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Introduction to intelligent structures and tensegrity systems

Looking back to the last decade of research in civil engineering, the following domains can be identified:

- Material sciences: development of high performance materials (high performance concrete, concrete with textile reinforcement), microstructure of the, etc.
- Structural mechanics: advances in structural dynamics, non-linear analysis, development of more sophisticated finite elements, capacity design, etc.
- Civil engineering informatics: adaptation of the object oriented paradigm, agent based software, applications of artificial intelligence, etc.

Figure 1: *Pont du Normandie, central span 859m, (1995)*

Although the results of this lead to impressive structures such as the Pont du Normandie (figure 1), these buildings are static and can not be modified without major effort. Their adaptation to changing environmental conditions or needs requires at least partial reconstructions.

In 1998, Kristie Shea and Ian Smith formulated the concept of "intelligent structures". The disciplines of structural engineering, artificial intelligence and control systems are merged to construct a structure, which is able to sense and react in uncertain environments (figure 2). Inspired by the consulting engineers Passera and Pedretti in Lugano, who proposed a "Tensegrity" structure for the swiss Expo.02, the same type of structure has been chosen to show the feasibility of this concept.

Tensegrity is short for tensional integrity and describes a structure, where tension and compression members do not touch (figure 3). Equilibrium is obtained by its self-stress state.

Appealing features of tensegrity systems are that they are self-supporting and do not need heavy foundations or anchorages. Due to their modular construction, they can easily be dismantled and transported. A use for temporary events is therefore possible. The structural principle is appealing because it combines efficient use of building materials with aesthetic principles in an original way.

The shape of the structure can be controlled by adjusting the length of the tension or compression members and thereby changing the amount of self-stress in the structure.

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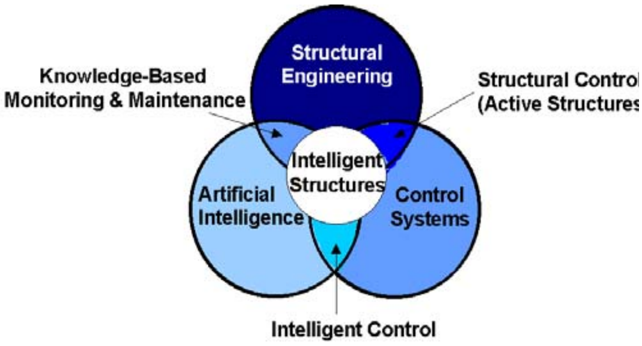

Figure 2: *Research domains related to the concept of intelligent structures*

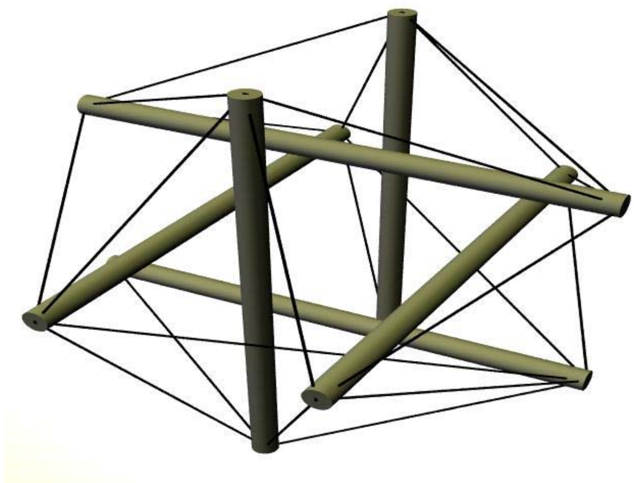

Figure 3: *Example of a tensegrity structure*

IMAC's tensegrity structure

Etienne Fest designed and constructed IMAC's full scale tensegrity structure (figure 4). It is assembled out of three modules, each module consists of 6 bars and 24 cables (figure 5). The covered surface is 3m x 3m and the height of the modules is 0.6m.

Although the community of researchers working in this or similar domains is a very small one, it is quite active. Below you find some links to researchers working on tensegrity systems.

- **R. Motro** (Université de Montpellier II): Analysis, control and design of tensegrity structures
- **S. Pellegrino** (Cambridge): Tensegrity structures, deployable tensegrity systems
- **R. Skelton** (UCSD): Control of tensegrity structures
- **A. Kwan** (Cardiff school of engineering): Tensile structures

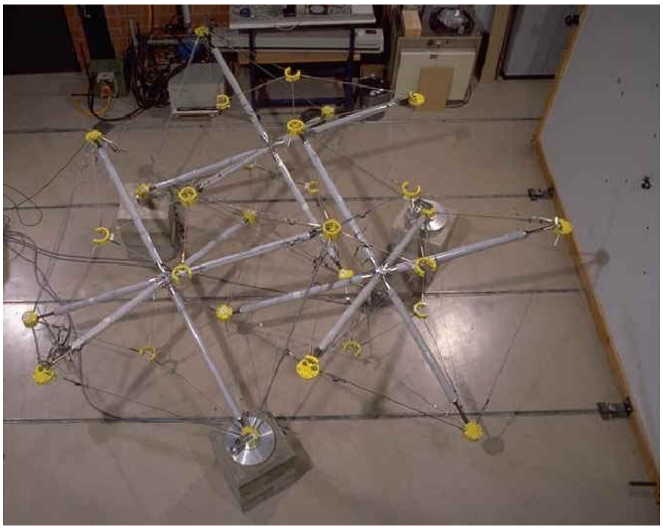

Figure 4: *Tensegrity structure at IMAC*

Tensegrity systems found also their way into practical applications:

- **Passera and Pedretti** (Consulting engineers, Lugano, CH)
- **Geiger engineers** (New York, USA)

Coming back to the notion of intelligent structures, we should start to explain briefly how control systems are applied to buildings (figure 6). Sensors are constantly measuring the displacements in significant points, a control command is calculated by a control computer and then applied to the structure by an actuator.

IMAC's tensegrity structure is currently equipped with sensors, motors are going to be attached to the bars.

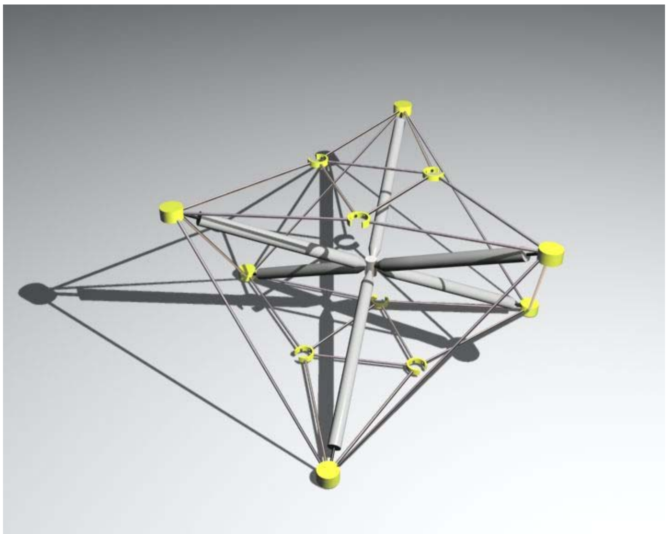

Figure 5: *Tensegrity module*

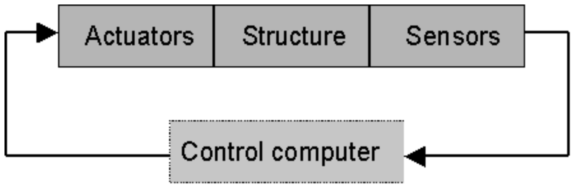

Figure 6: *Structural control*

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1st application of stochastic search to determine good control commands

Starting from the basic scheme for structural control, K. Shea used a stochastic search technique (simulated annealing) for the determination of good control commands. The objective function is formulated such that the upper nodes of the structure are kept on a constant slope. A constant "influence matrix" has been used for the evaluation of the objective function. During his diploma project, Yann Perelli showed, that the real structure behaves non-linear even for small deformations and, therefore, a constant matrix can not be used.

Click on the figure to view it in full-size!

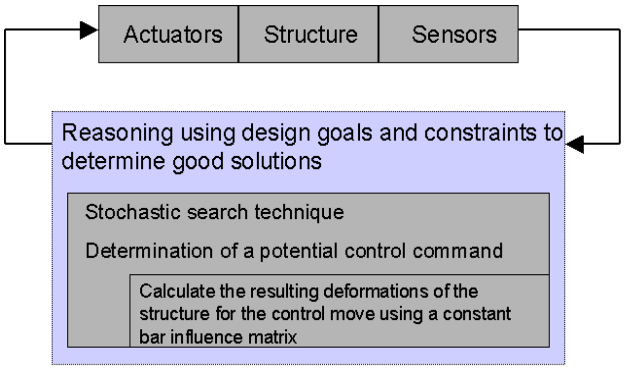

Figure 7: *Structural control with stochastic search techniques*

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Using "Dynamic Relaxation" for the evaluation of control moves

As a result of the proceeding tests, the evaluation of the objective function needs to take non-linear behavior into account. Dynamic relaxation has been chosen for this task. It uses the dynamic equation of a damped system with an externally applied load to solve a static problem. No fixed stiffness matrix is used, geometrical and material non-linear behavior can, therefore, be considered easily. The currently used implementation has been programmed by Stéphane Rossier. It uses kinetic damping to determine the crucial parameters of the algorithm as the time interval and the nodal masses.

Tests which applied control movements calculated by simulated annealing to the real structure showed the feasibility of stochastic search to determine good control solutions. Encouraged by that, another optimization method (PGSL: probabilistic global search Lausanne) has been tested. This search technique has been developed by Benny Raphael, a post-doctoral researcher at IMAC.

Currently, we are working on the integration of genetic algorithms as another possible search technique.

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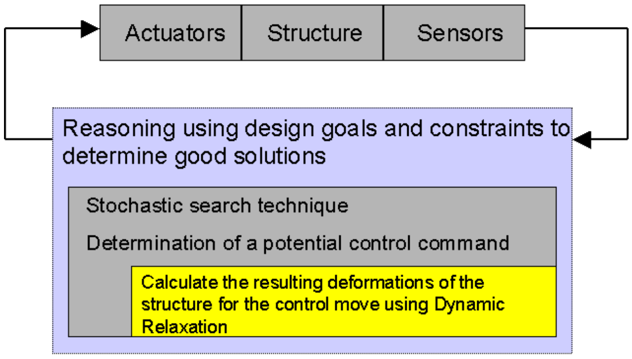

Figure 8: *Evaluation of the objective function with dynamic relaxation*

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Use of artificial neural networks for the enhancement of structural control

Although dynamic relaxation is able to model the structural behavior, it still lacks accuracy. It can be easily understood that small errors in the evaluation of the objective function will sum up to bigger ones during the application of a series of control commands. Since the model used for dynamic relaxation has already been "fine-tuned" and offers no further parameters for adjustment, a neural net is used to close the "gap" between measured and calculated deformations. It should be pointed out one more time that the neural network is not used to replace the structural calculation but to enhance it's accuracy.

Because the structural behavior and environmental condition will change over time, the neural network is foreseen to be constantly trained and updated with measured data.

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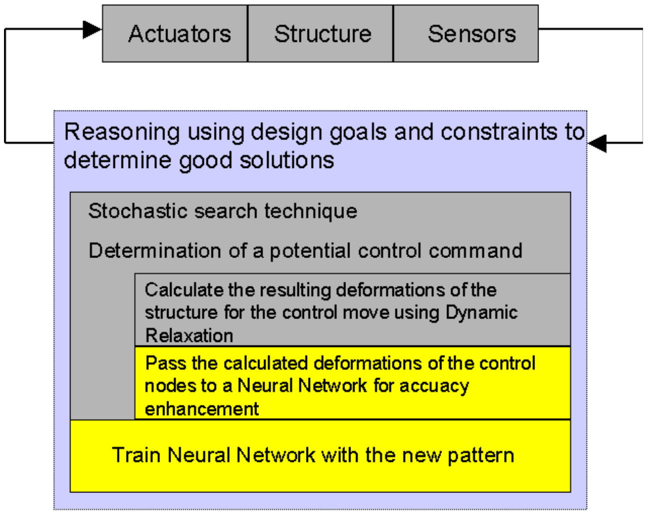

Figure 9: *Enhancement of the accuracy of dynamic relaxation with neur nets*

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Performance enhancement of active structures during service lives

An appealing computational technique to improve the performance of a control system over time is case-based reasoning (CBR).

CBR uses knowledge in the form of

previous case experience. One case stores a problem/solution set that occurred in a particular situation. When faced with a new problem, the system searches for similar cases and tries to adapt the most similar one to the current situation. The new solution may then be stored in the case-base, thereby improving performance of the system over time.

When you examine figure 10, you will find that all the previously described techniques (dynamic relaxation, stochastic search and neural nets) are integral part of the case-based reasoning system.

This CBR system has still to be implemented, with the case maintenance as one of the most important parts of the work.

Links to researchers in the domain of case-based reasoning:

- **B. Smyth** (University College Dublin): case-based reasoning, case maintenance
- **D. B. Leake** (Indiana University): case-based reasoning, cognitive science
- **D. W. Aha** (Naval research laboratory, Washington): machine-learning, case-based reasoning
- **The CBR homepage** (University of Kaiserslautern)

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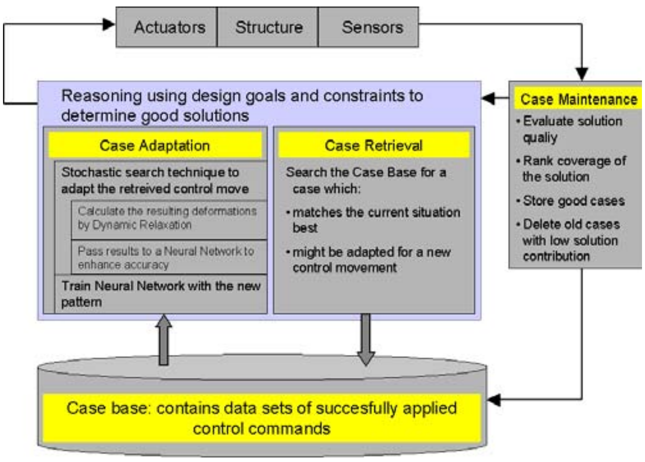

Figure 10: *Evaluation of the objective function with dynamic relaxation*

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TSACS: Tensegrity Structure Analysis and Control Software

All the presented concepts (except the case-base part) have been integrated into a **T**ensegrity **S**tructure **A**nalysis and **C**ontrol **S**oftware, short TSACS.

TSACS has proven it's feasibility for the control of the structure and is under constant development. A screen shot is presented in figure 11. It provides modules for the geometry generation, the structural calculation and the control of IMAC's tensegrity structure.

TSACS is the platform used to test the feasibility of optimisiation techniques and artificial intelligence for structural control.

Thank you very much for the time you spent in reading and understanding my research work. Feel free to pass me your comments by **mail** or pass by my office and have a chat!

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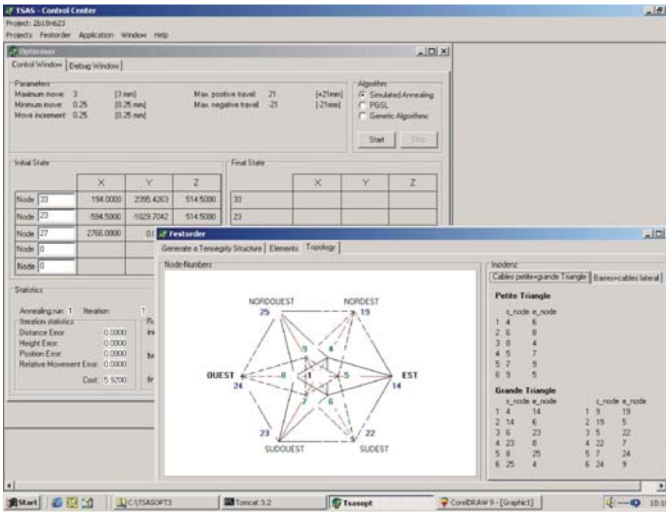

Figure 11: *Screenshot of TSCAS*

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