# LEARNING, SELF-DIAGNOSIS AND MULTI-OBJECTIVE CONTROL OF AN ACTIVE TENSEGRITY STRUCTURE

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## Abstract

This paper presents a full-scale active tensegrity structure at EPFL and demonstrates how it can learn as well as carry out self-diagnosis and self-compensation. Tensegrities are generally flexible structures: small loads may lead to large displacements. We thus control slope by actively modifying the self-stress state between cables and struts. The structure benefits from past experience through case-based reasoning. It memorizes past control commands and adapts them in order to react to new applied loads up to forty times more rapidly than without this previous control information. Redundancy of this structure provides opportunities for "fault tolerant" behavior. The active control system can also be used to perform self-diagnosis and then to self-compensate local damage. For many cases of local damage, the structure remains capable of satisfying control goals. This paper also summarizes a multi-objective optimization method for control according to four criteria. In contrast with other applications involving multiple objectives, such as design where users prefer choices, this is a control task, thereby requiring identification of a single solution only. Also, the single dominant objective usually generates hundreds of possible solutions. Four objectives are evaluated firstly using Pareto optimality and then a unique solution is chosen through successive filtering of candidate solutions using a hierarchy of objectives. The combination of advanced computing techniques with structural control of serviceability criteria is providing many new possibilities for structural engineers. These results are expected lead toward more autonomous and self-adaptive structures that are able to evolve as their environment changes.

## Introduction

Tensegrities are spatial and lightweight structures composed of compressed struts and tensioned cables that are stabilized by a self stress state. They are very flexible; small loads can induce large deflections. Serviceability control, performed by modifying the self stress state of the structure, has potential to create opportunities for using this type of structures in practical applications.

The active tensegrity structure built at EPFL contains five modules and covers a surface area of 15m$^2$. It rests on three supports that altogether block six degrees of freedom in three dimensions. Two theses have thus far been completed using this structure by Fest (2002) and Domer (2003).

Each module consists of twenty-four stainless steel cables and six composite fiber bars that are connected to each other through thirteen joints. Compressed struts converge toward a central node and this constitutes the particularity of this design as inspired by the office of Passera & Pedretti, Lugano (Switzerland). The central node reduces the buckling length of compressed elements and leads to more slender struts (Fest et al, 2003).

The structure is equipped with three displacement sensors (nodes 37, 43, 48) and ten actuators: see Figures 1 and 2. This makes it possible to actively control the structure. The actuators are placed longitudinally in in-line pairs within each module and this makes it possible to modify the self stress state through modifying the strut length. Control commands (sequences of active strut contractions and elongations) are identified using stochastic search (Domer et al, 2006). This is one of the first large-

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scale active tensegrity structures that are able to satisfy a serviceability criterion. Djouadi et al. (1998), Skelton et al (2000) and Sultan (1999) studied tensegrity structure control only through numerical simulation.

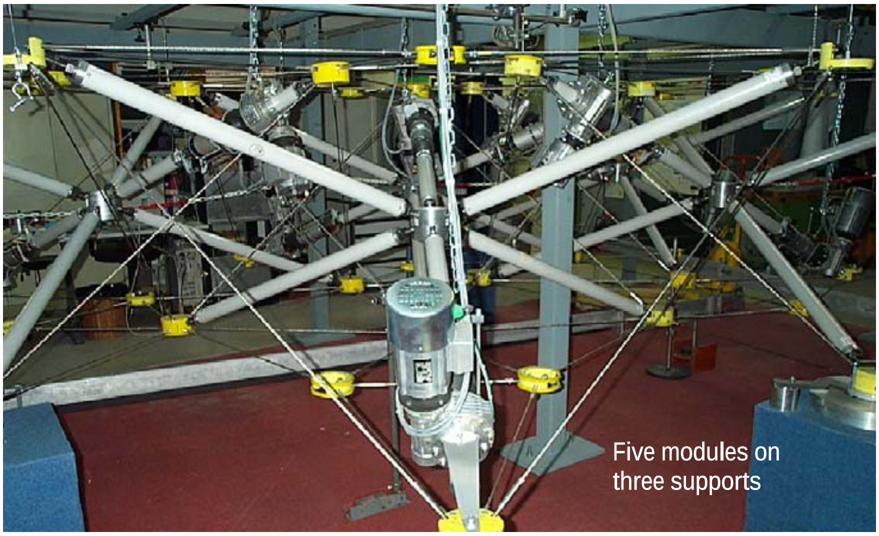

**Figure 1:** EPFL tensegrity structure equipped with 10 actuators and 3 displacement sensors

The active control system can also be used for system identification if members break. Actuators make it possible to perturb the structure while sensors measure the response. Local damage does not necessary lead to a total collapse since the structure is redundant. The active control system is then used to self-compensate a broken element and satisfy the serviceability criterion considering a certain loss of carrying capacity.

## Methodology

The goal is to control a serviceability criterion related to the structure in order to improve its usefulness. Our serviceability criterion consists of maintaining a constant slope of the upper surface of the structure. When a load alters the slope of the structure, we apply a control command. This modifies the self stress state and makes it possible to recover the initial slope.

However, finding an efficient control command is not an easy task due to high coupling between the elements and geometric non-linearity. Consequently we use a generate-analyze-verify process with stochastic search and case-based reasoning (Domer and Smith, 2005). The PGSL (Probabilistic Global Search Lausanne) stochastic search algorithm used in our case is a direct search algorithm developed at EPFL (Raphael and Smith, 2003). In order to take advantage of previous experience, altered configurations and corresponding control commands are stored in a case-base. When the structure is subjected to a load, the nearby configuration is retrieved from the case base and its corresponding control command is adapted to the new task. As cases are added in the case-base the average time necessary to identify a control command decreases (learning). Since the structure is able to improve performance progressively using past experience we considerer this to be a characterization of an intelligent structure.

In the case of local damage, localization is the "inverse problem" of determining a cause given an effect. It is possible to perturb the structure through micro-movements (±1mm) and measure its response through six indicators: RMS variation of the vertical displacements at the three measured nodes (37, 43, 48, see Figure 2) due to the micro-movement and slope variation in three directions due to the micro-movement. For this simple case, we used the algorithm described below. Measured indicator variations on the damaged physical structure are compared with numerically simulated indicator variations due to the same micro-movement and assuming a candidate local damage position. If measured and simulated variations vary in the same way, the assumption is kept. Otherwise the candidate is rejected and another local damage assumption is evaluated. The space of possible damage positions reduces iteratively with micro-movements until the damage is localized.

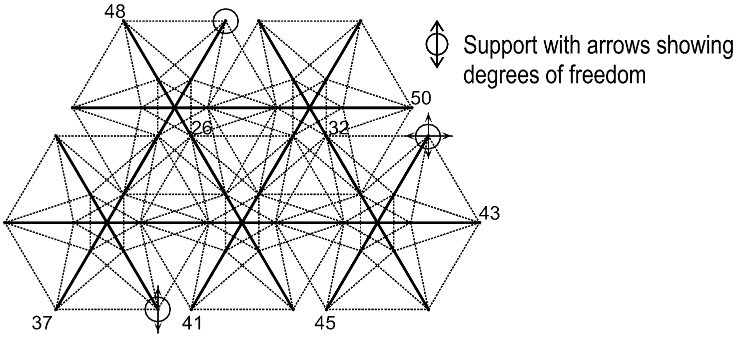

**Figure 2:** View of the structure from above with loaded nodes shown as numbers

Once the damage is localized, a self-compensating control command can be applied in order to satisfy the serviceability criterion. The structure can then be controlled despite a loss of carrying capacity. The principal constraint of this task is serviceability and not structural safety. Contrary to most traditional civil structures, the serviceability and structural safety of tensegrities are often conflicting objectives since measures that increase serviceability (for example, prestress) may lower structural safety through lower load-carrying capacity.

## Results

Control commands are identified by numerically simulating the behavior of the structure using the dynamic relaxation method. They are then applied to the laboratory structure. Errors due to modeling and nonlinear behavior during the control command application lead to inaccuracies. For one applied point-load, the slope compensation varies between 79 and 100%, whereas for two point-loads the slope compensation varies between 65 and 100%. These second load cases are more difficult to compensate because of nonlinearity effects. If the compensation is not sufficient, it is possible to search a second control command using the first search final state as the second search initial state.

The case-based reasoning method makes it possible to create a structure that learns through using its own experience. Memorizing past altered configurations and the corresponding control command makes it possible to react faster to new applied loads by adapting past solutions. Control command search using case-based reasoning method is always faster then using stochastic search only. Moreover, the number of iterations needed to identify a control command decreases with increasing number of cases in the case-base, see the example in Figure 3. Improvements of up to 40 times have been observed. The structure does not learn regularly because of the stochastic nature of the process. Cases are retrieved from the case-base by comparing their notional “distance” to the actual task, considering altered slope value and active strut lengths.

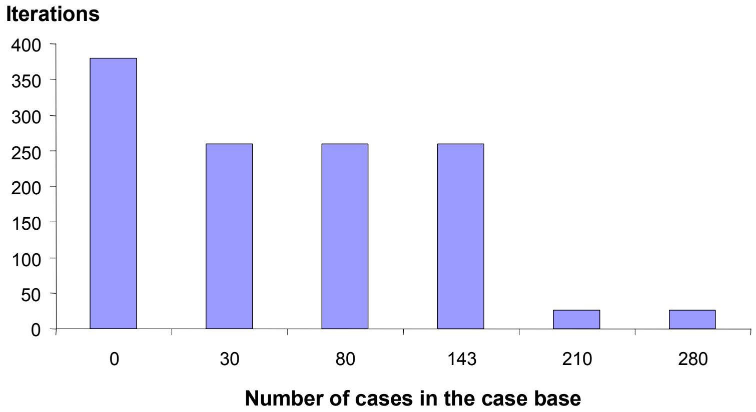

**Figure 3:** The structure learns as cases are added to the case-base (Domer and Smith, 2005)

The structure is perturbed by the control system to carry out self-diagnosis. This paper presents an initial numerical study. The goal of this study is to localize a broken lateral cable, knowing that the structure is not loaded. The initial example is that the broken cable is cable number 111. At the beginning, all thirty lateral cables in the five modules are present in the space of possible broken cables. The identification process assumes successively that each non rejected candidate has a broken lateral cable. The first micro-movement (strut 148: +1mm) makes it possible to eliminate twenty-two candidates since these situations involved behavior that was opposite in direction to that measured for cable 111. The second one (strut 60: +1mm) eliminates other four possible broken cables and then the third micro-movement (strut 60: -1mm and strut 148: +1mm) eliminates three more potentially broken cables and makes it possible to identify the broken lateral cable 111.

Micro-movements of active struts at the center of the structure eliminate candidates faster than micro-movements of active struts situated at the edge of the structure. Combining two micro-movements sometimes makes it possible to further eliminate candidates. It is not always possible to isolate one candidate with single micro-movements.

Once identified, this local damage can be compensated through applying a control command such that the structure still satisfies the serviceability criterion. Therefore the structure can still accept loads considering a loss of carrying capacity.

In this study point-loads are applied at nodes 37, 43 and 48. The maximum load in Newtons for which the structure can compensate the slope when the cable 111 is broken is presented at the second line of Table 1 (CC LD: Carrying Capacity with Local Damage). The maximum load for which the structure can compensate the slope when it is not damaged is shown at third line of Table 1 (CC NLD: Carrying Capacity with No Local Damage). The loss percentage of carrying capacity is indicated on the last line of Table 1. The loss of carrying capacity is understandably larger in the vicinity of the local damage (nodes 37 and 48 are close to cable 111). In these cases loads which should have passed through the broken element to reach the supports have to find another path.

**Table 1.** Loss of carrying capacity when the lateral cable 111 is broken

| **Node** | 37 | 43 | 48 |
|---|---|---|---|
| **CC LD [N]** | 350 | 440 | 310 |
| **CC NLD [N]** | 840 | 520 | 800 |
| **CC Loss %** | 58 | 15 | 61 |

## Multi-Criteria Control

Many combinations of contractions and elongations of active struts can satisfy a single serviceability objective to an acceptable degree. This presents an opportunity to enhance control command search through use of additional objectives. Additional objectives should not significantly decrease control command quality with respect to the slope objective. Goals are to increase robustness of both the structure and the active control system in order to carry out multiple control events over service lives. The following four conflicting objectives are used to guide search:

- Slope: maintain top surface slope of the structure constant when subjected to loading,
- Stroke: maintain actuator jacks as close as possible to their midpoint,
- Stress: minimize stress of the most stressed element,
- Stiffness: maximize the stiffness of the structure.

The general form of a multi-objective optimization problem can be expressed as follows:

Minimize objective functions $\vec{f}(\vec{x})$

subject to inequality constraints $\vec{g}(\vec{x}) \leq 0$

and equality constraints $\vec{h}(\vec{x}) = 0$

where $\vec{x} \in R^n$, $\vec{f}(\vec{x}) \in \Re^k$, $\vec{g}(\vec{x}) \in \Re^m$, and $\vec{h}(\vec{x}) \in \Re^p$. Here, *n* represents the number of variables, *k* the number of objective functions, *m* the number of inequality constraints and *p* the number of equality constraints.

A Pareto filtering approach is employed in order to avoid the use of weight factors. In case of a multi-objective minimization task, a solution $x^*$ is said to be Pareto optimal if there exists no feasible vector of decision variables *x* which would decrease some objective without causing a simultaneous increase in at least one other objective. This concept results in a set of solutions called the Pareto optimal set. The vectors $x^*$ corresponding to the solutions included in the Pareto optimal set are called non-dominated (Pareto, 1896).

The multi-objective search method adapted to our tensegrity structure serviceability control task involves building a Pareto optimal solution set and selecting one solution (see Figure 4). The Pareto optimal solution set is identified according to the four objectives and the five constraints described above. Solution generation and Pareto filtering is carried out using the ParetoPGSL algorithm. Solutions are generated in order to minimize all objectives. Dominated solutions are rejected. ParetoPGSL stops after 1500 generated solutions since solution quality does not improve any further.

The selection strategy that is adopted hierarchically reduces the solution space until identification of a control command. It is developed in four steps and reflects the importance of the objectives. Control commands for which slope compensation is less than 95% are first rejected. In practical situations, slope compensation would be acceptable if its value was above this threshold. To keep objectivity with respect to the three remaining objectives, the remaining solutions are divided into thirds according to solution quality. The worst third of the solutions with respect to the stroke objective is rejected. The worst half of the remaining solutions with respect to the stress objective is then rejected. Finally, the best solution with respect to the stiffness objective is identified among solutions that are left. This becomes the control command that is applied to the structure. Therefore, each of the three objectives in the last three steps leads to rejection of the same number of solutions.

Control solutions describe the structural configuration when slopes are compensated. Sequences of application of control commands that transform the altered slope state to the compensated slope state involve verifying that no failure would happen during intermediate steps. The control command is divided into 1 mm steps. Strut contractions are placed at the beginning of the sequence and elongations at the end. In this way, energy is generally first taken out of the structure before it is added. Calculations are made using the dynamic relaxation method. The position of the structure is evaluated for each 0.1 mm of actuator travel. The sequence is then applied to the physical structure for experimental validation.

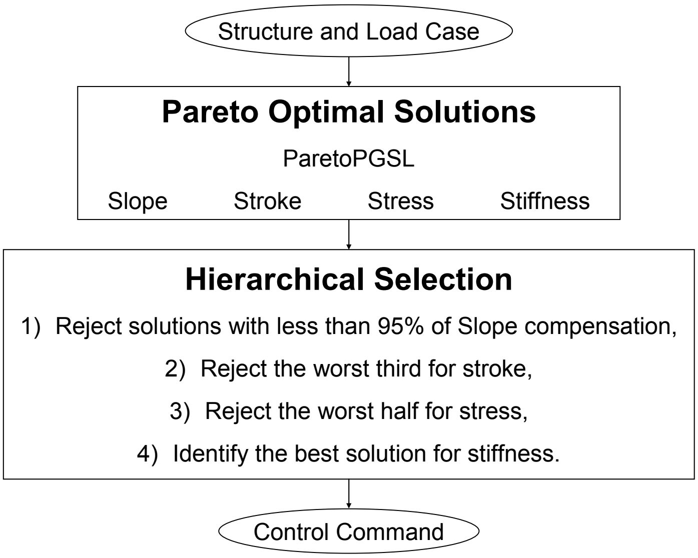

**Figure 4:** Multi-objective methodology: Hierarchical selection of Pareto optimal solutions

### Results of Multi-Criteria Control

This methodology is tested for 24 load cases involving up to two vertical point loads from 391 N to 1209 N in magnitude (see Table 2). Loaded nodes are numbered according to Figure 2. One and two point load cases numbered from 1 to 24 are presented in Table 2.

**Table 2**. Load cases applied to the structure

| Load case | Loaded | Load magnitude |
|---|---|---|
| 1 | 26 | 625 |
| 2 | 26 | 900 |
| 3 | 26 | 1209 |
| 4 | 32 | 625 |
| 5 | 32 | 859 |
| 6 | 32 | 1092 |
| 7 | 37 | 391 |
| 8 | 37 | 550 |
| 9 | 37 | 700 |
| 10 | 48 | 391 |
| 11 | 48 | 550 |
| 12 | 48 | 700 |
| 13 | 6 | 1092 |
| 14 | 37 and 45 | 391 |
| 15 | 37 and 45 | 624 |
| 16 | 37 and 45 | 742 |
| 17 | 39 and 48 | 157 |
| 18 | 39 and 48 | 215 |
| 19 | 39 and 48 | 274 |
| 20 | 41 and 50 | 391 |
| 21 | 41 and 50 | 624 |
| 22 | 45 and 48 | 391 |
| 23 | 45 and 48 | 624 |
| 24 | 45 and 48 | 742 |

Examine load case 5: 859 N point load at node 32. Pareto optimal solutions are generated using the ParetoPGSL algorithm (see Figure 5). Solutions are presented in four dimensions with respect to the four objectives. The slope objective is shown on the vertical axis. Stroke and stress objectives are represented with the horizontal axis. The gray bar evaluates the stiffness objective. Values close to zero are considered best for all objectives.

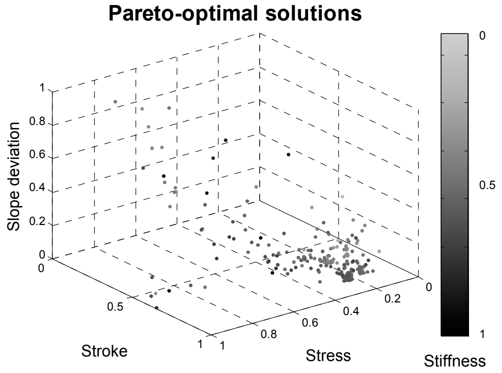

**Figure 5:** Pareto front respect to slope, stroke, stress and stiffness

The first step of the hierarchical selection strategy consists of rejecting all solutions for which slope compensation is less than 95% (see Figure 6).

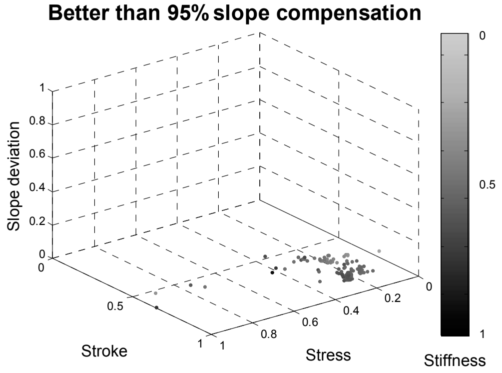

**Figure 6:** Solutions for which slope compensation is better than 95%

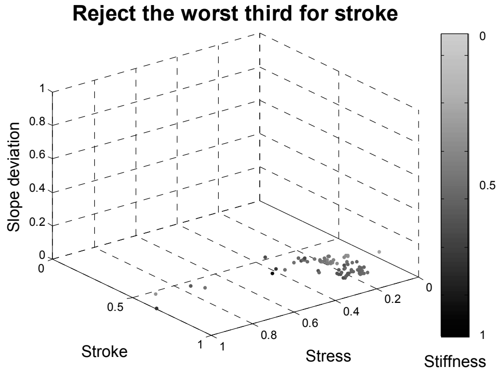

**Figure 7:** The worst third of the previous set with respect to stroke has now been rejected

The second step of the selection strategy involves dividing the remaining solution set into three parts according to stroke objective. The worst third is rejected (see Figure 7).

The third step of the selection strategy results in dividing the remaining solution set into two parts according to stress objective quality. The worst half is rejected (see Figure 8).

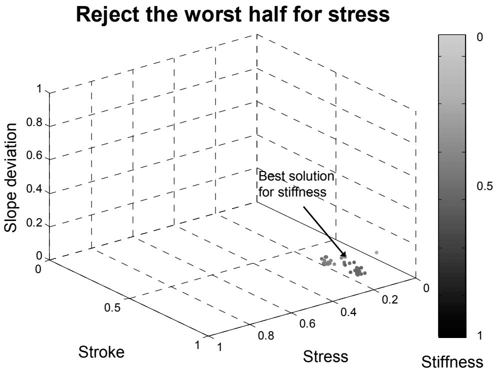

**Figure: 8.** The worst half of the previous set with respect to stress has now been rejected

The last step of the selection strategy consists of identifying the control command as the best solution with respect to stiffness objective. (see Figure 8). This solution represents the configuration of the structure when the slope is compensated. Sequence of application of the control command is then calculated to verify that no failure would happen and to observe slope evolution. The control command is applied to the loaded physical structure for experimental validation (see Figure 9). Slope evolution is plotted versus steps of 1mm of actuator travel.

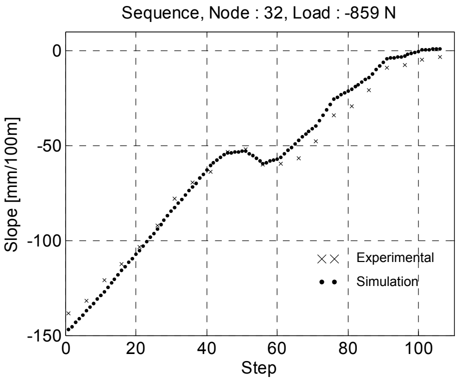

**Figure 9:** Experimental and numerical slope compensation sequence

Numerical simulation gives an altered slope of -147mm/100m and a compensated slope of 1mm/100m (99% compensated). Experimental testing gives an altered slope of 138mm/100m and a compensated slope of -4mm/100m (97% compensated). The average actuator travel is 1.5 mm. Stress

**Table 3.** Multiple load application scenario

| Load event | Loaded | Load Magnitude |
|---|---|---|
| 1 | 32 | 391 |
| 2 | 50 | 391 |
| 3 | 37 | 391 |
| 4 | 48 | 391 |
| 5 | 26 | 391 |
| 6 | 6 | 150 |

values are numerical only because the structure is not equipped with force sensors that would provide experimental data. Simulation and laboratory test results for slope are generally in good agreement.

Structural control for multiple load application events (Table 3) is presented in Figure 10. Slope evolution is plotted versus steps of 1mm of actuator travel. Structural behavior when control commands are identified using multi-objective search and single objective search are evaluated. Control commands are more rapidly effective when they are identified with multi-objective search. Single objective control command exhibit a more pronounced zig-zag profile that requires more steps to correct the slope. Multi-objective commands are useful to maintain robustness of both the structure and the control system whereas in single objective sequence no such maintenance can be assured. At the sixth control command multi-objective method makes it possible to compensate the slope whereas a single objective method leads to buckling of a strut.

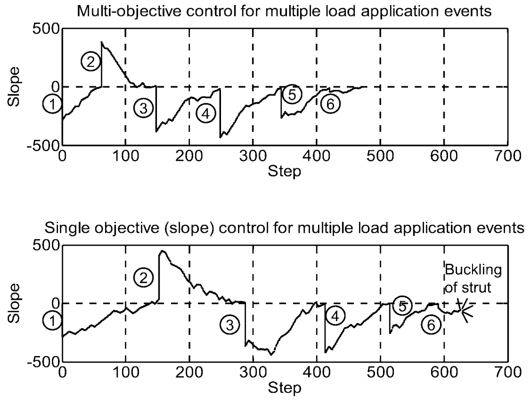

**Figure 10:** Multiple loads applied sequentially: multi-objective and slope-objective control commands

## Conclusions

This paper presents a study of the application active control to a tensegrity structure so that opportunities for innovative applications can be identified. The following conclusions come out this research:

- When subjected to a load, a control command (sequence of strut contractions and elongations) makes it possible to modify the self stress state in order to maintain serviceability criteria.
- Use of previous control commands increases performance and creates an opportunity for the structure to learn.
- The active control system can also be used to perform self-diagnosis by comparing measured behavior of the damaged physical structure and simulated behavior resulting from an assumption of local damage location. These studies demonstrate good potential to localize a broken cable.
- The active control system can also be used to self-compensate a local damage and still satisfy the serviceability criterion. Simulation studies show opportunities for using damaged structures through considering loss of carrying capacity.
- In situations where satisfying a dominant objective results in many solutions, a Pareto approach together with hierarchical elimination of solutions is attractive, especially when tasks require single solutions such as during structural control.
- Multiple load application events are controlled more efficiently using multi-objective control.

These results lead toward more autonomous and self-adaptive structures that evolve in changing environments.

## Acknowledgments

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