3, 8	Endurance time method

Table 1. Continued.

Author	Year	Control type	Device type	Forces	Structural characteristics: Type	Structural characteristics: MDOF	Method
Patil and Jangid	2011	Semi-active	Viscous & Friction	Wind	Linear shear frame	76	Sequential set procedure
Li et al.	2011	Semi-active	MR dampers	Seismic	Nonlinear MRF	20	GA
Agranovich and Ribakov	2010	Active/ semi-active	LQG control	Seismic	Linear RC shear frame	8	Heuristic solution
Apostolakis and Dargush	2010	Passive	Hysteretic (friction)	Seismic	MRF, BRB	2, 4, 6	GA
Bruant et al.	2010	Active	Piezoelectric sensor/actuator	Sinusoidal	2D elastic plate	–	GA
Li et al.	2010	Semi-active	MR damper	Seismic	Nonlinear	20	GA
Ameduri et al.	2009	Active	Shape metal alloy wires	Noise	Rectangular panel	–	GA
Bao et al.	2009	Semi-active	MR	Dynamic	Shell structure	–	GA
Lavan et al.	2008	Passive	Viscous	Seismic	Inelastic nonlinear shear	8	3 optimization methods
Kokil and Shrikhande	2007	Passive	Viscous	Seismic	Single bay 3D shear building; soil-structure interaction	10	Steepest descent
Aydin et al.	2007	Passive	Viscous	Seismic	2D regular shear frame	10	Base force optimization
Bhaskararao and Jangid	2006	Passive	Friction	Seismic	2D shear frame	10	Parametric study
Amini and Tavassoli	2005	Active	Controller	Seismic	Linear, 20 shear frame	3, 12, 16	Gradient descent, neural network
Bishop and Striz	2004	Passive	Viscous	Asymmetric loading	Linear, space trusses	72, 78	GA
Lopez Garcia and Soong	2002	Passive	Linear viscous	Seismic	2D linear shear frame	4, 8, 12, 16, 20	Simplified sequential search algorithm (SSSA)
Singh and Moreschi	2002	Passive	Viscous/ viscoelastic	Seismic	3D Torsional	6, 24	GA
Takewaki	2000	Passive	Viscous	Seismic	2D linear shear frame	10	Optimality criteria method; transfer function

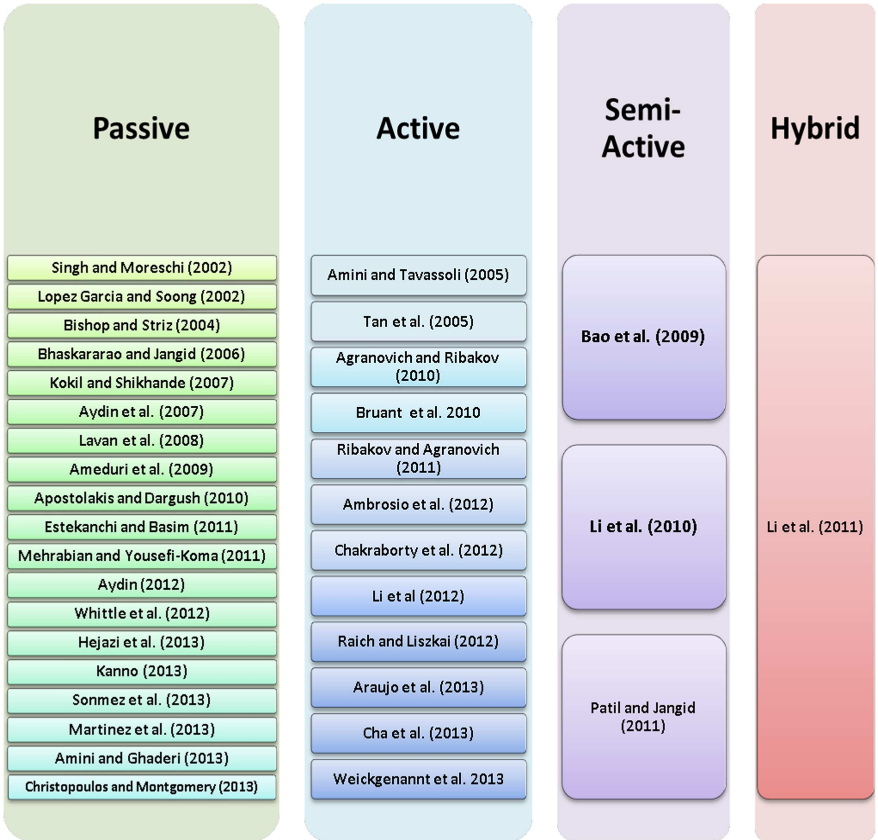


Figure 4. Summary of the placement articles reviewed in this paper.

6. Final comments

This article summarized recent efforts in the placement and optimization of vibration control devices in three categories of passive, active, and semi-active control. A summary of the papers reviewed in this paper is presented in Table 1 and Figure 4. Optimal placement of actuators and sensors improves the energy consumption of the system and reduces the total cost. Additionally, the locations of these devices affect the stability and reliability of a control system.

For passive control of building structures, researchers compared their results with uniform distribution along the height of the structure to show that optimal placement techniques can improve a system's performance and also be more cost efficient. The papers published so far deal mostly with 2D frames and trusses, and shell structures. Only a few researchers have presented research on the placement of large 3D real-world structures, such as highrise building structures. In passive control systems, the optimum location of dampers appears to be at locations where inter-story drifts are the largest in the uncontrolled structure.

Until 2003, Frecker [83] presented a review of optimal actuator placement in the area of active control of structures. Recently, active control researchers have used piezoelectric patches in very small 2D plates and cantilever structures, which offer a different challenge, especially for composite materials, while a 3D truss system was analyzed for sensor and actuator placement optimization. The tallest structure used for optimization of actuator placement in the area of active structural control is a 3D, 20-story, steel benchmark structure.

In semi-active control, the focus has been mostly on optimal placement of MR dampers. Most examples include 2D frames, the tallest being a 76-story 3D reinforced concrete benchmark structure equipped with friction dampers.

Research on the optimum placement of control devices in semi-active, as well as hybrid, control schemes is wide open. These systems appear to be more effective in combating the external dynamic forces, such as those due to winds and earthquakes, but the placement optimization of such systems has not been researched in any depth.

In terms of optimization methodology, the general method of choice in most cases appears to be nature-inspired heuristic approaches, especially GA, followed by swarm optimization techniques [84,85], such as ant or bee colony optimization. Figure 5

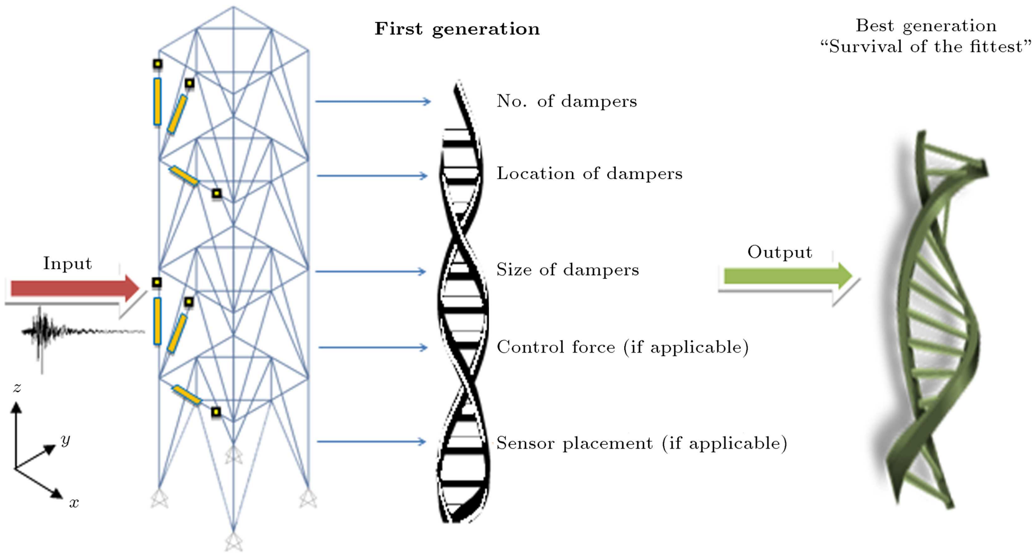


Figure 5. Multi-objective genetic algorithm illustration for optimal damper placement.

shows, schematically, a general multi-objective genetic algorithm for optimal vibration device placement for most general cases. The optimization variables are varied and many, and include the number, location and size of the control devices. For active and semi-active control, the number and location of sensors and the magnitude of the control force are additional variables. This is a complicated optimization problem involving both integer and real variables. Significant additional research is needed, especially in the areas of semi-active and hybrid vibration control of large structures with hundreds or thousands of members, to make the adaptive/smart structure technology cost effective.

References

1. Fisco, N.R. and Adeli, H. "Smart structures: Part I - Active and semi-active control", *Scientia Iranica, Transaction A: Civil Engineering*, **18**(3), pp. 275-284 (2011).

2. Fisco, N.R. and Adeli, H. "Smart structures: Part II - Hybrid control systems and control strategies", *Scientia Iranica, Transaction A: Civil Engineering*, **18**(3), pp. 285-295 (2011).

3. Gutierrez Soto, M. and Adeli, H. "Tuned mass dampers", *Archives of Computational Methods in Engineering*, **20**(4), pp. 419-431 (2013).

4. Bitaraf, M., Hurlebaus, S. and Barroso, L.R. "Active and semi-active adaptive control for undamaged and damaged building structures under seismic load", *Computer-Aided Civil and Infrastructure Engineering*, **27**(1), pp. 48-64 (2012).

5. Nigdeli, S.M. and Boduroğlu, M.H. "Active tendon control of torsionally irregular structures under near-fault ground motion excitation", *Computer-Aided Civil and Infrastructure Engineering*, **28**(9), pp. 718-736 (2013).

6. Singh, M.P. and Moreschi, L.M. "Optimal placement of dampers for passive response control", *Earthquake Engineering and Structural Dynamics*, **31**(4), pp. 955-976 (2002).

7. Adeli, H. and Kumar, S. "Distributed genetic algorithms for structural optimization", *Journal of Aerospace Engineering*, **8**(3), pp. 156-163 (1995a).

8. Adeli, H. and Kumar, S. "Concurrent structural optimization on a massively parallel supercomputer", *Journal of Structural Engineering*, **121**(11), pp. 1588-1597 (1995b).

9. Lopez Garcia, D. and Soong, T.T. "Efficiency of a simple approach to damper allocation in MDOF structures", *Journal of Structural Control*, **9**(1), pp. 19-30 (2002).

10. Bishop, J.A. and Striz, A.G. "On using genetic algorithms for optimum damper placement in space trusses", *Structural and Multidisciplinary Optimization*, **28**(2-3), pp. 136-145 (2004).

11. Adeli, H. and Sarma, K., *Cost Optimization of Structures - Fuzzy Logic, Genetic Algorithms, and Parallel Computing*, John Wiley and Sons, West Sussex, United Kingdom (2006).

12. Fuggini, C., Chatzi, E., Zangani, D. and Messervey, T.B. "Combining genetic algorithm with a meso-scale approach for system identification of a smart polymeric textile", *Computer-Aided Civil and Infrastructure Engineering*, **28**(3), pp. 227-245 (2013).

13. Bhaskararao, A.V. and Jangid, R.S. "Seismic response of adjacent buildings connected with friction dampers", *Bulletin of Earthquake Engineering*, **4**(1), pp. 43-64 (2006).

14. Kokil, A.S. and Shrikhande, M. "Optimal placement of supplemental dampers in seismic design of structures", *Journal of Seismology and Earthquake Engineering*, **9**(3), pp. 125-135 (2007).

15. Aydin, E., Boduroglu, M.H. and Guney, D. "Optimal damper distribution for seismic rehabilitation of planar structures", *Engineering Structures*, **29**(2), pp. 176-185 (2007).

16. Adeli, H., *Advances in Design Optimization*, Chapman and Hall, London (2004).

17. Lavan, O., Cimellaro, G.P. and Reinhorn, A.M. "Non-iterative optimization procedure for seismic weakening and damping of inelastic structures", *Journal of Structural Engineering*, **134**(10), pp. 1638-1648 (2008).

18. Ameduri, S., Diodati, G. and Concilio, A. "SMA embedded panel optimized through a genetic approach", *Journal of Intelligent Material Systems and Structures*, **20**(13), pp. 1529-1540 (2009).

19. Hsiao, F.Y., Wang, S.S., Wang, W.C., Wen, C.P., and Yu, W.D. "Neuro-fuzzy cost estimation model enhanced by fast messy genetic algorithms for semiconductor hookup construction", *Computer-Aided Civil and Infrastructure Engineering*, **27**(10), pp. 764-781 (2012).

20. Apostolakis, G. and Dargush, G.F. "Optimal design of moment-resisting steel frames with hysteretic passive devices", *Earthquake Engineering and Structural Dynamics*, **39**(4), pp. 355-376 (2010).

21. Marano, G.C., Quaranta, G. and Monti, G. "Modified genetic algorithm for the dynamic identification of structural systems using incomplete measurements", *Computer-Aided Civil and Infrastructure Engineering*, **26**(2), pp. 92-110 (2011).

22. Kim, H. and Adeli, H. "Discrete cost optimization of composite floors using a floating point genetic algorithm", *Engineering Optimization*, **33**(4), pp. 485-501 (2001).

23. Estekanchi, H.E. and Basim, M.C. "Optimal damper placement in steel frames by endurance time method", *Structural Design of Tall and Special Buildings*, **20**(5), pp. 613-630 (2011).

24. Chabuk, T., Reggia, J.A., Lohn, J., and Linden, D. "Causally-guided evolutionary optimization and its application to antenna array design", *Integrated Computer-Aided Engineering*, **19**(2), pp. 111-124 (2012).

25. Aydin, E. "Optimal damper placement based on base moment in steel building frames", *Journal of Constructional Steel Research*, **79**(1), pp. 216-225 (2012)

26. Whittle, J., Williams, M.S., Karavasilis, T.L. and Blakeborough, T. "A comparison of viscous damper placement methods for improving seismic building design", *Journal of Earthquake Engineering*, **16**(4), pp. 540-560 (2012).

27. Takewaki, I. "Optimal damper placement for planar building frames using transfer functions", *Structural and Multidisciplinary Optimization*, **20**(4), pp. 280-287 (2000).

28. Hejazi, F., Toloue, I., Jaafar, M.S., and Noorzaei, J. "Optimization of earthquake energy dissipation system by genetic algorithm", *Computer-Aided Civil and Infrastructure Engineering*, **28**(10), pp. 796-810 (2013).

29. Kanno, Y. "Damper placement optimization in a shear building model with discrete design variables: A mixed-integer second-order cone programming approach", *Earthquake Engineering and Structural Dynamics*, **42**(11), pp. 1657-1676 (2013).

30. Sonmez M., Karabork T. and Aydin E. "Using an artificial bee colony algorithm for the optimal placement of viscous dampers in planar building frames", *Structural and Multidisciplinary Optimization*, **48**(2), pp. 395-409 (2013).

31. Putha, R., Quadrifoglio, L. and Zechman, E. "Comparing ant colony optimization and genetic algorithm approaches for solving traffic signal coordination under oversaturation conditions", *Computer-Aided Civil and Infrastructure Engineering*, **27**(1), pp. 14-28 (2012).

32. Tao, H., Zain, J.M., Ahmed, M.M., Abdalla, A.N. and Jing, W. "A wavelet-based particle swarm optimization algorithm for digital image watermarking", *Integrated Computer-Aided Engineering*, **19**(1), pp. 81-91 (2012).

33. Martinez, C.A., Curadelli, O. and Compagnoni, M.E. "Optimal design of passive viscous damping systems for buildings under seismic excitation", *Journal of Constructional Steel Research*, **90**, pp. 253-264 (Nov. 2013).

34. Amini, F. and Ghaderi, P. "Hybridization of harmony search and ant colony optimization for optimal locating of structural dampers", *Applied Soft Computing*, **13**(5), pp. 2272-2280 (2013).

35. Plevris, V. and Papadrakakis, M. "A hybrid particle swarm - gradient algorithm for global structural optimization", *Computer-Aided Civil and Infrastructure Engineering*, **26**(1), pp. 48-68 (2011).

36. Amini, F. and Ghaderi, P. "Hybridization of harmony search and ant colony optimization for optimal locating of structural dampers", *Applied Soft Computing*, **13**(5), pp. 2272-2280 (2013).

37. Adachi, F., Yoshitomi, S., Tsuji, M. and Takewaki, I. "Nonlinear optimal oil damper design in seismically controlled multi-story building frame", *Soil Dynamics and Earthquake Engineering*, **44**, pp. 1-13 (2013).

38. Adeli, H., Weaver, W., Jr. and Gere, J. "Algorithms for nonlinear structural dynamics", *Journal of Structural Division*, **104**(2), pp. 263-280 (1978).

39. Christopoulos, C. and Montgomery, M. "Viscoelastic coupling dampers (VCD) for enhanced wind and seismic performance of high-rise buildings", *Earthquake Engineering and Structural Dynamics*, **24**(15), pp. 2217-2233 (2013).

40. Amini, F. and Tavassoli, M.R. "Optimal structural active control force, number and placement of controllers", *Engineering Structures*, **27**(9), pp. 1306-1316 (2005).

41. Osornio-Rios, R.A., Amezquita-Sanchez, J.P., Romero-Troncoso, R.J. and Garcia-Perez, A. "MUSIC-neural network analysis for locating structural damage in truss-type structures by means of vibrations", *Computer-Aided Civil and Infrastructure Engineering*, **27**(9), pp. 687-698 (2012).

42. Akhand, M.A.H. and Murase, K. "Ensembles of neural networks based on the alteration of input feature values", *International Journal of Neural Systems*, **22**(1), pp. 77-87 (2012).

43. Theodoridis, D., Boutalis, Y. and Christodoulou, M. "Dynamical recurrent neuro-fuzzy identification schemes employing switching parameter hoping", *International Journal of Neural Systems*, **22**(2), pp. 1250004-16 (2012).

44. Tan, P., Dyke, S.J., Richardson, A. and Adbullah, M. "Integrated device placement and control design in civil structures using genetic algorithms", *Journal of Structural Engineering*, 130(10), pp. 1489-1496 (2005).

45. Adeli, H. and Saleh, A. "Optimal control of adaptive/smart bridge structures", *Journal of Structural Engineering*, **123**(2), pp. 218-226 (1997).

46. Aldemir, U., Yanik, A. and Bakiogl, M. "Control of structural response under earthquake excitation", *Computer-Aided Civil and Infrastructure Engineering*, **27**(8), pp. 620-638 (2012).

47. Agranovich, G. and Ribakov, Y. "A method for efficient placement of active dampers in seismically excited structures", *Structural Control and Health Monitoring*, **17**(5), pp. 513-531 (2010).

48. Ribakov, Y. and Agranovich, G. "Control of structural seismic response by a limited set of active dampers", *Structural Design of Tall and Special Buildings*, **20**(5), pp. 594-611 (2011).

49. Bruant, I., Gallimard, L. and Nikoukar, S. "Optimal piezoelectric actuator and sensor location for active vibration control, using genetic algorithm", *Journal of Sound and Vibration*, **329**(10), pp. 1615-1635 (2010).

50. Mehrabian, A.R. and Yousefi-Koma, A. "A novel technique for optimal placement of piezoelectric actuators on smart structures", *Journal of the Franklin Institute*, **348**(1), pp. 12-23 (2011).

51. Hung, S.L. and Adeli, H. "Parallel backpropagation learning algorithms on cray Y-MP8/864 supercomputer", *Neurocomputing*, **5**(6), pp. 287-302 (1993).

52. Adeli, H. and Hung, S.L., *Machine Learning - Neural Networks, Genetic Algorithms, and Fuzzy Systems*, John Wiley and Sons, New York (1995).

53. Siddique, N. and Adeli, H., *Computational Intelligence - Synergies of Fuzzy Logic, Neural Networks and Evolutionary Computing*, Wiley, West Sussex, United Kingdom (2013).

54. Sgambi, L., Gkoumas, K. and Bontempi, F. "Genetic algorithms for the dependability assurance in the design of a long span suspension bridge", *Computer-Aided Civil and Infrastructure Engineering*, **27**(9), pp. 655-675 (2012).

55. Ambrosio, P., Resta, F. and Ripamonti, F. "An H2 norm approach for the actuator and sensor placement in vibration control of a smart structure", *Smart Materials and Structures*, **21**(12), pp. 1-11 (2012).

56. Chakraborty, D., Rathore, P.K. and Roy, T. "Optimal actuators locations in smart fibre reinforced polymer structures using genetic algorithm", *Applied Mechanics and Materials*, **110-116**, pp. 1278-1283 (2012).

57. Li, D.-X., Liu, W. and Jiang, J.-P. "Optimal placement of controls for truss structures in space", *IEEE Intelligent Systems*, **27**(5), pp. 51-56 (2012).

58. Reuter, U. "A fuzzy approach for modelling non-stochastic heterogeneous data in engineering based on cluster analysis", *Integrated Computer-Aided Engineering*, **18**(3), pp. 281-289 (2011).

59. Liu, F. and Er, M.J. "A novel efficient learning algorithm for self-generating fuzzy neural network with applications", *International Journal of Neural Systems*, **22**(1), pp. 21-35 (2012).

60. Yan, L. and Ma, Z.M. "Comparison of entity with fuzzy data types in fuzzy object-oriented databases", *Integrated Computer-Aided Engineering*, **19**(2), pp. 199-212 (2012).

61. Yan, L. and Ma, Z.M. "Incorporating fuzzy information into the formal mapping from web data model to extended entity-relationship model", *Integrated Computer-Aided Engineering*, **19**(4), pp. 313-330 (2012).

62. Subramanian, K. and Suresh, S. "Human action recognition using meta-cognitive neuro-fuzzy inference system", *International Journal of Neural Systems*, **22**(6), pp. 1250028-15 (2012).

63. Sarma, K.C. and Adeli, H. "Bi-level parallel genetic algorithms for optimization of large steel structures", *Computer-Aided Civil and Infrastructure Engineering*, **16**(5), pp. 295-304 (2001).

64. Baraldi, P., Canesi, R., Zio, E., Seraoui, R. and Chevalier, R. "Genetic algorithm-based wrapper approach for grouping condition monitoring signals of nuclear power plant components", *Integrated Computer-Aided Engineering*, **18**(3), pp. 221-234 (2011).

65. Raich, A.M. and Liszkai, T.R. "Multi-objective optimization of sensor and excitation layouts for frequency response function-based structural damage identification", *Computer-Aided Civil and Infrastructure Engineering*, **27**(2), pp. 95-117 (2012).

66. Puscasu, G. and Codres, B. "Nonlinear system identification and control based on modular neural networks", *International Journal of Neural Systems*, **21**(4), pp. 319-334 (2011).

67. Araujo, A.L., Madeira, J.F.A., Mota Soares, C.M. and Mota Soares, C.A. "Optimal design for active damping in sandwich structures using the direct multisearch method", *Composite Structures*, **105**, pp. 29-34 (2013).

68. Cha, Y.-J., Raich, A., Barroso, L. and Agrawal, A. "Optimal placement of active control devices and sensors in frame structures using multi-objective genetic

algorithms", *Structural Control and Health Monitoring*, **20**(1), pp. 16-44 (2013).

69. Weickgenannt, M., Neuhaeuser, S., Henke, B., Sobek, W. and Sawodny, O. "Optimal sensor placement for state estimation of a thin double-curved shell structure", *Mechatronics*, **23**(3), pp. 346-354 (2013).

70. El-Khoury, O. and Adeli, H. "Recent advances on vibration control of structures under dynamic loading", *Archives of Computational Methods in Engineering*, **20**(4), pp. 353-360 (2013). (2013).

71. Bao, Y., Huang, C., Zhou, D. and Zhao, Y. "Semi-active direct velocity control method of dynamic response of spatial reticulated structures based on MR dampers", *Advances in Structural Engineering*, **12**(4), pp. 547-558 (2009).

72. Li, L., Song, G. and Ou, J. "A genetic algorithm-based two-phase design for optimal placement of semi-active dampers for nonlinear benchmark structure", *Journal of Vibration and Control*, **16**(9), pp. 1379-1392 (2010).

73. Patil, V.B. and Jangid, R.S. "Response of wind-excited benchmark building installed with dampers", *Structural Design of Tall and Special Buildings*, **20**(4), pp. 497-514 (2011).

74. Kim, H. and Adeli, H. "Wind-induced motion control of 76-story benchmark building using the hybrid damper-tuned liquid column damper system", *Journal of Structural Engineering*, **131**(12), pp. 1794-1802 (2005).

75. Li, L., Song, G. and Ou, J. "Hybrid Active Mass Damper (AMD) vibration suppression of nonlinear high-rise structure using fuzzy logic control algorithm under earthquake excitations", *Structural Control and Health Monitoring*, **18**(6), pp. 698-709 (2011).

76. Freitag, S., Graf, W. and Kaliske, M. "Recurrent neural networks for fuzzy data", *Integrated Computer-Aided Engineering*, **18**(3), pp. 265-280 (2011).

77. Graf, W., Freitag, S., Sickert, J.U. and Kaliske, M. "Structural analysis with fuzzy data and neural network-based material description", *Computer-Aided Civil and Infrastructure Engineering*, **27**(9), pp. 640-654 (2012).

78. Bianchini, A. "Fuzzy representation of pavement condition for efficient pavement management", *Computer-Aided Civil and Infrastructure Engineering*, **27**(8), pp. 608-619 (2012).

79. Cho, B.H., Jo, J.S., Joo, S.J., and Kim, H. "Dynamic parameter identification of secondary mass dampers based on full-scale tests", *Computer-Aided Civil and Infrastructure Engineering*, **27**(3), pp. 218-230 (2012).

80. Kang, N., Kim, H., Choi, S., Jo, S., Hwang, J.S. and Yu, E. "Performance evaluation of TMD under typhoon using system identification and inverse wind load estimation", *Computer-Aided Civil and Infrastructure Engineering*, **27**(6), pp. 455-473 (2012).

81. Adeli, H. and Kim, H. "Wavelet-hybrid feedback-least mean square algorithm for robust control of structures", *Journal of Structural Engineering*, **130**(1), pp. 128-137 (2004).

82. Kim, H. and Adeli, H. "Hybrid feedback-least mean square algorithm for structural control", *Journal of Structural Engineering*, **130**(1), pp. 120-127 (2004).

83. Frecker, M.I. "Recent advances in optimization of smart structures and actuators", *Journal of Intelligent Systems and Structures*, **14**(4-5), pp. 207-216 (2003).

84. Ghodrati Amiri, G., Abdolahi Rad, A., Aghajari, S. and Khanmohamadi Hazaveh, N. "Generation of near-field artificial ground motions compatible with median predicted spectra using PSO-based neural network and wavelet analysis", *Computer-Aided Civil and Infrastructure Engineering*, **27**(9), pp. 711-730 (2012).

85. Shafahi, Y. and Bagherian, M. "A customized particle swarm method to solve highway alignment optimization problem", *Computer-Aided Civil and Infrastructure Engineering*, **28**(1), pp. 52-67 (2013).

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