An Adaptive Structure Controlled By Swarm Behaviour

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1. Introduction

This paper describes the research project that has been done on an adaptive structure based on swarm behaviour. During the research the Smart Adaptable Module (S.A.M) was developed: a modular structural system that is flexible in all possible directions. The system is built up of elements in compression and elements in tension, where the latter also act as actuators. By changing the length of the elements in tension, the structure can change its shape and alter its internal forces. The system is not only inspired by tensegrity, but also by the biological skeleton of bones and muscles. Bones that can take compression and bending, muscles and their antagonists make the structure move and take the changing loads. Festo pneumatic muscles are tested for application in the structural system. Different adaptive strategies have been modelled in a software package called Virtools.

2. Motive

For many years architects and engineers have been developing kinetic buildings. This has been inspired by different architectural ideas over the years. An important motivation for kinetic architecture however has always been the progression of technique. It has also been an interaction between architecture and technique. Examples range from buildings that are flexible in their build-up and are easy to transform or transport, to structures that can unfold as those of Pineiro, Otto and Hoberman. Although the spectacular examples mainly make use of the pantographic principle, from observing nature we can learn how organisms cope with movement and we can learn how muscles drive motion into structures.

Trans-ports is a project of the Rotterdam based architectural office ONL (Rotterdam, The Netherlands). The project consists of a series of pavilions all over the world that are connected by a data network. The pavilions react and adapt to their direct environment, but also to other pavilions in the network. In this way it connects the global to the local. A flexible skin containing sensors and displays collects and shares information with users. One way of showing response to that process is changing shape. Figure 1 shows a representation of a pavilion of Trans-ports. An alternative representation is thought of as a transformable space structure that holds the flexible skin.

Figure 1. Representation of Trans-ports (from: K. Oosterhuis (2002), Programmable Architecture, Arca Edizioni, Milan, Italy).

3. Adaptive systems

What we can also learn from nature is how adaptive systems work. Without the ability to adapt, some say, no life would have been possible at all. Natural adaptive processes can be classified into short-term, long-term and evolutionary adaption [SOB02]. The tracking of the sun of the Helianthus Annuus during growth is an example of short-term adaption (Figure 2). Long-term adaption processes take a life-cycle. The Taraxacum Officinale adapts to the different functions during its lifecycle. From a yellow flower that attracts insects, it changes to a fluffball for the purpose of spreading its seeds. Evolutionary adaption takes several life-cycles. Hereby species adapt to changing climate and environment.

Figure 2. Short-term adaption; Helianthus Annuus (Sunflower).

Although we can simulate all of those adaptive processes, short-term adaption is still most suited for implementing in technical adaptive systems. Systems like this consist in principle of three primary elements: an element that can feel (sensor), an element that controls (processor) and an element that can do (actuator). Summarized, this is called adaptronics. Of particular interest are smart elements that combine more than one function. For example, if piëzo materials undergo a certain strain, they produce an electric current and so act as a sensor. The other way round: when a current is applied to the material, it deforms and so acts as an actuator. Natural reflexes can be mimicked if actuators react to certain impulses without the processor being involved.

Integrating adaptive systems in buildings is not new. Examples are fully automated greenhouses where the internal climate is monitored and controlled by a system of sensors, actuators and a computer that is linked to an external weather station. Airhalls increase internal pressure to become stiffer if the windload increases. In highrise buildings tuned mass dampers or active braced structural systems are being used to minimize discomfort or damage during wind or earthquake loads. The Glasgow Wing Tower turns itself in the wind to reduce internal forces and made possible a 50% lighter structure.

4. S.A.M

To meet the criteria of a pavilion in motion like in Trans-ports, S.A.M was developed. S.A.M is a structural building block in which muscles drive motion. The Smart Adaptable Module (S.A.M, Figure 3.) consists of three elements in compression, one in bending, and nine elements in tension. The elements in compression have fixed lengths and meet in the central node, that is the middle of the central member. The elements can pivot around this point. The elements in tension connect the free ends of all other elements. By changing their lengths, the shape of the module can be changed. The module can be connected to similar modules by adding extra elements in tension between the tops and the bottoms of the modules.

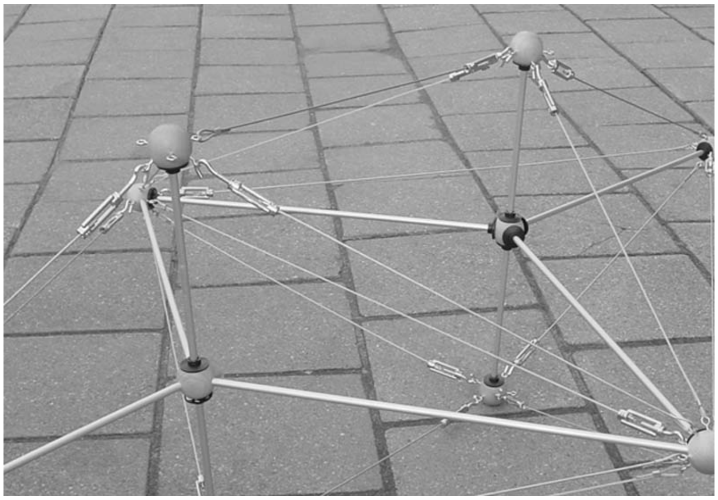

Figure 3. Model of two units of Smart Adaptable Module, connected top and bottom.

Starting points for the development of S.A.M were:

1. A space frame structure for being able to span a certain distance and cope with problems of global instability.
2. A structure built up of triangles for being able to meet random shapes.
3. A modular system for being able to apply S.A.M in different sized projects and to implement swarm intelligence.
4. A system built up of members in tension and compression where the first also act as actuators; as in a mammal skeleton.

The shape of the module depends on seven parameters: the length of the central element, the length of the compression members and five angles between the compression members and the central member (Figure 4.). The single unit of S.A.M has four degrees of statical indeterminacy. This means that if the seven parameters are known and the force in four of the actuators, the forces in all members of the unit can be determined. Furthermore, a sensitivity matrix can be developed that will give an indication of what change in the shape of the structure leads to the least or the maximum change of forces in the structure.

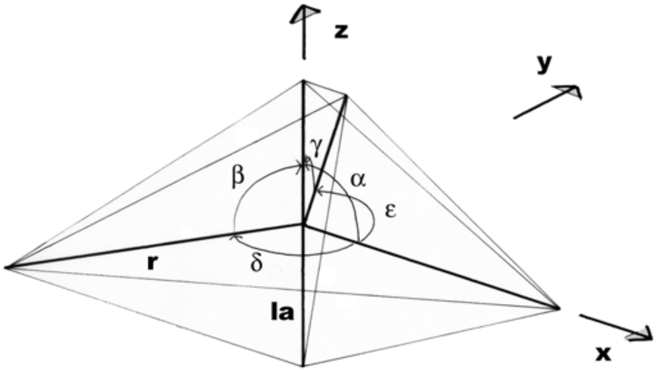

Figure 4. Parameters that define the shape of S.A.M.

5. Pneumatic actuator

Muscles are one of the most advanced and important tools of nature. Movement is a process driven by muscles where on microscale Myocin, Actin and Z-membranes are involved. Contraction takes place if in a chemical process links are formed between Myocin and Actin filaments. If strained, the capacity of the muscle is reduced trough a smaller overlap between the two types of filaments. If in compression, the same occurs through a disorder of the filaments. The typical stress-strain relation of a mammal muscle is shown in Figure 5.

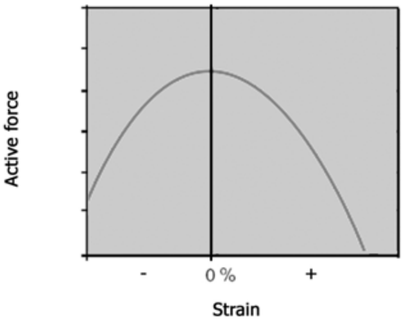

Figure 5. Typical force-strain relation of mammal muscle.

Festo is a company in industrial automation that produces pneumatic muscles (Figure 6). These are flexible tubes that can shorten their length by increasing the internal air pressure. With rising air pressure, the diameter of the tube grows, which gives it a tensile force in the longitudinal direction. Strains up to -25% are possible with the maximum sized elements. Valves control the air pressure and can be automated or controlled by software. As a cheap alternative for pistons, the muscles are mainly used for industrial applications. In Figure 7 we see the stress-strain relation of a pneumatic muscle at constant air pressure.

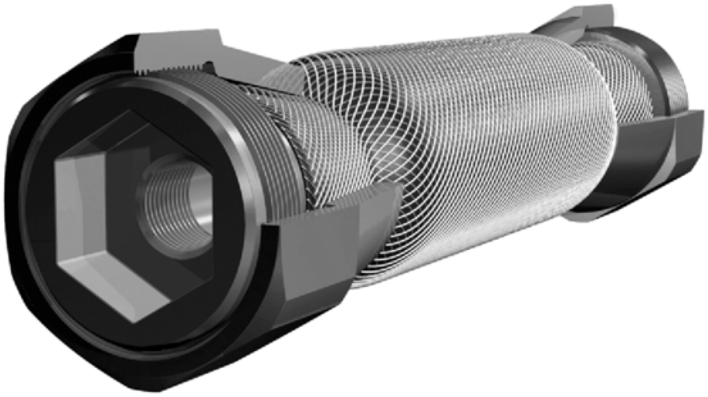

Figure 6. Festo Pneumatic Muscle.

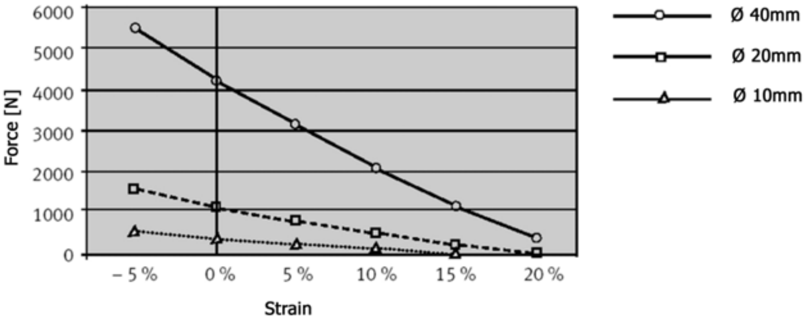

Figure 7: Stress-strain relations of a three types of pneumatic muscles at constant air pressure.

As the stiffness of the pneumatic muscle depends on the internal air pressure, the muscle can mimic other materials properties. Within its limitations it can even behave as an un-natural material with a non-linear stress-strain relation. If applied in the S.A.M structure, the muscles can increase their force where the length is kept constant (isometric behaviour), or contract with a constant force (isotonic behaviour).

A mock-up of S.A.M was built to see how the muscles would act in a realistic scenario. Four muscles were organised around a compression member to bring that in controlled motion. The valves were operated manually (Figure 8).

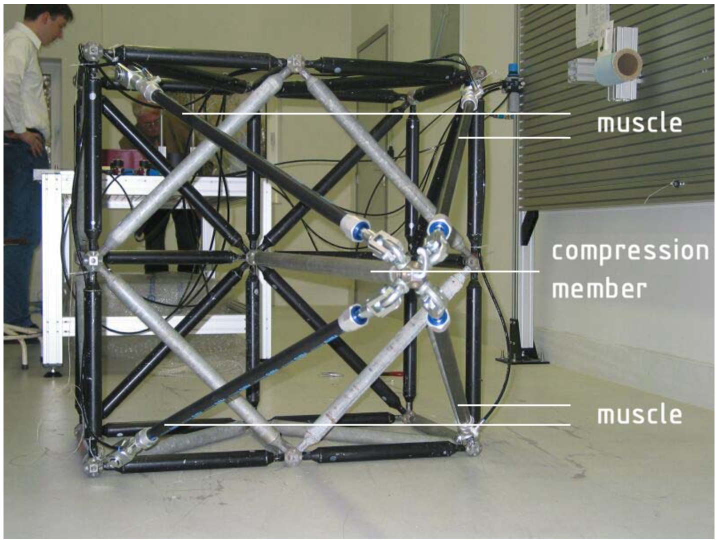

Figure 8. Muscles applied in mock-up.

6. Swarm controls

The traditional way of thinking about control is in a centralized way. One central machine controls certain processes top down i.e. monitors and steers them. Complex systems however, as we know the internet for example, are out of control and self organising. A swarm exists of a great number of members, as we can see in nature around us: a swarm of bees, a flock of birds or a shoal of fish. In general there are three rules to make a swarm what it is: a great number of members, a certain amount of communication between neighbours in the group and a behaviour of the members that can be characterised as relatively simple.

From the interaction within the swarm certain complex tasks can be performed that cannot be done by the members individually. Bees for example are non-intelligent organisms that perform simple tasks. They would die if they were not part of a hive. The swarm however, it is able to find a suitable location to build a new hive. This process is not lead by the queen bee, but the intelligence to do so emerges from the swarm.

Peer-to-peer networks on the internet like the Gnutella network, are also self-organizing complex systems. Every computer running a Gnutella client contacts only a limited group of neighbouring computers. Because those computers contact their neighbours and so on, within a few seconds thousands of computers can be accessed. There is no central server that controls the Gnutella network, but using it, one has access to an immense source of information.

A swarm is a system that has no central control, but behaves as a single entity. It is a complex system controlled by the interaction of peers. The model of the swarm is the model that is used to control S.A.M. Simple rules for the behaviour of the units were developed and called strategies.

7. Simulation

To simulate the behaviour of S.A.M, the structure was modelled in Virtools, a computer program that is used to build 3D games and web applications. In Virtools one can program a real-time environment where conditions set the boundaries for events that have not been defined yet. Two strategies for S.A.M to react on changing external forces have been implemented in 3D models. The first uses the capability of artificial muscles to simulate certain material properties (Active-Passive or A/P), the second makes use of shape adaptation to minimize the sum of forces.

Virtools modelling looks similar to programming in a computer language. The interface however is easier to understand. By connecting building blocks in a loop a sequence of events is defined. Every building block performs a certain task. Through the manipulation of parameters one changes the input and output of the building blocks. This will affect the final result. The 3D output can be viewed in a separate screen. The model can be compiled and can then be viewed with a web browser.

The A/P (Active-Passive) adaptation is based on the philosophy that a member will try to resist deformation until the internal forces reach a certain limit. After that it relies on its neighbours. When a member is undergoing a certain force, it will in the first instance become stiffer during elongation. Once the member reaches a maximum strain, it will stay at the same stress level, and start yielding to prevent it from breaking. It will depend now on the surrounding elements that will have to take the force. The stiffness of the elements is shown schematically in Figure 9. A computer model of this behaviour is built. Screendumps are shown in Figure 9.

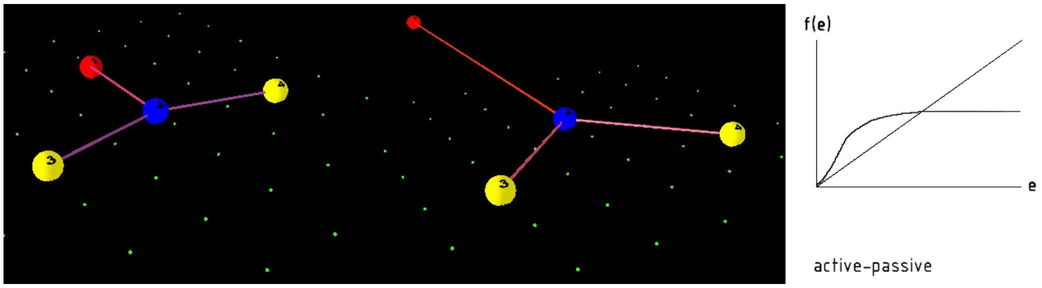

Figure 9. Screendump of Active-Passive model.

The second strategy is based on shape adaptation. If a certain force is brought into the model shown in Figure 10, one can summarize the absolute values of the forces. It is clear that the given force can be supported with the minimum sum of forces in the structure if this is in position 2. This would be the preferred shape for the structure for a given load. If now we can sense the stresses in the structure, and if we know what forces are present everywhere, we can calculate what the structural form should be for the optimum force distribution. This strategy is programmed in the S.A.M Single Unit Model. Figure 10 shows the behaviour of the structure in non-adaptive mode and in adaptive mode if the foremost node is loaded with a vertical downward load.

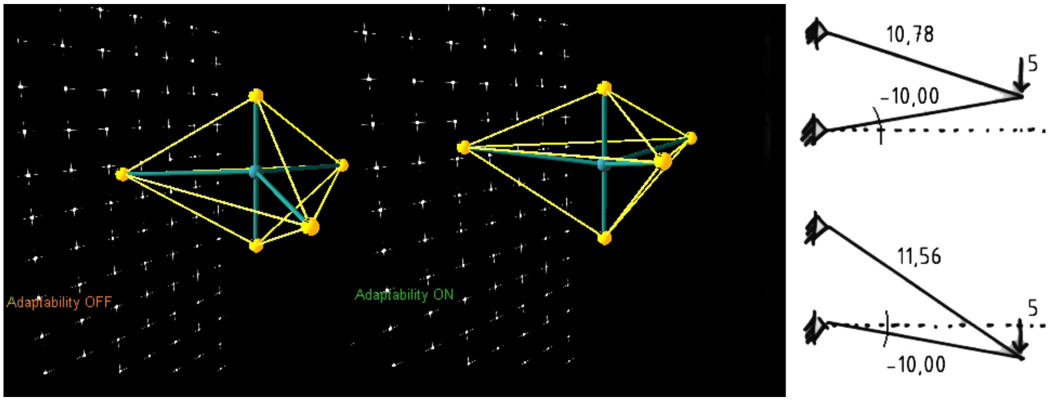

Figure 10. Screendump of S.A.M Single Unit Model.

8. Conclusion

Although the results of the research project as a whole were fairly qualitative, it gives a good insight in the behaviours and the potentials of an adaptive space structure.

ONL and the Structural Design Laboratory (SDL) of the University of Technology in Delft are using pneumatic muscles for further research and application (Figure 11). ONL exposed the muscles in a preliminary version of Trans-ports in the Architectures Non Standard exhibition in Centre Beaubourg in Paris, France. The SDL is exploring application of the muscles in other types of adaptive structures.

The modelling of S.A.M has demonstrated the boundaries of the hardware and software used. In the way the model of S.A.M was set up, the program could not cope with more than ten units on a powerful desktop pc. This number is to small to find swarm effects and to see how the swarm effects influence the behaviour of the structure. One recommendation is therefore to re-model S.A.M in a common computer language such as Java or C++ to make a more efficient use of the computing resources. With the strategies that have been discussed in the above paper the behaviour can then be explored.

Figure 11. Representation of Trans-ports in 2004 in Centre Beaubourg, Paris, France.

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