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BIOMIMETIC CHARACTERISTICS OF AN ACTIVE DEPLOYABLE STRUCTURE

Ph.D. Research Proposal

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SUMMARY

Biomimetic structures are structures that demonstrate increased functionality through mimicking qualities of biological organisms. Self-repair and adaptation mechanisms are examples of biological qualities that can be adapted in structural engineering. Over the last decades, great strides have been made in advancing theory and practice of active structural control. However, little scientific progress has been made on biomimetic structures. Advances in sensor, actuator, and microprocessor technologies provide increasing possibilities for implementing active control systems in the built environment. Intelligent control methodologies such as self-diagnosis, self-repair and learning could be integrated into structural systems to provide innovative solutions. The general goal of this thesis is to study biomimetic characteristics of an active and deployable tensegrity bridge. Building on previous research carried out at EPFL, this thesis proposal includes the following objectives: 1) design an active control system in order to ensure damage tolerance of a deployable tensegrity pedestrian bridge; 2) extend existing strategies for self-diagnosis of the deployable tensegrity bridge to avoid ambiguous results; 3) extend existing strategies in order to achieve a more robust self-repair scheme; 4) develop algorithms that allow the active control system to learn efficiently using case-based reasoning; 5) validate the methodologies developed with experiments on a near full-scale (1/3) model. A literature survey of biomimetics, structural control, tensegrity structures, deployable structures, deployable tensegrity structures, active tensegrity structures, case-based reasoning, system identification, and multi-objective search has identified that these objectives are original. Results obtained from the preliminary studies demonstrate the potential of this research strategy. A research plan containing 19 subtasks that will be completed by the end of April 2012 leaves sufficient buffer time before the official end of this Ph.D. research on September 30, 2012.

KEYWORDS

Biomimetics, active control, active structures, self-diagnosis, self-repair, learning, damage tolerance, deployable structures, tensegrity structures, pedestrian bridges, stochastic search,

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1. INTRODUCTION

1.1. Motivation

Application of biological systems to design engineering systems and structures has been practiced since human-beings understood that nature generates good solutions. The transfer of knowledge from life forms to synthetic constructs is attractive due to the fact that the living organisms are optimized and efficient thanks to natural selection. Engineering structure functionality could thus be increased through mimicking qualities of biological organisms. Such replication can be achieved by integrating intelligent control methodologies within active structures. Recent advances in computing, wireless technology, as well as increasing possibilities for data acquisition and actuation technologies have now provided the enabling technologies for biomimetic structures and other systems.

There has been a growing amount of research into structural control due to several factors such as new challenges (e.g. space missions) and damage caused by earthquakes. Aerospace engineers have used active control in order to make spacecraft and aircraft move within their environment. In built environments, structural control has been proposed for enhancing safety of structures under extreme conditions since the last quarter of the 20th century. However, long-term reliability of control systems has been a matter of controversy in the case of actively controlled civil structures. Despite the fact that structural control has been applied for earthquake protection in the US and Japan, where earthquakes are the primary concern, most engineers believe that active control is not the best way to protect civil engineering structures against such phenomena due to large return periods and concern related to long-term reliability of active control systems. Instead, actively controlled structures are more suited to satisfy serviceability criteria in changing environments. The aim of an intelligent structure is to enhance the structural performance by sensing the changes in behavior and in loading, adapting the structure to meet goals, and retrieving past events to improve future performance (Shea and Smith, 1998). When active control systems are used to satisfy serviceability criteria, long term reliability of the control system is of less concern than when primary control objectives are associated with safety criteria (Shea et al., 2002). In this thesis, active control is used to improve damage tolerance instead of ensuring safety requirements of the structure. Integrating biomimetic approaches within research into intelligent structures has the potential to identify efficient solutions through inspiration of solutions from nature.

Deployable structures are structures that have the ability to be transformed from a packed up compact configuration to expanded operational configurations that have safe and serviceable load carrying capacities. Their ability to change shape is a significant advantage for transportation and storage. To achieve deployment, deployable structures have active elements that are usually active only during deployment

A tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components within a continuum of tensioned components (Motro, 2003). Tensegrity systems are spatial reticulate systems that have applications in a range of fields such as aerospace engineering, sculpture, architecture, civil engineering, marine engineering and biology. Tensegrity structures have several promising properties. A high strength to mass ratio provides possibility of designing strong and lightweight structures.

Among different traditional approaches, the tensegrity concept is one of the most promising for active and deployable structures. Being relatively lightweight and flexible, tensegrity structures need only small amount of energy for shape control. More generally, tensegrities usually have wide ranges of feasible solutions for control of geometry, stiffness and vibration.

1.2. Objectives

The intention of this thesis is to study biomimetic characteristics of an active deployable tensegrity structure. The structure will be an actively controlled deployable tensegrity pedestrian bridge, which is currently being designed in context of another Ph.D. thesis at IMAC (Rhode-Barbarigos). The active control system will be extended within the scope of this thesis plan. More specifically, the active control system will be optimized in such a way that the structure will be damage tolerant during its service life. Building upon the previous studies conducted at IMAC (Fest, Domer, Adam and Rhode-Barbarigos), the following objectives are part of this thesis (see Section 5.2 for further details):

1. **Design** an active control system for the purpose of ensuring the damage tolerance of a deployable tensegrity pedestrian bridge

   The deployable bridge already has active elements designed for deployment function in context of Rhode-Barbarigos' Ph.D. thesis research at IMAC. New active members are to be defined in order to satisfy robustness criteria during the service life of the structure. Optimum locations for actuation means will be determined by studying damage cases.

2. Extend existing strategies for **self-diagnosis** of the deployable tensegrity bridge to avoid ambiguous results:

   The active control system of the structure will be capable of identifying excessive loading and damage in order to switch to self-repair phase. Existing brute-force search strategies, which are proposed by Adam (2007) for self-diagnosis, will be evaluated for application to the deployable tensegrity bridge and improved for better search performance.

3. Extend existing strategies in order to achieve a robust **self-repair** scheme:

   Results of the pilot study will be compared with damage identification and learning procedure proposed previously. The damage identification and self repair procedures presented by Adam (2007) will be extended. Clustering techniques will be employed to ensure an effective use of actuation means. Multi-objective self-repair procedures will be developed to take into account additional robustness objectives. Robustness of both the structure and the active control system will be addressed.

4. Design and develop algorithms that allow the active control system to **learn**, using CBR by extending previous methods:

   Case-based reasoning (CBR) will be used to provide an active control system that can solve new problems rapidly using the solutions of past problems. Increasing the number of cases will improve control solution computation time. Focus will be on maintaining the case-based maintenance so that it contains a good distribution of useful cases, thereby extending previous work.

5. **Verify** the control system components with experiments on a near full-scale (1/3) model

   The configuration of the control system obtained using computational methods in mechanics and advanced computing will be verified by experimental results. The experiments will be carried out on a near full-scale (1/3) model of the structure.

2. STATE OF THE ART

2.1. Biomimetics

Biomimetics is the field of scientific endeavor, which attempts to design systems and synthesize materials through biomimicry (Ramachandra Rao, 2003). A goal of biomimetics is to discover enviable qualities and characteristics in biological systems and apply them to develop solutions in science and engineering. Biomimetics have a large number of potential applications, ranging from computer systems, aerospace engineering, electronics and robotics to architecture and marine engineering.

Self reproducing automata were proposed by Von Neumann (1966) as pioneer of bio-inspired computer systems. Self reproduction and self-repair characteristics of this system is inspired by biological cells, which can reproduce by cell division (Von Neumann, 1966). Denning (1976) developed four related architectural principles which can guide construction of error-tolerant operating systems. Damage detection and correction is elaborated in order to provide error-tolerant systems (Denning, 1976). Kuc (1993) implemented a sonar-driven robot, *ROBAT,* to track an object moving in three dimensions using qualitative interpretation of sonar signals.

Mange (1997) et al. described a complex system that was inspired by molecular biology and allowed development of new field-programmable gate arrays endowed with quasi-biological properties. This kind of computer architecture is useful in environments where human intervention is necessarily limited, such as nuclear plants and space applications. In this study, self-reproduction (automatic production of one or more copies of the original organism) and self-repair (automatic repair of one or more faulty cells) were highlighted (Mange et al., 1997). Sipper (1997) et al. showed that certain properties that are unique to the living world, such as self-replication, self-repair, and growth, can also be attained in artificial objects (integrated circuits) by adopting certain features of cellular organization, and by transposing them to world of integrated circuits on silicon. Mange et al. (1999) presented a silicon-based artificial cell, followed by a description of mechanisms operating at cellular level: cellular differentiation, cellular division, regeneration, and replication. They presented also the composition of the cell as an ensemble of lower-level elements, known as 'molecules' (Mange et al., 1999).

Teuscher et al. (2001) introduced bio-inspired computing tissue that constitutes a key concept for implementation of 'living' machines. They studied an error-tolerant *BioWall* application. BioWall was a reconfigurable computing tissue that was capable of interacting with its environment by means of a large number of touch-sensitive elements coupled with a color display. They stated that biomimetic computer tissues could help human beings understand natural phenomena, along providing more intelligent machines (Teuscher et al., 2001). Floreano and Mondada (1998) described a methodology for evolving neurocontrollers of autonomous mobile robots without human intervention. Sterrit (2005) et al put forward that autonomic computing is a major strategic and holistic alternative approach to the design of complex distributed computer systems. Autonomic computing was based on strategies used by biological systems to successfully deal with similar challenges of complexity, dynamism, heterogeneity and uncertainty (Sterrit et al., 2005).

In the 19th century, an architecture style called "organic architecture" emerged. Organic architecture is considered the counter point of rational design, based on modular principles. Antoni Gaudí, Alvar Alto and Frank Lloyd Wright are considered as the main representatives of this architectural language. According to organic architecture, constructive ideal evolves from the human body (Kowaltowski et al., 2007). Anshuman and Kumar (2005) have carried out a comparative analysis of intelligent building facades and sixteen large media-facades from a social-psychology perspective. Recently, biomimetic approaches have become very common in material science applications. Zhou et al. (2007) developed bio-inspired wearable characteristic surface imitating cuticles of soil animals. Schneider et al. (2009) mimicked ovipositor of the wood-boring wasp Sirex noctilio for the development of a novel type of neurosurgical probes. Surface texturing and various microstructure geometries were fabricated and investigated as to their tribological properties during penetration of a probe into brain tissue (Schneider et al., 2009)

In spite of many applications in several fields, biomimetics applications in civil engineering need to be identified and realized. Aside from recent work at EPFL (see section 3), no scientific application of biomimetics on a civil engineering structure has been found in the literature. Although computer scientists have used biomimetic methods for diverse aims, experimental and analytic application of such approaches are new to structural engineering.

2.2. Structural Control

Advances in theory and practice of active structural control technology have modified the general perception about structures. Due to incorporated intelligence, structures become dynamic objects capable of interacting with complex environments (Shea et al., 2002). Some space structures are actively controlled to mitigate affect of vibrations and deformations, as well as to create deployable and variable geometry structures. In civil structures, structural control has principally focused on improving the overall structural response for primarily safety and secondarily, serviceability purposes. Serviceability has not been primary concern in active control investigations until the beginning of the 21st century. Conventionally, structural control has been carried out by providing a supplementary system that could apply forces to a structure under loading in order to alleviate external excitations caused by earthquakes or high winds (Elseaidy et al., 1997).

Structural control systems are categorized as passive, active, hybrid and semi-active (Shea et al., 2002). In an active control system, an external power source supplies energy to control actuators that apply forces to the structure in a prescribed manner. The applied force can both add and dissipate energy from the structure. A function of the response of the system measured with optical, mechanical, electrical or chemical sensors create the signals sent to the control actuators (Housner et al., 1997). Active control of civil engineering structures was first introduced by Yao (1972) as a means of protecting tall buildings against high winds. The modern concept of an active structure was first proposed by Soong and Manolis (1987). In this work, active control involves a wide variety of actuators, including active mass dampers, hybrid mass dampers, tendon controls, which employ hydraulic, pneumatic, electromagnetic, and motor driven actuation.

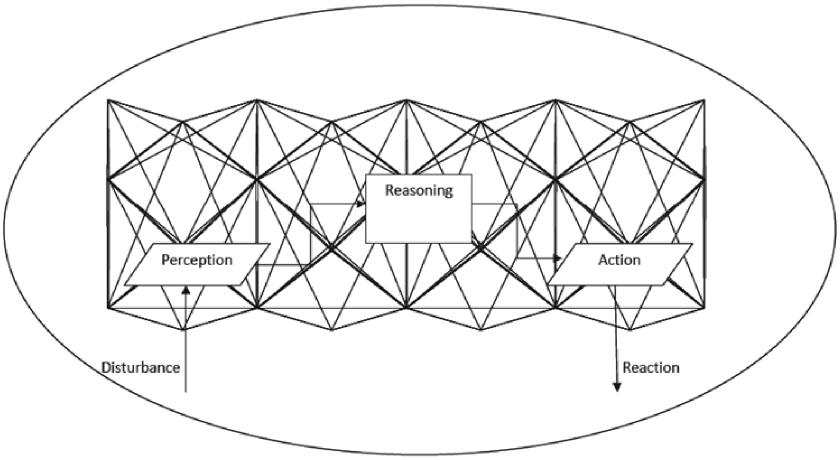

Figure 1. Active structure

Unlike an active control system, a passive control system does not require an external power source. Forces developed in response to the motion of the structure are conveyed by passive control devices. The energy of such a system cannot be increased but only dissipated by the passive control devices (Housner et al., 1997). Nawrotzki (2001) compared four different passive control techniques for seismic safety of buildings:

In the first technique, namely base isolation system, the structure is uncoupled horizontally. In the second system, tuned mass damper (TMD), an additional mass on top of the building is combined with a spring/damper system. The third technique is similar to TMD, but the whole top story is used as mass. This technique is called elastically coupled top storey. A 3D base control system, which is a combination of horizontal and vertical damping with helical springs and viscous dampers, is also investigated. 3D base control systems have the best outcomes in terms of acceleration damping and reducing displacements (Nawrotzki, 2001). Passive control systems make use of natural motion of masses. On the other hand, active control systems, such as active mass damper (AMD) use sensors to set actuators in motion that apply restoring forces (Housner et al., 1997).

Hybrid control of structures implies combined use of active and passive control (Housner et al., 1997). Hybrid systems use passive and active systems together, for instance, combining

TMD with sensors and actuators in order to improve reliability of TMDs and efficiency of AMDs (Shea et al., 2002).

Semi-active control systems are a subclass of active control systems. External energy requirements are very low for this kind of control systems. Typically, they do not add mechanical energy to the structural system. They are often considered as controllable passive devices. Semi-active systems are run by very low power. Many can operate on battery power, which is critical during seismic events when main power source to structure may fail (Housner et al., 1997).

There are a number of applications using active control for small-size structures. However, passive control is most often proposed for civil engineering. In the literature, no civil engineering structure that uses active control strategies for shape control and self-repair purposes could be found in the literature aside from recent work at EPFL (see section 3).

2.3 Tensegrity Structures

The tensegrity concept was first envisaged by Fuller in the second half of the 20th century (Fuller, 1959, Fuller and Applewhite, 1975). Fuller proposed the word "tensegrity" as a contraction of "tensional integrity" (Lalvani, 1996). According to Motro (2003), "A tensegrity system is a system in a self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components". Skelton and de Oliveira (2009) defined it as "Configurations of rigid bodies is a tensegrity configuration if there exists string connectivity able to stabilize the configuration.". Tensegrity systems are spatial reticulate systems that are composed of struts and cables. Stability is provided by the self-stress state between tensioned and compressed elements independent of all external actions.

Tensegrity structures are attractive due to several benefits (Skelton et al., 2000):

Stability through Tension: A large stiffness-to-mass ratio can be obtained for tensegrity structures.

Efficiency: Material is needed only in essential load paths of a tensegrity structure. Orthogonal parts are not highly stressed, unlike other structures.

Ease of Deployability: Since compressive members are either disjoint or connected with ball joints, tensegrity structures are very good candidates to be designed to have large displacements and to be deployable.

Ease of Tuning: Fine tuning and adjustment may be easier for tensegrity structures than for conventional structures.

More Reliable Models: Tensegrity structures comprise axially loaded members. While the global structure bends with external loads, the individual components of it do not experience bending moments. Considering the general difficulties in modeling the structural members that experience deformation in more than one dimension, models of the behavior of tensegrity structures are more simple compared to models that include bending members.

High Precision Control: Tensegrity structures can be more precisely controlled given that they can be more precisely modeled.

Integration of Structure and Control Disciplines: Members of tensegrity structures can serve as actuation tools as well. They offer a promising model for putting together structure and control design.

Biomimetic Characteristics: Nature has produced several tensegrity structures after a great deal of trial and error processes. Tensegrity structure phenomenon in nature is a promising path to be followed to explore new design concepts and to exploit experience of nature.

In order to distinguish between types of tensegrity systems that fit the general tensegrity definitions, Skelton classifies tensegrity systems into classes with respect to contacts between rigid bodies in the system. A *class 1* tensegrity system has no contacts between its rigid bodies, and a tensegrity system with as many as k rigid bodies in contact is called a *class k* tensegrity system (Skelton and de Oliveira, 2009).

Tensegrity structures are found in nature. For example, the molecular structure of nature's strongest fiber, the dragline silk of a Nephila Clavipes has a class 1 tensegrity structure. It is a complex-folded protein comprising primarily two amino acids, glycine and alanine. In the molecular structure of alanine, there are rectangular plates providing the rigid bodies in the tensegrity definition, and amorphous strands forming the tensile members of tensegrity (Skelton and de Oliveira, 2009, Termonia, 1994). The shoulder and elbow joints of human are respectively class 2 and class 3 tensegrity systems. Ingber went one step further defining tensegrity as "architecture of life" (Ingber, 1998). The complexity created by very simple elements of tensegrity structures attracted attention of various artists. Snelson, who is a sculptor, and Fuller, who is an architect, are two pioneers in tensegrity field (Fuller, 1959, Snelson, 1965).

Tensegrity systems have been known for over 50 years in art community (Uitz, 1922) and architectural community (Pedretti, 1998, Gough, 1998, Motro, 2003, Lalvani, 1996, Skelton and de Oliveira, 2009, Pugh, 1976). However, as one surveys current activities in research and application, it is clear that the tensegrity concept is still evolving and much of its application potentials still need to be identified and realized.

2.4 Deployable Structures

Deployable structures are assemblies of prefabricated members or elements that can be transformed from a closed compact or folded configuration to a predetermined expanded form of a complete stable structure capable of supporting loads (Gantes, 2001). Fast and easy assembly procedures, ease of transportation and storage, minimum skill requirements for erection, dismantling and relocation, and the competitive overall cost are advantages of deployable structures that provide effective solutions to engineers (Gantes et al., 1989). However, high nonlinear behavior during deployment of such structures has been a major concern for engineers. Stresses in deployment phase are very sensitive to small changes in geometry or member properties, and can become dangerous. Practical limitations during deployment procedure create further challenges in design process. For that reason, both a qualitative understanding of the behavior and a quantitative evaluation of stresses occurring throughout the deployment process need to be considered during the design of deployable structures (Gantes et al., 1989).

Deployable structures are used in masts (Mikulas, 1994, Pellegrino, 1995, Jensen and Pellegrino, 2001) and antennas (Li and Wang, 2009b, Takano et al., 2002, Guest and Pellegrino, 1996, Roederer, 1989, Freeland, 1983, Mikulas, 1994, Pellegrino, 1995, Jensen and Pellegrino, 2001, Rogers et al., 1993, Hachkowski and Peterson, 1995, Ando et al., 2000, Zhao et al., 2009) in aerospace engineering. Also, some research studies about deployable structures can be found in the literature (Gantes and Konitopoulou, 2004, Chen et al., 2005, Tan and Pellegrino, 2008). Moreover, biomedical applications of deployable structures are used especially in surgery (Kuribayashi et al., 2006). Gruber et al. approached to deployable structures in a biomimetic manner studying bionic concepts applicable to deployable structures and interpreting findings for implementation concepts for a human lunar base (2007). There have been also mathematical approaches to deployable structures from a geometrical point of view (Kiper et al., 2008). Xun and Yan (2008) studied a method based on neural networks and its application in vibration signal analysis of a deployable structure in order to process the non-linear vibrations of the mechanism. In addition, the thermal effect is an important issue to be considered in deployable structures because of their high sensitivity to geometrical and mechanical changes. Li and Wang (2009a) made a deployment dynamic analysis of deployable antennas considering thermal effects. Soykasap (2009) studied on dynamic response of a deployable boom from an energy point of view. On the other hand, despite the fact that a significant amount of research has been conducted in the field of deployable structures, none of them focused on a civil engineering aspects such as robustness, serviceability and partially defined loading.

2.5 Deployable Tensegrity Structures

An object that has smaller weight and volume is usually preferable to another that makes the same job with greater weight and volume. Tensegrity mechanisms embody an alternative to conventional mechanisms to satisfy increasing requirements for lightweight systems. Furthermore, some of these mechanisms have the advantage of being foldable, therewith being small-volume when needed (Arsenault and Gosselin, 2006). Small amounts of energy needed for folding and deployment of tensegrity structures renders them a suitable candidate to be deployable (Tibert, 2002, Fest et al., 2004, Domer and Smith, 2005, Adam and Smith, 2008).

Deployment mechanisms of tensegrity structures differ from that of classical scissor-like and pantograph structures by the notion of self-stress. The self-stress notion is such that the structure can acquire its rigidity by stabilization of infinitesimal mechanisms that exist in equilibrium geometry. The special kind of infinitesimal mechanisms, where associated strains are equal to zero, are called “finite mechanisms”. This notion distinguishes tensegrity mechanisms and structures from classical scissor-like or pantograph mechanisms structures (Vassart et al., 2000). Three modes of deployment in terms of length modifications have been defined by Vassart et al. (2000). The first one is strut mode, where only strut lengths are modified unlike cable mode, where only cable lengths are modified. When both element lengths are modified, mixed mode is point at issue.

There are few studies related to deployable tensegrity structures in the literature, and none of the structures are civil engineering structures. Tibert and Pellegrino elaborated deployable tensegrity structures for space applications and reviewed form-finding methods for tensegrity structures (2003). One of the outcomes was that tensegrity masts were relatively stiff axially and flexible in bending. It has been found out that there was lack of stiffness during deployment (Vassart et al., 2000, Tibert, 2002, Tibert and Pellegrino, 2003). Le saux et al. (1999) conducted research into the problem of touching of bars to each other during deployment. Sultan and Skelton’s (2003) approach to deployment of tensegrity structures was connecting the equilibrium points between the initial state and the final state. Smaili and Motro (2007) investigated deployment behavior of deployable curved tensegrity systems by finite mechanism activation. Motro et al. (2006) proposed tensegrity rings that could be brought together in a “hollow rope”. This paper proposed a general method for creating tensegrity cells founded on n-prism geometry and these structures will be studied in this thesis.

2.6 Active Tensegrity Structures

Tensegrity structures are spatial, reticulate and lightweight. They are suitable to be equipped with active control systems that control the structural shape (Adam and Smith, 2006). In the literature, there are few studies validating numerical results through experimental testing on shape and stress control of tensegrity structures. The research conducted on active control of tensegrity structures is composed of merely numerical simulations on simple structures, except for the previous studies at IMAC, which are detailed in section 3 (Djouadi et al., 1998, Sultan, 1999, Skelton et al., 2000, Kanchanasaratool and Williamson, 2002, Van De Wijdeven and De Jager, 2005, Domer, 2003, Adam, 2007). Djouadi et al. (1998) developed an active control method for structures that exhibit nonlinear structural behavior and applied it on tensegrity structures. The structure used in Djouadi's study was an antenna mast. Sultan (1999) developed mathematical models for dynamics of tensegrity structures using Lagrangian approach. These equations are then used for a simple, efficient, tendon control reconfiguration procedure. Also, linear parametric dynamical models were developed for certain classes of tensegrity structures in the same study. Skelton et al. (2000) gave theoretical backgrounds of tensegrity mechanics. Kanchanasaratool and Williamson (2002) developed a non-linear model for a particular class of tensegrity structures based on the method of constrained particle dynamics subject to the principle of virtual work. Wijdeven and De Jager (2005) designed an optimization method to design a reference trajectory for shape changes of an arbitrary tensegrity structure and implemented the procedure on a simple 2D tensegrity structure. Aside from EPFL (see section 3), there have been no studies that involve research into active control of tensegrity structures including experimental validation of results on large-scale models.

2.7 Case-Based Reasoning

Human-beings resolve new problems by searching similar tasks in their memory in order to adapt the methods that succeeded at similar situations in the past (Adam and Smith, 2006, Kolodner, 1993, Leake, 1996a). The same principle is applied by CBR systems from a biomimetic perspective. Given that CBR is intuitively obvious to engineers, it is an attractive technique in computer-aided engineering (CAE) (Raphael and Smith, 2003b). Solutions of past tasks are useful starting points to solve similar current tasks. Thus, case bases should include cases that are analogous to anticipated new tasks (Leake and Wilson, 1999). Some of the advantages of CBR are as follows (Raphael and Smith, 2003b):

- A good case can be an easy shortcut in the search for good solutions when many possible solutions exist.

- The closed-world statement related with abductive tasks is explicitly and obviously related to the number of cases accessible for conditions where important information cannot be modelled explicitly, for instance in aesthetics and politics.

- Inherent advantages of the case (implicit information such as good aesthetics) are transmitted to the new task when modification of the case for the new solution is small.

-Cases are generally the best way to represent knowledge, especially under circumstances where there are no known and reliable models.

-The capacity of the system can be improved by just putting in a case.

A development process is essential in order to acquire a suitable set of cases and to customize the system as case based solutions are unique for each application (Bergman et al., 2003). In CBR, a problem is solved tracking the following stages (Raphael and Smith, 2003b):

- representation
- retrieval
- adaptation
- storage
- maintenance

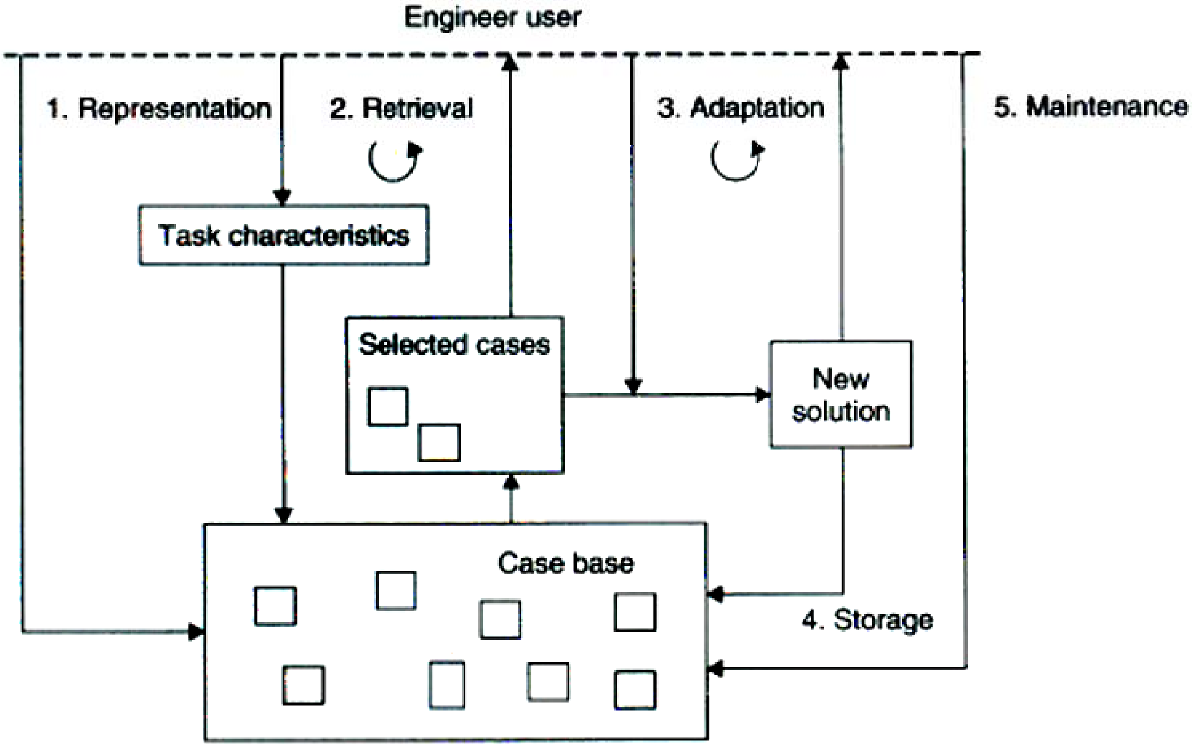

Figure 2. Stages of CBR (Raphael and Smith, 2003b)

CBR may have difficulty with problems of which solution requires the combination of many cases (Mueller, 2006, Kolodner, 1993). There has been a considerable controversy on competence of CBR systems to perform evaluation and repair. Leake (1996b) argued that evaluation and repair steps are difficult challenges for CBR systems. On the other hand Sycara (1988)and Kolodner (1993) stated that CBR can be used for evaluation and repair. Smyth and Keane (1995) demonstrated that despite conventional deletion policies were effective in controlling the swamping problem from a performance standpoint, they may induce degradation of competence. A solution that uses a model of case competence to guide the learning and deletion of cases is proposed.

The utility problem arises when the cost of search for relevant knowledge outweighs the benefit of applying this knowledge. In CBR systems, the impact of utility problem is greatly dependant on the size and growth of the case base. Larger case bases lead to more expensive retrieval stages, an expensive overhead in CBR systems (Smyth and Keane, 1995).

Despite the fact that learning is crucial toward the ultimate aim of obtaining intelligent structures, no study using the CBR approach in learning procedure of a civil engineering structure could be found in the literature outside of work at EPFL.

2.8 System Identification

The aim of system identification is determining the state of a system along with key parameters through comparisons of predictions with observed responses (Ljung, 1999). System identification tasks are classified into identification of linear systems, identification of nonlinear systems, online identification and real-time identification (Åström and Eykhoff, 1971). Statistical methods such as least squares, generalized least squares, correlated residuals, and maximum likelihood methods are efficient for linear systems (Åström and Eykhoff, 1971). Eykhoff (1974) researched into applications of system identification methods in nuclear reactors, power distribution strategies and aerospace engineering. A unified approach to nonlinear system identification was introduced by Billings and Fakhouri (1982). Frank (1990) studied on fault detection and isolation in automatic processes, and presented a robust fault detection method decoupling the effects of faults from each other and from the effects of modeling errors. Richalet (1993) demonstrated the relationship between control robustness and identification uncertainty. Bloch et al. (1995) presented a method that can detect faults, their type and locations simultaneously. Gray et al. (1998) presented an algorithm for identification of nonlinear systems and apply it to identification of the outlet flow of a coupled water tank system identification of engine dynamics within the control of the speed of a helicopter rotor. Morimoto and Hashimoto (2000) approached to identification and control of plant production from an artificial intelligence point of view. They applied an intelligent control technique consisting of two decision systems, an expert system, and an optimizer based on neural networks and genetic algorithms (GA), to optimization of hydroponic tomato cultivation and storage. Kowalczuk and Kozlowski (2000) presented a continuous-time approach to identification of continuous-time systems. Ohsumi et al. (2002) proposed a novel approach to system identification of continuous-time stochastic state space models from random input-output continuous data. Akanyeti et al. (2008) used system identification techniques that produce linear and non-linear polynomial functions that model the relationship between a robot's sensor perception and motor response. Benfratello et al. (2009) studied system identification from a civil engineering standpoint and formulated a time domain dynamic identification technique based on a statistical moment approach for civil structures under base random excitations in linear state. One of the recent developments in system identification field is swarm intelligent domain. Ant colony optimization, particle swarm optimization and stochastic diffusion search are the subclasses of swarm optimization. Majhi and Panda (2009) introduced the problem and importance of adaptive nonlinear system identification and proposes two new approaches based on swarm intelligence to identify complex nonlinear dynamic plants. The proposed new approaches are fast, relatively accurate and involve less computation.

Structural identification has been of much interest to the researchers from civil and structural engineering fields, particularly in structural health monitoring context. Farrar and James (1997) proposed an ambient vibration system identification method and experimentally verified that the proposed method can be used accurately to assess the dynamic properties of bridges and other structures in a non-intrusive manner. Shenton and Zhang (2001) developed a method for system identification that is based on fitting the theoretical probability density function for the time between zero crossings to a measured distribution of the crossing interval times. This new methodology in conjunction with the peak meter, was concluded to have potential to reduce time, labor and cost of conducting ambient vibration surveys of large civil engineering structures. Catbas et al. (2008) presented reliability estimation studies for a long span truss bridge. Brownjohn and Middleton (2008) studied vibration serviceability of high-frequency floors from a system identification point of view. The conclusion was that there were no shortcuts to predicting response of high-frequency floors to footfall excitation.

Gul and Catbas (2009) used statistical pattern recognition methodologies to detect changes in different laboratory structures. Liu et al. (2009) proposed a competent approach to evaluating the efficiency of retrofitting distortion-induced fatigue cracking in steel bridges by using both analytical results from 3D finite element models and field monitored data from structural health monitoring were used to estimate the fatigue reliability of the connection details after retrofitting. Frangopol et al. (2008) presented a general approach for the development of prediction functions and a procedure for the performance assessment of structures based on monitored extreme data. Strauss et al. (2008) put forward a new approach for incorporate monitoring data in structural reliability assessment based on performance prediction functions using monitoring data. Kim and Frangopol (2009) proposed an approach for the determination of optimal monitoring planning of structural systems based on reliability importance assessment of structural components. Viguié and Kerschen (2009) studied the problem of mitigating the vibration of nonlinear mechanical systems using nonlinear dynamical absorbers. The proposed absorber was effective in a wide range of forcing amplitudes. A qualitative tuning methodology was also developed and validated using numerical simulations in this work. ASCE is currently preparing a comprehensive state-of-the-art report on structural identification of constructed systems (Smith et al., 2009). Types of data interpretation, feature selection, model identification and validation, model prediction and data mining, and benefits of data interpretation aspects are covered in data interpretation section of this report. It is concluded that many challenges, including application and adaptation of advanced computing methods and stochastic search, remain in the field.

Although system identification is widely used in civil engineering practice, especially for bridges, it has never been combined with reasoning and learning methods for a deployable civil engineering structure.

2.9 Multi-Objective Search

An optimization task that has more than one objective is treated through multi-objective optimization techniques. Resolving an optimization task require requires the generation of a set of possible solutions, defined as those able to satisfy best and with different performances objectives of the optimization task. These solutions are known as *Pareto optimum* or non-dominated solutions. Pareto (1896) laid the foundations of multi-objective optimization by introducing the Pareto optimum concept (1896, Wan, 1975). In a multi-objective minimization task, a solution *x** is said to be Pareto optimal if no feasible vector of decision variables can be found that improves values for any objective function without causing a simultaneous increase in other objectives. The solution is then selected between mutually non-dominated candidates. However, in the absence of preference information, none of the Pareto optimal solutions could be said to be better than the others.

Recent advances in multi-objective optimization resulted in reliable techniques for generating non-dominated solutions. Evolutionary techniques are currently used in various fields due to their effectiveness and robustness in searching for a set of trade-off solutions (Coello et al., 2007). However, the selection of the "best solution" to be adopted among the Pareto optimum set is a challenge. Several decision support systems have recently been proposed to help in the selection of the best compromise alternatives. Major approaches to Multi-Criteria Decision Making (MCDM) include multi-attribute utility theory and outranking methods (Coello, 2000). Incorporating preferences is also considered to help in handling conflicting objectives (Fleming et al., 2005). Adam and Smith (2007) proposed and validated experimentally a multi-objective approach to compute control commands for quasi-static control of tensegrity structures. The search method is based on building a Pareto optimal solution set. A hierarchical selection strategy is then adopted to reduce the solution space until identification of a control command. Grierson (2008) proposed a MCDM strategy employing a tradeoff-analysis technique to identify compromise designs for which the competing criteria are mutually satisfied in a Pareto optimal set.

Mäkilä (1989) was the first to use Pareto approach to solve a control task. Khargonekar et al. (1991) put forward that Pareto optimality is suitable to solve control tasks that involve trade-offs between competing objectives. Lirov (1991) proposed a method to construct heuristics that deals with search problems with multi-objective criteria that can be ranked in some hierarchy. Ringuest and Gulledge (1992) presented an algorithm that provides an approach for optimizing multiple objective problems subject to linear constraints. Jazskiewicz (2002) proposed a GA for multi-objective combinatorial optimization. Cavin et al. (2004) presented a new method for optimizing the implementation of a new single chemical process in a multi-purpose batch plant using a flexible meta-heuristic algorithm. Brar et al. (2005) used fuzzy logic for modeling the conflicting objectives of a thermal power generation scheduling problem. Yan and Zhou (2006) presented a design method using fuzzy logic and GA for the purpose of multi-objective control. Willis and Jones (2008) presented an optimization framework to solve complex simulation models with multiple objectives.

While multi-objective search strategies have been implemented in a variety of fields, no experimental studies of multi-objective structural control could be found in civil engineering literature, aside from the study at EPFL.

3. RELEVANT RESEARCH AT IMAC, EPFL

3.1 Active Tensegrity Structures

Tensegrity has been one of the research fields studied at IMAC since 1996. Shea and Smith (1998) put forward that the ultimate goal of intelligent structures is to maintain and improve structural performance by recognizing changes in behaviors and loads, adapting the structure to meet performance goals, and using past events to advance future performance. Shea et al. (2002) imparted a computational procedure founded on intelligent control methodology that combines reasoning with explicit knowledge, search, learning and planning to demonstrate the concept of intelligent control applied on civil engineering structures. First, a full-scale tensegrity structure was built (Fest, 2003). The structure comprises 5 modules, each module consisting of 24 cables and 6 bars. It covers a total surface area of 15 m^2 and has a static height of 1.20 m. It can withstand a distributed dead load of 300 N^2/m^2. Cables are made of stainless steel and bars are made of reinforced polymer. Bars meet in the center of a module at the central node in order to enhance the buckling resistance of the bars. There has been a considerable controversy between the first definitions of tensegrity and the more recent ones. Tensegrity purists argue that members designed to carry compression forces must not contact in a tensegrity structure in order that structure to be defined as tensegrity. On the other hand, modern experts in the field use bar-bar connections in tensegrity designs (Djouadi et al., 1998).

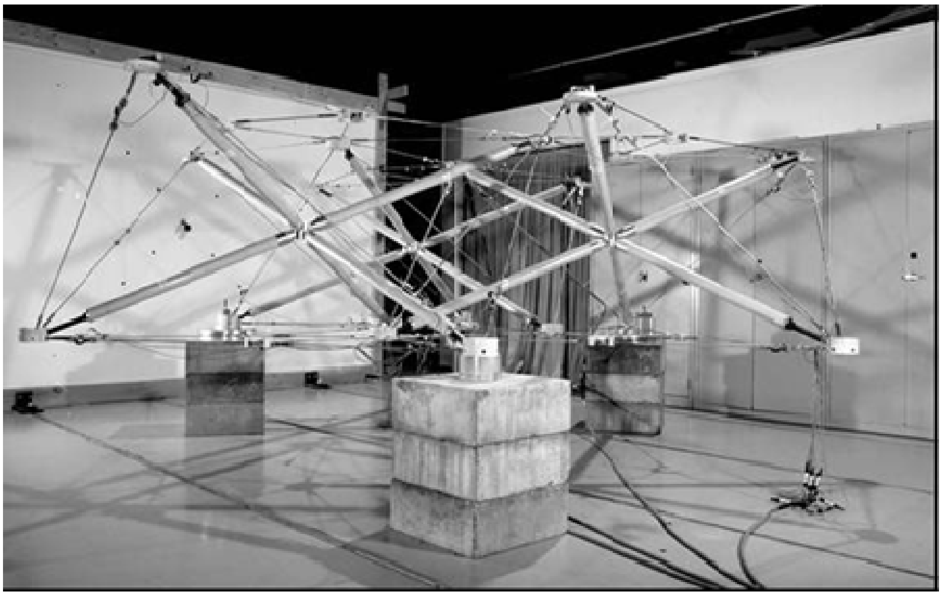

Figure 3. Elevation View of the First Tensegrity Structure at IMAC

The first tensegrity structure at IMAC is an active structure. Inductive displacement sensors placed o the structure let the researchers have experimental data. In order to control the self-stress state, ten active struts were used.

First, Fest presented a comprehensive description of the laboratory structure, as well as the control system. Then, an algorithm to determine control commands that enable the structure to satisfy the serviceability objective was established. The serviceability objective was to maintain a constant slope of the top surface of the structure when the structure was subjected to an additional load. The objective was to be achieved by contracting or elongating the active struts. The process of finding the control commands was exponentially complex and required generate-test procedures. A single-objective stochastic search algorithm (Raphael and Smith, 2003a) was chosen to perform the process (Domer, 2003, Fest et al., 2004)

3.2 Learning

Once the active tensegrity structure had been obtained, Domer and Smith (2005) studied on a learning control system. Stochastic search and CBR was used. Successful control commands were stored in a case-base and used afterward in similar situations in order to use previous experience for new situations. A database system, Tensegrity Structure Analysis and Control Software (TSACS) was established for the purpose of generating and administrating data needed for analysis and control of the structure (Domer, 2003). The system architecture of TSACS is demonstrated in Figure 3.

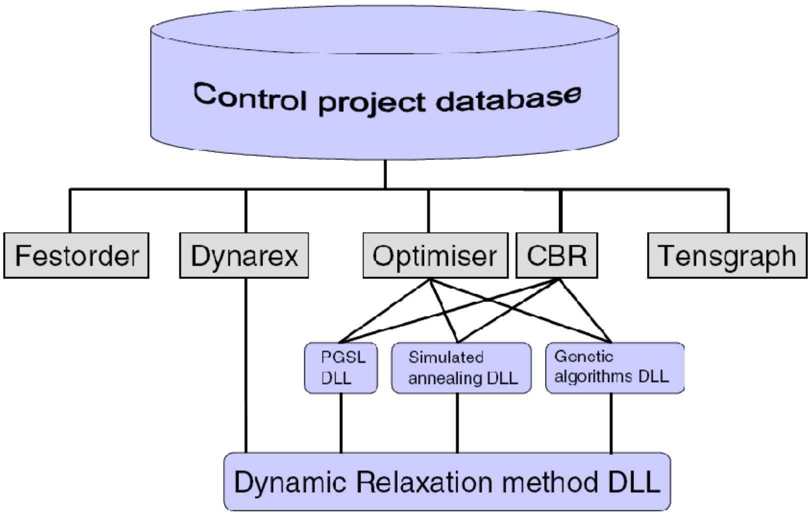

Figure 4. System Architecture of TSACS (DLL: dynamic link library) (Domer, 2003)

The core modules of the application and their functions are as follows:

Festorder: Generating geometry and topology data
Tensgraph: Visualizing the shape of the structure
Dynarex: Form-finding and structural calculation of structures stored
Optimiser: Searching for good control commands by using stochastic search
CBR: Improving the behavior of the system over time

While Fest used Simulated Annealing (SA) (Fest, 2003), results of Domer’s studies showed that GA and Probabilistic Global Search Lausanne (PGSL) outperformed SA. PGSL with cases was even 20 times faster than without cases. No maintenance problem occurred for the studied structure. K-means clustering was used to avoid bottlenecks. Cases are clustered and only the similarities of cases in the cluster close to the current case are calculated. Number of clusters was determined such that retrieval time decreased significantly without affecting system competence.

The computational framework developed by Domer comprises the following modules:

- A central database to assure efficacy and accuracy of data used
- General tools for the analysis of tensegrity structures: generating structures employing IMAC's module, displaying a 3-D model of the generated system and performing a structural analysis.
- A software module to search for good control commands that are governed by a predefined objective function and constraints, search techniques implemented are SA, PGSL and GA.
- A module which models the CBR process to re-use good past control commands and adapt them to the current situation. Performance is maintained by clustering stored cases.

Although Domer achieved decreased computation time, he did not study control command quality enhancement. Besides, it was assumed that both load positions and magnitudes were known in Domer's studies.

Subsequently, Adam described intelligent control methodologies such as self diagnosis, multi-objective shape control, self-repair and reinforcement learning and validated them experimentally. The learning procedure used by Adam is given in Figure 4. At this procedure, when a loading event occurs, corresponding response of the structure is compared to the past cases. If there is a similar case in the case base, it is retrieved and adapted. Then, control commands are applied and the active members are actuated. If there is no past case that is similar to the current case, self-diagnosis procedure is applied as multi-objective control command. Then, the active members are actuated by using these control commands. The adapted cases are used taking out the current case.

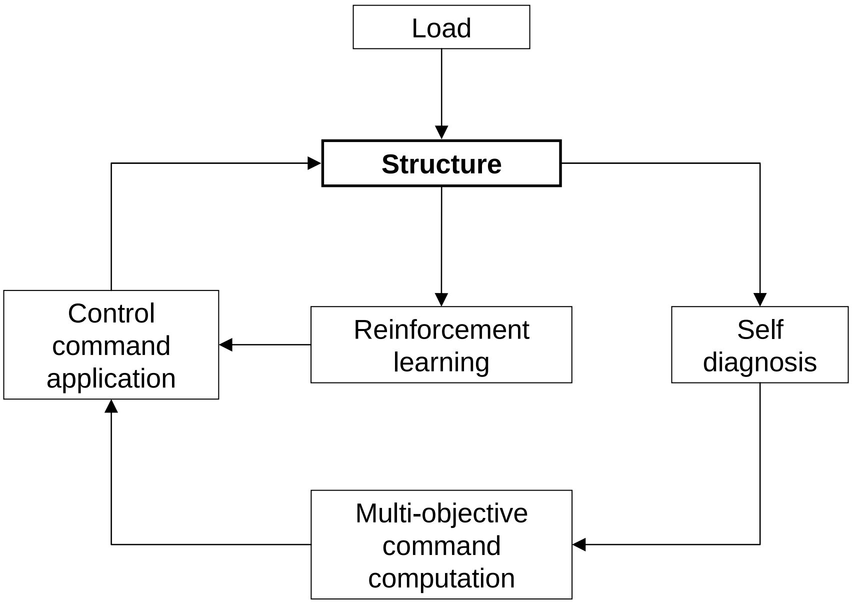

Figure 5. Learning process used by Adam (2007)

Adam (2007) stated that the proposed algorithm of reinforcement learning can be applied to more complex structures in view of the fact that cases were classified and iteratively replaced in the case base. Case-base management methodologies, such as clustering were not needed. Moreover, case base size was expected to reach a saturation point where cases were retrieved for each control event and no more cases were added in the case base. The control loop used by Adam is shown in Figure 6.

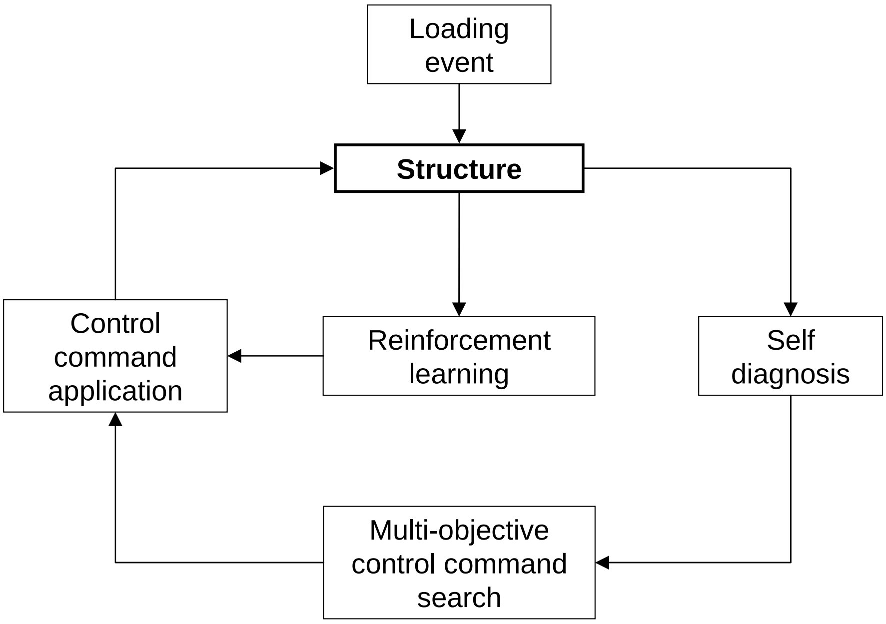

Figure 6. Intelligent control methodologies used by Adam (2007)

The intelligent control methodology used by Adam is briefly demonstrated Figure 6. Once a loading event occurs in the structure, self-diagnosis and multi-objective control command search or directly reinforcement learning procedure decides the suitable control command. Then, the structure undergoes alterations by having length changes in the active members.

3.3 Multi-Objective Control

Adam used multi-objective control to select control commands for shape control of the active tensegrity structure described section 3.1. The control objectives were:

Slope: maintaining top surface slope of the structure,
Stress: minimizing stress ratio of the most stressed element,
Stroke: maintaining active strut jacks as close as possible to their midpoint,
Stiffness: maximizing the stiffness of the structure.

Multi-objective search was used in conjunction with Pareto approach in order to elude any lack of precision related to weight coefficients (Adam, 2007). It was concluded that Pareto filtering followed by a hierarchical selection strategy was preferable to compute control commands that maintain robustness of both the structure and the active control system better than single objective control, where multiple loading events were successively applied. Multi-objective control is efficient when used together with self-diagnosis to control an active tensegrity structure. Besides, it was demonstrated that controlling multiple characteristics of an active tensegrity structure such as shape, stress and stiffness was feasible. However, Adam started with a list of all possible cables that can be broken in the structure. This scheme would be inefficient for bigger structures.

3.4 Self-Diagnosis and Self-Repair

Adam (2007) proposed a self-diagnosis methodology to identify loads that are applied to the structure and locate damage. Active control was extended to adaptation in partially defined environments by self diagnosis. Partially defined damage was a known type and unknown location. Active control system was used to support self-diagnosis. It was concluded that although load identification did not always identify exact loading situations, differences between self-diagnosis results and experimental results were smaller than difference between numerical simulation and real behavior. These results allowed for improvement of slope compensation in comparison with introducing load magnitude and location manually. On the other hand, when damage location was not exact, self-repair could lead to a stress increase. Stresses varied between candidate solutions since no information on stresses was used for self diagnosis.

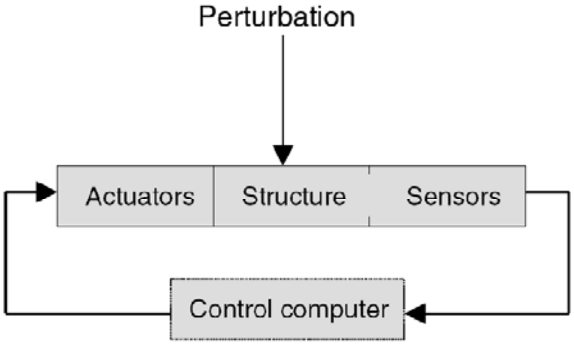

Figure 7. Self-repair procedure used by Adam (2007)

In Figure 7, the self-repair procedure used by Adam is given. The sensors on the structure gather the necessary data. Control computer processes the data and creates the movements to be applied on actuators. Actuators apply the movements to the structure in order to diminish the affect of the perturbation to which the structure is subjected.

Deficiencies in the literature establish the originality of the objectives of the proposed research. The following conclusions are drawn:

- Although computer scientists have used biomimetic approaches for programming targets, the application of biomimetic computing approaches have rarely been integrated in civil engineering structures.

- The number of studies on tensegrity structures in the literature is a small percentage of the total number of studies on structural systems. The absence of appropriate analytical tools has hindered the tensegrity concept from taking its rightful place among other structural engineering solutions.

- Tensegrity structures have been numerically studied and they have been tested mainly on small, simple and symmetric tensegrity models.

- Deployable tensegrity structures have been studied only for the purpose of space applications. No study of a deployable tensegrity civil engineering structure could be found in the literature.

- Most of the studies on active control of civil structures are carried out numerically only.

- System identification has never been combined with reasoning and learning methods for a deployable civil engineering structure.

- Aside from the study at EPFL, no experimental studies of multi-objective structural control could be found in civil engineering literature.

- Except for the study at EPFL, no experimental demonstration of self-repair of civil engineering structures could be found in the literature.

- Aside from the study at EPFL, learning methodologies have not been applied to control system for civil engineering structures.

- A number of studies have been carried out on passive control strategies for civil engineering structures. On the other hand, no civil engineering structure that uses active control strategies for shape control and self-repair purposes could be found in the literature.

The objectives of this research have been formulated to fill these research voids through building on and extending previous work at EPFL and elsewhere.

4. PRELIMINARY RESULTS

4.1. Need for Active Control In Terms of Damage Tolerance

The deployable tensegrity bridge described in Rhode-Barbarigos' research proposal is based on hollow rope concept (Motro et al., 2006). It has been analyzed for its potential to be actively controlled with purpose of maintaining damage tolerance.

First, the bridge is analyzed under ultimate limit state loading assuming that the cables in the structure are damaged individually.

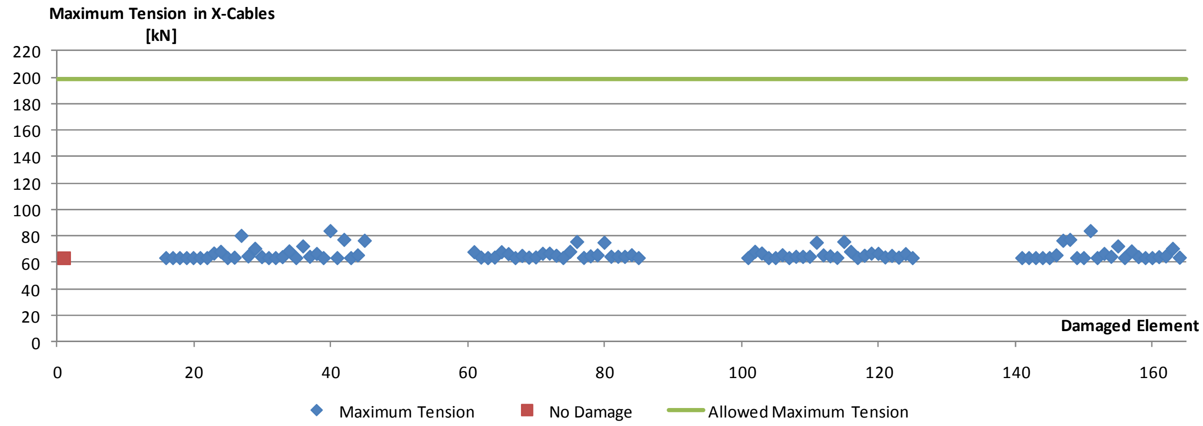

Figure 8. Maximum tension in x-cables after individual cable damage and no damage

In Figure 8, x-axis shows which element is damaged, and y-axis shows the corresponding maximum tension value in the x-cables for each damaged element. The bold line indicates the limit stipulated by SIA-codes. The results given in Figure 1 show that maximum tension in x-cables are below the limit stipulated by the SIA code if any one of the cables is damaged.

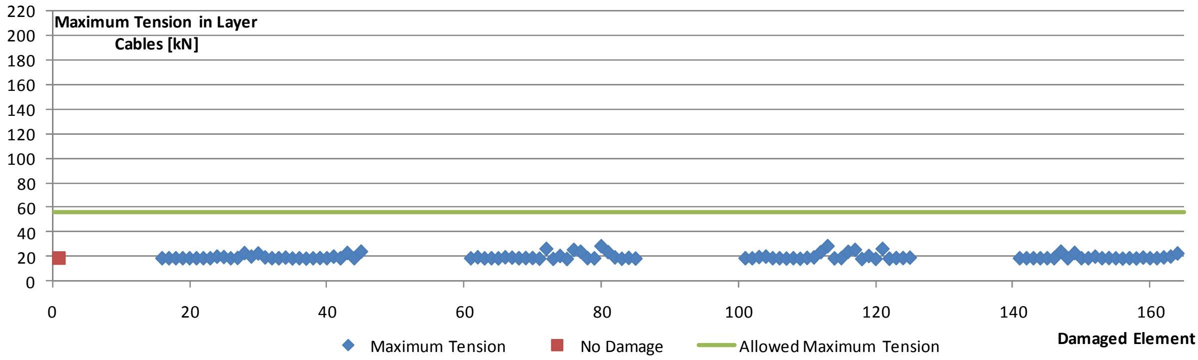

Figure 9. Maximum tension in layer cables after individual cable damage and no damage

In Figure 9, x-axis shows which element is damaged, and y-axis shows the corresponding maximum tension value in the layer cables for each damaged element. The bold line indicates the limit stipulated by SIA-codes. If any cable is damaged, maximum tension in layer cables are lower than SIA-code requirements.

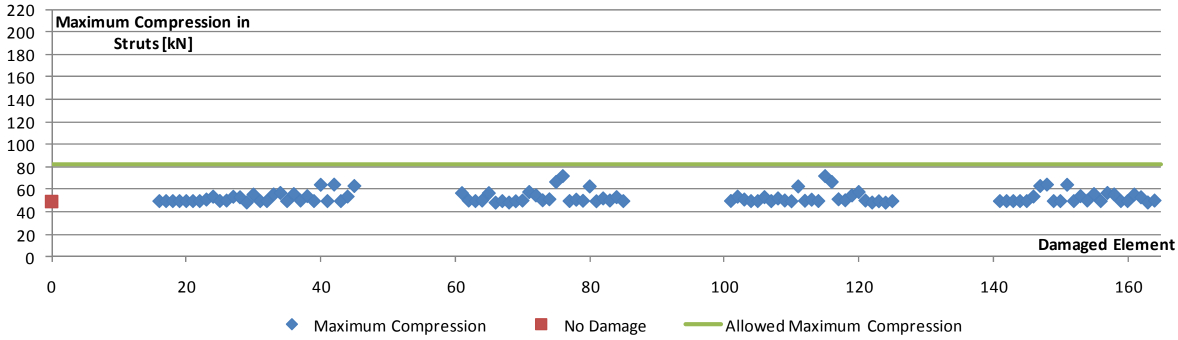

Figure 10. Maximum compression in struts after individual cable damage and no damage

In Figure 10, x-axis shows which element is damaged, and y-axis shows the corresponding maximum compression value in the x-cables for each damaged element. The bold line indicates the limit stipulated by SIA-codes. Maximum compression criterion is governed by the buckling strength of the struts. The results indicate that there would be no excessive compression in any of the struts if any of the cables is damaged.

It has been demonstrated that the safety requirements of SIA-codes are met for this structure, if any of the cables are damaged. Next, maximum displacements in the structure have been investigated in the case of cable damage.

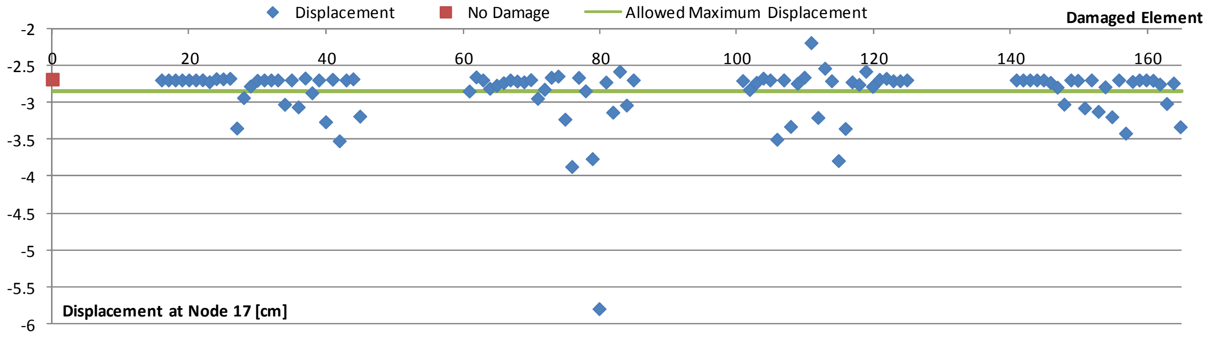

Figure 11. Displacement at midspan node 17 after individual cable damage and no damage

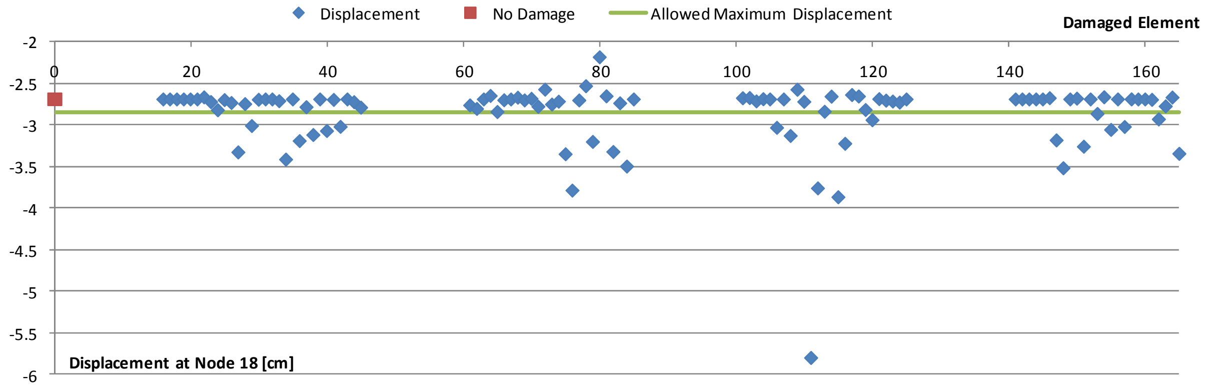

Figure 12. Displacement at midspan node 18 after individual cable damage and no damage

In Figure 11 and Figure 12, x-axes show which element is damaged, and y-axes show the corresponding displacement value at the two midspan nodes (Node 17 and Node 18) for each damaged element. The bold line indicates the displacement limit calculated by using SIA-codes. As can be seen from Figure 4 and Figure 5, displacements at midspan nodes, which are the maximum displacements in the structure, are above the limit stipulated by SIA-codes. That is to say, the structure cannot accommodate the affects of cable damage in terms of serviceability. Therefore, this structure must be actively controlled in order to make sure that the structure will be serviceable in cases of cable damage, which can be possible due to events, such as vandalism and maintenance operations.

The structure is also analyzed in terms of twisting behavior. In Figure 13, x-axis shows the cable that is damaged, and y-axis shows the twisting angle between two lateral midspan nodes. The angle between two lateral midspan nodes at the individual cable damage scenarios is found to be within a band of (-0.1°; 0.1°), except for the case of individual damages of cable 80 and cable 111 (see Figure 12), which are directly connected to the midspan nodes. Even if cable 80 or cable 111 goes slack, the twisting magnitude is below 0.5°.

Figure 13. Angle between the midspan nodes after individual cable damage and no damage

4.2 Formulation of Optimization Problem

The active control task is formulated as an optimization problem. It is mathematically formulated as follows:

$$\min f = \sum_{n=1}^{NAG}(|\Delta Li|) \qquad \text{(Eq. 1)}$$

where ΔLi is the actuation length for active group i and NAG is the number of active groups. The objective of this task is minimizing the total actuation length (Eq.1) along with the following constraints defined by SIA-Codes:

$$N_{xc} \leq N_{xc,limit} \qquad \text{(Eq. 2)}$$

$$N_{lc} \leq N_{lc,limit} \qquad \text{(Eq. 3)}$$

$$N_{s} \leq N_{s,limit} \qquad \text{(Eq. 4)}$$

$$\delta_{midspan} \leq \delta_{limit} \qquad \text{(Eq. 5)}$$

where:

N_{xc}: Maximum tension in x-cables

N_{lc}: Maximum tension in layer cables

N_{s}: Maximum compression in struts

$\delta_{midspan}$: Maximum displacement of the two midspan nodes (Node 17 and Node 18)

Due to the complexity of the problem, a stochastic search method is more suitable than a deterministic method. The nature of the problem is combinatorial and includes a large number of continuous variables. Also, the optimization constraints cannot be expressed explicitly with the optimization variables. Therefore, PGSL (Raphael and Smith, 2003a, Raphael and Smith, 2000) is a convenient search method to be used.

4.3 Case Studies

Damage scenarios are chosen considering the displacements at the midspan nodes. The greatest displacements that come into being in case of individual cable damage have been determined (see Table 1), and the resulting cable damage is repaired by actuating the active cables. When these cables are damaged, the maximum displacement magnitudes at the midspan nodes are between 5.807 cm 3.504 cm. However, SIA code requirement for displacement magnitude is a maximum value of **2.85 cm** for the studied structure.

The consecutive cables, of which numbers are highlighted with the same shading in Table 1, are symmetric along the middle pentagon layer of the structure.

Table 1. Greatest midspan displacements in case of individual cable damage in the structure

Damaged Cable No.	Displacement at Node 17 [cm]	Displacement at Node 18 [cm]
42	-3.525	-3.026
148	-3.026	-3.525
76	-3.874	-3.793
115	-3.793	-3.874
79	-3.767	-3.208
112	-3.208	-3.767
80	-5.807	-2.189
111	-2.189	-5.807
106	-3.504	-3.038
84	-3.038	-3.504

Results show that damage of the cables that are symmetric along the middle pentagon layer of the structure result in the same displacement behavior at two different lateral midspan nodes. The cables that makes the midspan nodes undergo the greatest displacements have been chosen for the case studies with the assumption that it would be possible to bring back the displacements that are caused by the damage of the remaining cables with an active control system that is capable of repairing the structure even in the cases at which the cables that makes the midspan nodes undergo the greatest displacements are damaged.

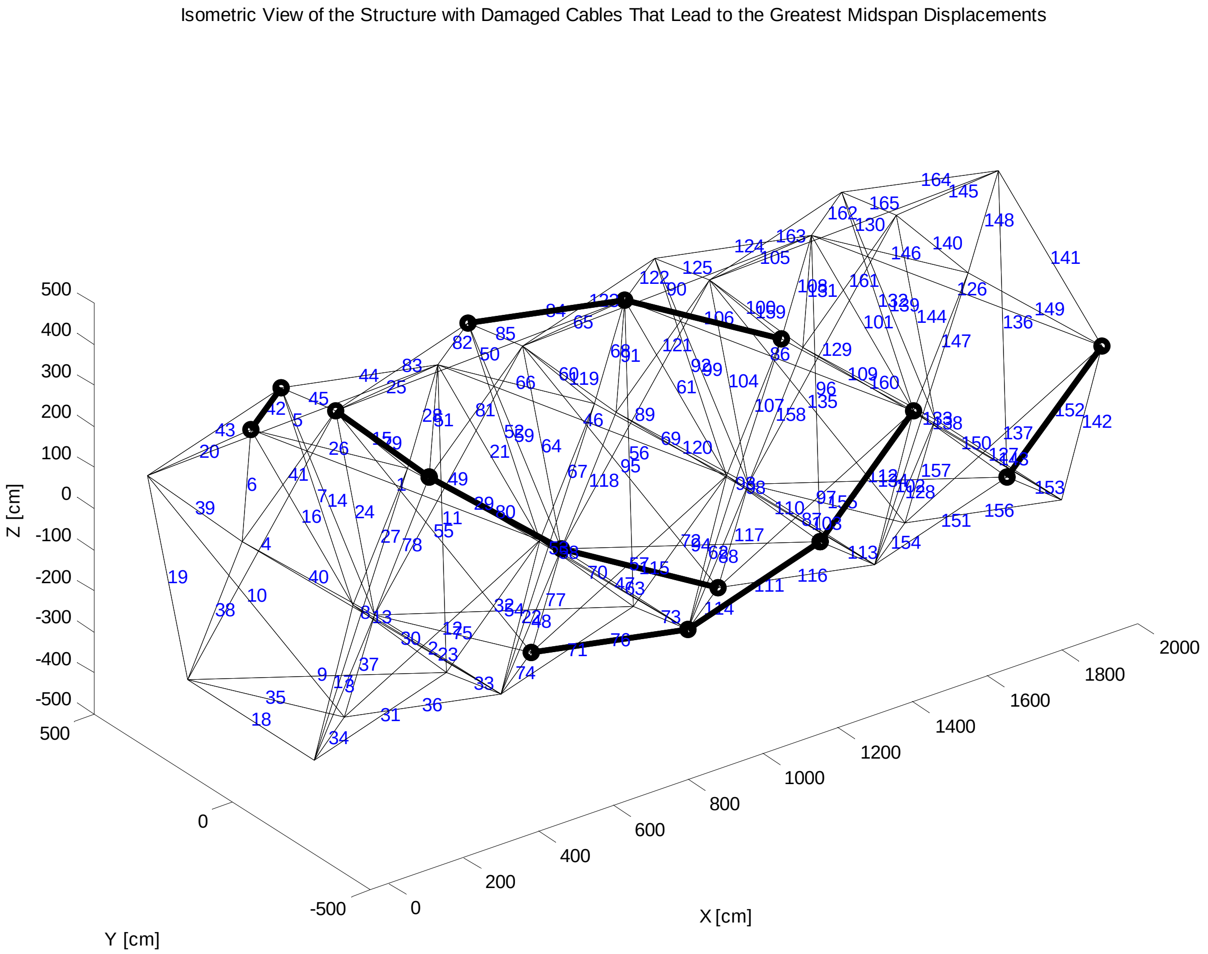

Figure 14. Most critical cables

The cable members of the structure are categorized into 4 groups as follows:

Group 1: Cables that are **not coplanar** with diagonal struts.

Group 2: X-cables that are **not coplanar** with diagonal struts and layer cables of the **first three pentagons**.

Group 3: Cables that are **coplanar** with diagonal struts.

Group 4: X-cables that are **coplanar** with diagonal struts and layer cables of the **last three pentagons**.

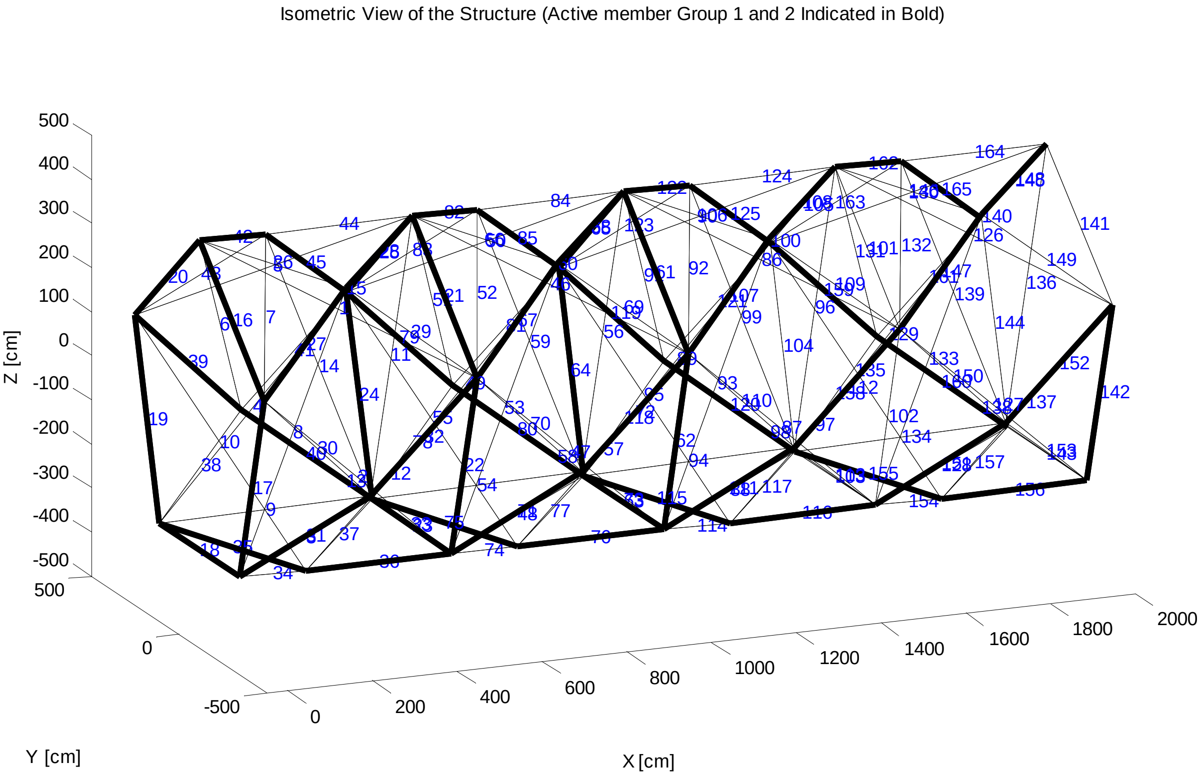

Figure 15. Active Cable Group 1 and Group 2

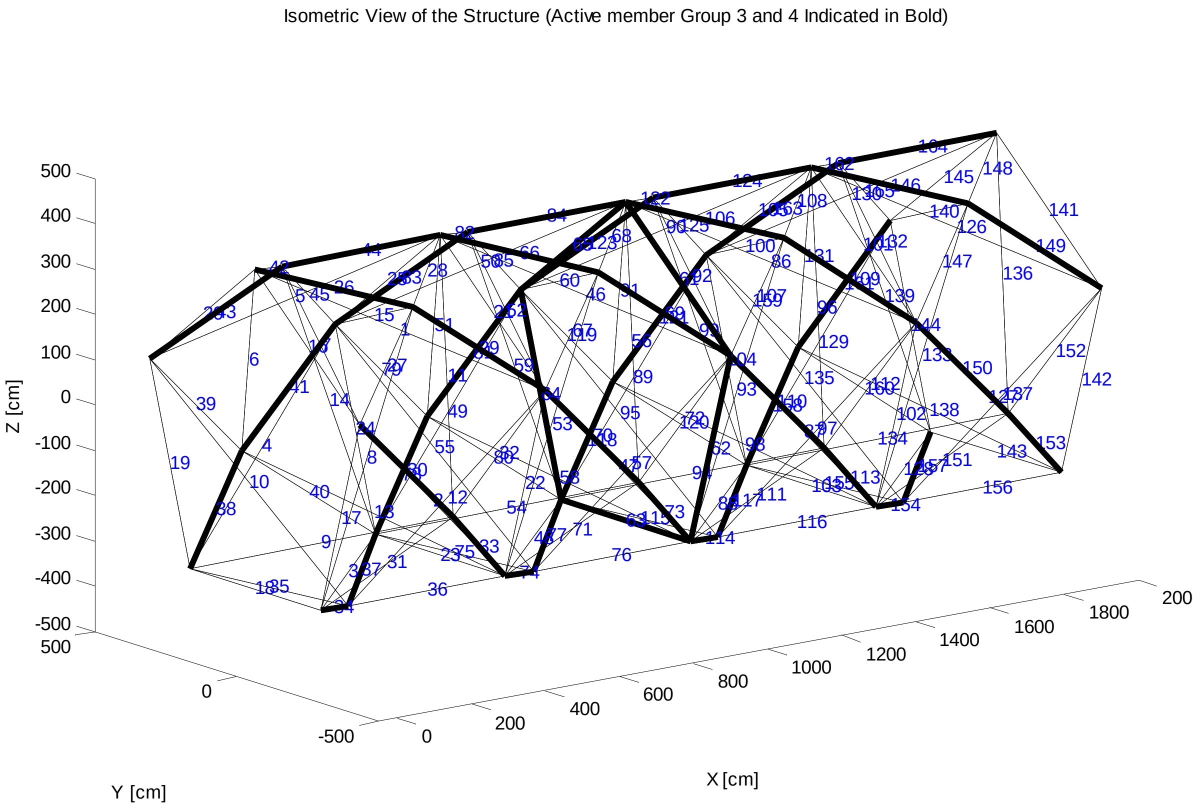

Figure 16. Active Cable Group 3 and Group 4

For each cable that leads to greatest midspan displacements, 4 cases have been studied (see Table 1).

The total actuation lengths needed to repair the structure in terms of cable damage are given in Figure 17 and Figure 18. When only active cable group 1 or 2 is actuated, the total actuation lengths are smaller than the situation at which only active cable group 3 or 4 is actuated. This result shows that, in this case, the active members needed for the purpose of **damage tolerance** are in good accordance with the active members needed for the purpose of **deployment** (Group 1 and Group 2).

In Figure 17 and Figure 18 x-axes show cables that are damaged at each case. Y-axes show the total actuation length of all the cables that are actuated at each case. (e.g. in the first case, cables 39, 40, 75 and 76 are damaged at once. The structure is repaired by using the active cable group 1. The sum of the magnitudes of actuation lengths in this case is slightly below 20 mm. In the second case, cables 39, 40, 75 and 76 are damaged together. The structure is now repaired by actuating the active cable group 2. The sum of the magnitudes of actuation lengths in this case is also slightly below 20 mm.)

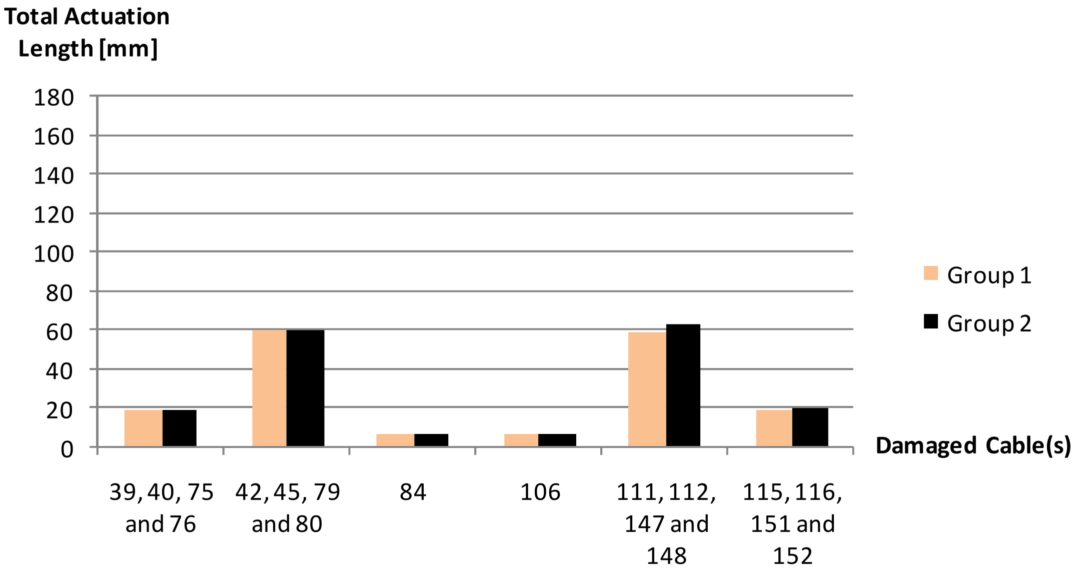

Figure 17. Actuation lengths needed to repair the structure after cable damage (active cable Group 1 and Group 2)

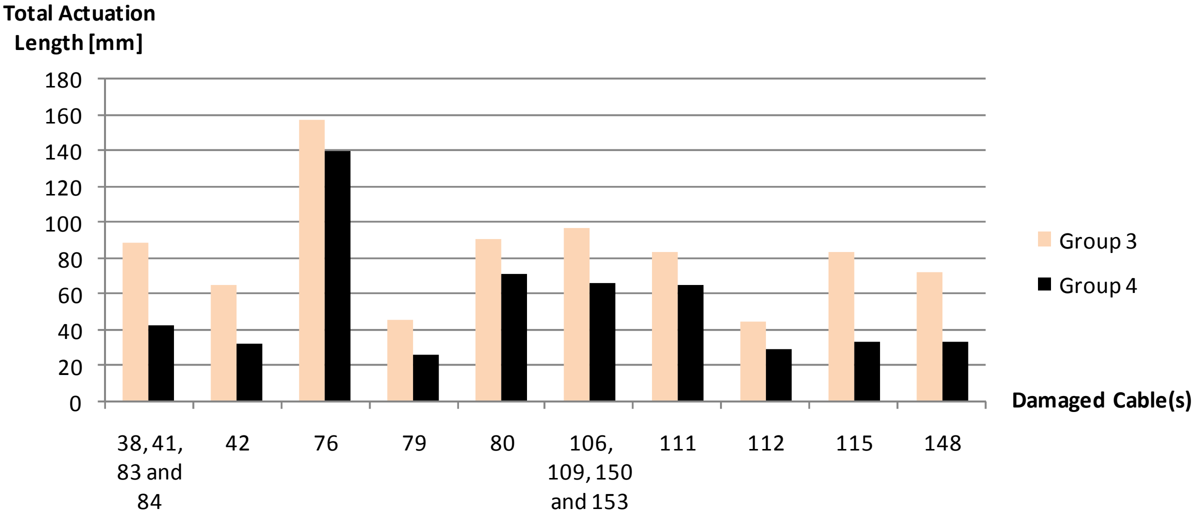

Figure 18. Actuation lengths needed to repair the structure after cable damage (active cable Group 3 and Group 4)

In this preliminary study, 32 damage cases are simulated by using dynamic relaxation method in MATLAB. Self-repair possibilities of the active deployable tensegrity bridge by using active cables are investigated. Results show that the structure is capable of applying self-repair actions.

4.4 Conclusions of the Preliminary Study

4.4.1 Feasibility of Active Control

The tensegrity bridge is shown to be meeting the safety requirements of SIA-codes even any of its cables is damaged. On the other hand, in case of damage in some of the cables, the structure fails to satisfy serviceability conditions set by SIA-codes. Therefore this structure is a good candidate to be actively controlled for the purpose of damage tolerance.

4.4.2 Damage Tolerance vs. Deployment

The active cable groups that are devoted to deployment (Group 1 and Group 2) while designing the structure by Rhode-Barbarigos perform better than the other two groups (Group 3 and Group 4), in terms of their capability of maintaining serviceability in case of cable damages. That is, Group 1 and Group 2 are better candidates to be active than Group 3 and Group 4.

4.4.3 X-cables vs. Layer Cables

It can be deduced from the data shown in Figure 17 that if Group 1 or Group 2 is activated, there is minor difference between the total actuation lengths. On the other hand, this is not valid when only Group 3 or Group 4 is actuated (see Figure 18). Taking into consideration the technical difficulties in actuating the layer cables and better performance of Group 1 and Group 2 than that of Group 3 and Group 4, **Group 1 is the best candidate** set of elements to be active.

4.4.4 Grouping of Cables

Grouping active cables has its strengths and weaknesses. If the active cables are grouped, the damage in one cable leads to greater displacements since all cables in the same group go slack. On the other hand, the disadvantages of embedded actuation such as added mass and cost, increased control complexity and energy consumption mean that grouping of active cables is preferable.

4.4.5 Influence of Symmetry

For the case studies, no significant trend is observed between the repair opportunities in damage case scenarios at which cables that are symmetrical along the middle pentagon layer of the structure are damaged.

4.4.6 Optimization of Actuator Locations

Some clusters have a very small influence during the repair process. Therefore, the number of active members in the structure can be reduced. In order to determine the optimum locations of the active members, further studies without using the members that have smaller *absolute mean values of average actuation lengths* and greater *non-actuated cases/considered cases* ratios are to be performed. A sensitivity analysis can serve as a preliminary study for the optimization of actuator positions. The efficiencies of each group of cables in terms of their influences on the midspan displacements are to be determined.

5. RESEARCH PLAN

5.1 Summary of Objectives

This research will be carried out in close cooperation with the Ph.D. research by Rhode-Barbarigos, entitled "An Active Deployable Structure". Rhode-Barbarigos will study the deployment of a tensegrity bridge, design an active control system to ensure deployment of the bridge, study the structure in service (after deployment), and construct a near full-scale tensegrity bridge model. In conjunction with this research, the following objectives and tasks are to be achieved:

The objectives of this research are stated below:

1. **Design** an active control system for the purpose of ensuring the damage tolerance of a deployable tensegrity pedestrian bridge
2. Extend existing strategies for **self-diagnosis** of the deployable tensegrity bridge to avoid ambiguous results
3. Extend existing strategies in order to achieve a robust **self-repair** scheme

4. Design and develop algorithms that allow the active control system to **learn**, using CBR by extending previous methods

5. **Verify** the control system components with experiments on a near full-scale (1/3) model

5.2 Task Description

The aim of this research plan is to extend previous research on active control of structures conducted at IMAC (see Section 3), including self-diagnosis, self-repair and learning aspects. Foreseen tasks are categorized as follows:

Phase A: Literature review
Phase B: Optimization and design of an active control system for the purpose of ensuring damage tolerance.
Phase C: Establishment of procedures for system identification and self-diagnosis
Phase D: Establishment of procedures for self-repair
Phase E: Development of algorithms in order to provide a learning active control system
Phase F: Experimental verification
Phase G: Documentation

Phases and corresponding tasks are elaborated below:

Phase A: Literature review

A1 *Literature survey*

An extensive relevant literature review will be performed throughout the duration of this research. This task will not only provide the necessary theoretical background but will also ensure that this research benefits from other advances in biomimetics, active control of structures, self-diagnosis, self-repair, adaptive structures, intelligent structures, tensegrity structures and deployable structures.

Phase B: Optimization and design of active control system for damage tolerance

In context of another Ph.D. thesis, Rhode–Barbarigos will provide an active control system in relation with deployment strategies and a control algorithm that provides the deployment of the structure. The context of this thesis includes the optimization of an active control system for the purpose of damage tolerance only. The active members will be defined such that structural serviceability is maintained in situations of partially defined damage.

B1 *Determination of most critical cables*

Pilot study shows that some cable members of the deployable tensegrity bridge are more critical than the others. The most critical cables in terms of serviceability and damage tolerance will be determined. Damage at critical cables in the structure will be simulated and structural response to each damage will be evaluated.

B2 *Damage case studies*

Some case studies have already been carried out in order to determine the mechanical behavior of the bridge with damaged elements. Further case studies, at which the most critical cables are damaged, will be carried out. The damage of different combinations of most critical cables will be simulated in order to interpret structural response. The actuation lengths needed for each cable to maintain the serviceability criteria, which are defined by SIA-codes, at damaged states will be determined. Results of the case studies will lead to the design of an optimum active control system ensuring damage tolerance.

B3 *Optimization of the active control system*

The most critical active members in terms of serviceability at damaged states will be decided. The active members that are critical in terms of damage tolerance may be also critical for the deployment process. Therefore, this task will be carried out in close cooperation with Rhode-Barbarigos. Locations and activation characteristics of the active elements needed for optimum control will be determined.

Phase C: Establishment of procedures for system identification and self-diagnosis

C1 *Study of the existing self diagnosis strategies for the context of the deployable tensegrity bridge*

Self-diagnosis involves identifying load positions and magnitudes as well as damage locations. Damage will be simulated by removing single or multiple cables. The results of the pilot study will be compared with damage identification and learning procedure proposed previously. The self-diagnosis techniques used by Adam (2007) will be studied for application to the deployable tensegrity bridge.

C2 *Improvement of the existing self-diagnosis method*

The current self diagnosis method will be improved for better search performance. Adam started with a list of all possible cables that can be broken in the structure (2007). This scheme will be replaced with a more efficient one, which can be applicable to more complex structures. Optimization of sensor positions will be carried out. A sensitivity analysis will be made in order to obtain the sensor positions that lead to better diagnosis.

C3 *Integration of system identification into self-diagnosis procedure*

Self-diagnosis will be supported with system identification techniques so that the system will not need additional measurement locations. The methodology will be founded on evaluating measured and calculated responses with respect to behavior indicators such those developed by Adam. In order to achieve the demanding requirements of self-diagnosis task, stochastic search and CBR will be utilized.

Phase D: Establishment of procedures for self-repair

D1 *Grouping of active members*

The pilot study showed that active members can be grouped without affecting efficiency of self-repair. Different groups of cables, which have different behaviors in the way they affect the structure, are expected to provide a more efficient way of self-repair. Different rates of influence of different actuation lengths in different groups will be compared and the best combination will be applied on the structure.

D2 *Evaluation of self-repair strategies for the context of the deployable tensegrity bridge*

Self-repair procedures such as those presented in (Adam, 2007) will be evaluated for application to the deployable tensegrity bridge. Control objectives and application of multi-objective approach will be assessed for the deployable tensegrity bridge.

D3 *Enhancement and adaptation of self-repair methods*

Self-repair methodologies will be extended in order to increase performance. Multi-objective search will be used to improve control command selection. In situations of damage, self-repairing control commands will be computed using damage location solutions, which will be computed by self-diagnosis techniques, as input. Instead of considering a single serviceability objective for self-repair, a multi-objective control strategy will be proposed. Enhancement of control command search through use of additional objectives can lead to increase robustness of both the structure and the control system.

D4 *Integration of Pareto optimum concept into self-repair process*

Pareto filtering will be utilized in order to avoid the use of arbitrary assigned weight factors. A set of Pareto optimal solutions according to multiple objectives will be built. The solution generation process will be carried out using ParetoPGSL (Raphael and Smith, 2000, Raphael and Smith, 2003a) algorithm, which generates solutions that minimize each objective on its own and then solutions that minimize the sum of all objectives.

D5 *Control command selection strategy*

In previous work at IMAC, a hierarchical selection strategy was proposed to decide on one single solution among Pareto optimal solutions. The selection strategy hierarchically reduces the set of Pareto optimal solutions until a solution singles out. Multi-criteria decision making (MCDM) techniques will be evaluated for a better selection of candidate solutions.

Phase E: Development of algorithms in order to provide a learning active control system

E1 *Evaluation of the current learning strategies and their application to the deployable tensegrity bridge*

The learning procedure proposed by Adam (2007) will be applied to the CBR process of the active control system. Adam divided the learning algorithm into memorization, retrieval, adaptation and replacement processes. The adaptation procedure adapts a past case that is better than a current case, taking out the current case.

E2 *Enhancement of the efficiency of the current learning method*

The learning procedure will be extended. In the CBR system used by Adam, the adapted cases are used taking out the current case. Adam's replacement procedure will be enhanced by applying more elaborate techniques to the CBR system. In order to model a competent CBR system and exploit this model to guard against competence depletion, the size of the case-base will be controlled in a manner that avoids accumulation of too many cases. Cases will be categorized into four classes. *Pivotal* and *auxiliary* cases will represent the extremes of the competence model. Intermediate categories, namely *spanning* and *support* cases will correspond to cases of which deletion may or may not reduce competence depending on what other cases remain in the case-base. By performing this categorization, it will be possible to obtain a picture of the case-related competence of the system. Smyth and Keane's (1995) approach to the utility problem will be adapted for use in this situation.

E3 *Assessment of the efficiency of the system to be proposed*

Since the deployable tensegrity bridge is a relatively large civil engineering structure, the efficiency of previously used learning procedures will be studied. A compromise between the swamping problem and competence degradation will be identified. In this context, decreased time for control command computation and increased control quality over retrieved cases will be regarded as the attributes of a more efficient system.

Phase F: Experimental verification

F1 *Comparison of general tendencies between computational simulations and a 1/10 scale model of the tensegrity bridge*

A 1/10 scale model of the tensegrity bridge will be constructed by using nylon tendons and timber bars. The joints will be simple steel hooks, which allow movement of the nylon wires. The damage scenarios studied in the scope of task B1 will be applied on this model, and damage will be simulated by manually taking out cables. The tendencies will be compared to the outcomes of task B1.

F2 *Tests regarding self-diagnosis method used*

Once the near full scale (1/3) deployable tensegrity bridge is built, self-diagnosis methodologies used will be tested experimentally on the structure. Selected cables will be taken out of the structure in order to simulate damage. Therewith, computational results will be compared to actual behavior of the structure.

F3 *Tests regarding self-repair method used*

Proposed self-repair methods will be tested experimentally. Selected cables will be taken out of the structure. Self-repairing actions of the structure, which is equipped with a reasoning system, will be examined.

F4. *Tests regarding learning strategies used*

Learning behavior of the active control algorithms will be examined during the experiments related to self-diagnosis and self-repair. It will be investigated whether the algorithms provide a robust and efficient control system by learning phenomenon.

Phase G: Documentation

G1 *Annual progress report*

An annual progress report that will demonstrate the advances toward the objectives of the thesis will be presented.

G2 *International peer-reviewed journal papers*

Research results will be presented at international peer-reviewed journals.

G3 *International conference papers*

Research results will be presented at international conferences.

G4 *Preparation of the Ph.D. thesis*

The ultimate goal of this research is the preparation of a Ph.D. thesis with the provisional title of “Biomimetic Characteristics of an Active Deployable Structure”.

5.3 Task Plan

See Table A1 in Annex.

5.4 Target Dates

Target dates are given below in Table 2.

Table 2. Target dates

Target	Date
Start of the Ph.D.	January 1, 2009
Ph.D. research proposal	September 24, 2009
First draft of the thesis	May 31, 2012
Oral exam	August 31, 2012
End of the Ph.D.	September 30, 2012

6. IMPORTANCE OF THIS RESEARCH

Mimicking the features of nature is a promising way to provide efficient structures. Information technology (IT) is useful for achieving biomimetic applications in structural engineering. Use of advanced informatics for reasoning and learning presents important challenges in the context of intelligent structures. These techniques combined with deployability, will lead to new opportunities for future challenges in structural engineering. Also, the application field of intelligent systems that use CBR technology embraces a number of industrial applications such as maintenance of subway systems, rapid cost estimation for plastic parts production, analyzing telecommunication cards and electronic system test data, failure analysis of semiconductors, intelligent product assistants, troubleshooting in airplane engines, and heating, ventilating and air-conditioning (HVAC) systems. Applying advanced informatics to a structural system, tensegrity, has potential to contribute innovatively to other fields.

Although research into biomimetics is not new, application to active structures, deployable structures and tensegrity structures presents unique challenges. This research will contribute to demonstrating that biomimetic approaches can result in innovative structural engineering solutions when combined with advanced computing methodologies.

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Chapters 4, 5 and 6 will be extended as results are obtained and as new ideas emerge.

8. FUNDING

Equipment that will be used during this research will be funded by the Swiss National Science Foundation.

9. COLLABORATION

This thesis will be directed by Prof. I.F.C. Smith and supervised by Dr. Nizar Bel Hadj Ali at IMAC, EPFL. The following experts will also be asked to provide additional advice:

Prof. René Motro, Montpellier University, France
Dr. Bernard Adam
Dr. Bernd Domer
Dr. Daniele-Claude Martin, Ulm University, Germany

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