Control concept for ultra-lightweight structures

Architecture with Brains

Ultralight, Adaptive Structures

Traffic, snow and wind are typical, everyday loads that buildings are subjected to. In contrast, extreme events such as earthquakes or "the worst winter in living memory" are very rare – yet buildings still have to be designed to cope with them. Today, this means using large quantities of materials to ensure safety margins that are hardly ever needed. So that future buildings can use less material but still cope with extreme events, the University of Stuttgart is investigating ultra-lightweight, adaptive structures with intelligent hydraulics that compensate for a wide range of different loads.

Static Adaptation and Active Vibration Control

The Stuttgart researchers are studying both static and dynamic forces and their effects. Static forces are due to factors such as snow, while dynamic forces (i.e., vibrations) are caused by factors such as wind gusts. To reduce the resulting stresses, the load situation first has to be captured by sensors. The control algorithm then uses the measurement values to compute the optimum control for the actuators that adjust the structure to the external loads. For static forces, the structure is adapted statically. If vibrations need damping, however, the sensors have to continuously capture the stress and control the actuators dynamically. As a result, load-bearing elements can be smaller and lighter: The structural mass saved in the construction is replaced by short-term energy inputs.

The Stuttgart SmartShell Prototype

To test their control concepts, the Stuttgart university institutes worked together with Bosch Rexroth to construct the Stuttgart SmartShell prototype, the first adaptive load-bearing shell structure in the world. Constructed from wood in a four-layer laminate, it is only 40 mm

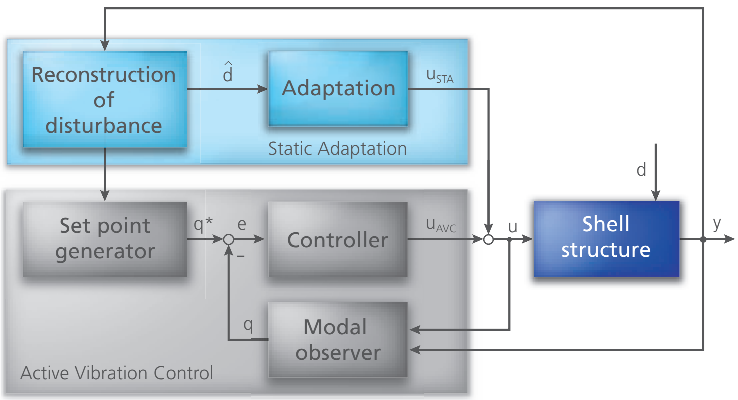


Figure 3: Control concept for static adaptation and active vibration control.

thick. Comparable structures built by traditional, passive methods require several times as much material. The shell weighs 1.4 metric tons and rests on four supports, three of which can be moved by hydraulic cylinders.
Each of the active supports is mounted on a tripod of actuators (figure 2) that allow it to be positioned freely in three-dimensional space. The kinematic relationships between the lengths of the hydraulic cylinders in the tripod arrangement and the positions of the supports are continuously computed online. A wide range of sensors are available for measuring the system state. For example, the hydraulic cylinders are equipped with high-resolution displacement sensors and force sensors. Strain gauges mounted on the shell structure capture the strain at specific measurement points.

The Control Concept

In the first step, simulation models are used to determine the necessary static adaptation. The models represent the behavior of the structure under different loads, and the optimum positions of the supports are calculated from that. To dampen vibrations with maximum efficiency, a description of the dynamic behavior was added to the model. The control concept for vibration damping is based on a dynamic behavior model and on feedback control that is computed from the model and used in the Stuttgart SmartShell. Because the feedback control is derived directly from the analytical model description, it can be adapted to the time-variable parameters of the shell, such as the static load situation or the set points for the support point positioning. The feedback control is designed to optimize the damping properties of the control while at the same time minimizing the energy required for damping. Both these adaptivity requirements can be met simultaneously (figures 4, 6) by combining the set points for the static adaptation and active vibration control (figure 3).

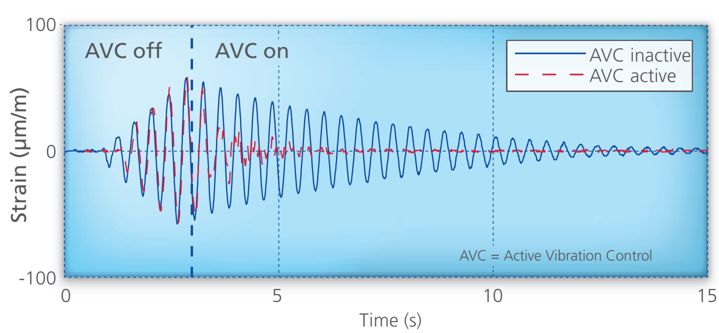
Prototype Implementation

The control system (figure 5) of the Stuttgart SmartShell essentially has to:

- Control the hydraulics
- Cyclically monitor the status and safety
- Read the measurement data from the cylinders and strain gauges
- Estimate the vibration state and reconstruct the static load
- Generate the set points for the static adaptation and vibration control
- Perform high-precision actuator control

The system that performs these complex tasks consists of a dSPACE DS1006 Processor Board and a Motion Logic Control (MLC) unit from Bosch Rexroth. While the MLC performs the control tasks for the hydraulic system and sends the control inputs for positions and forces to the individual hydraulic drives, the DS1006 estimates the state and generates the static and dynamic set points. The DS1006 also computes the direct and inverse kinematics. These are used to convert the set points for the support point

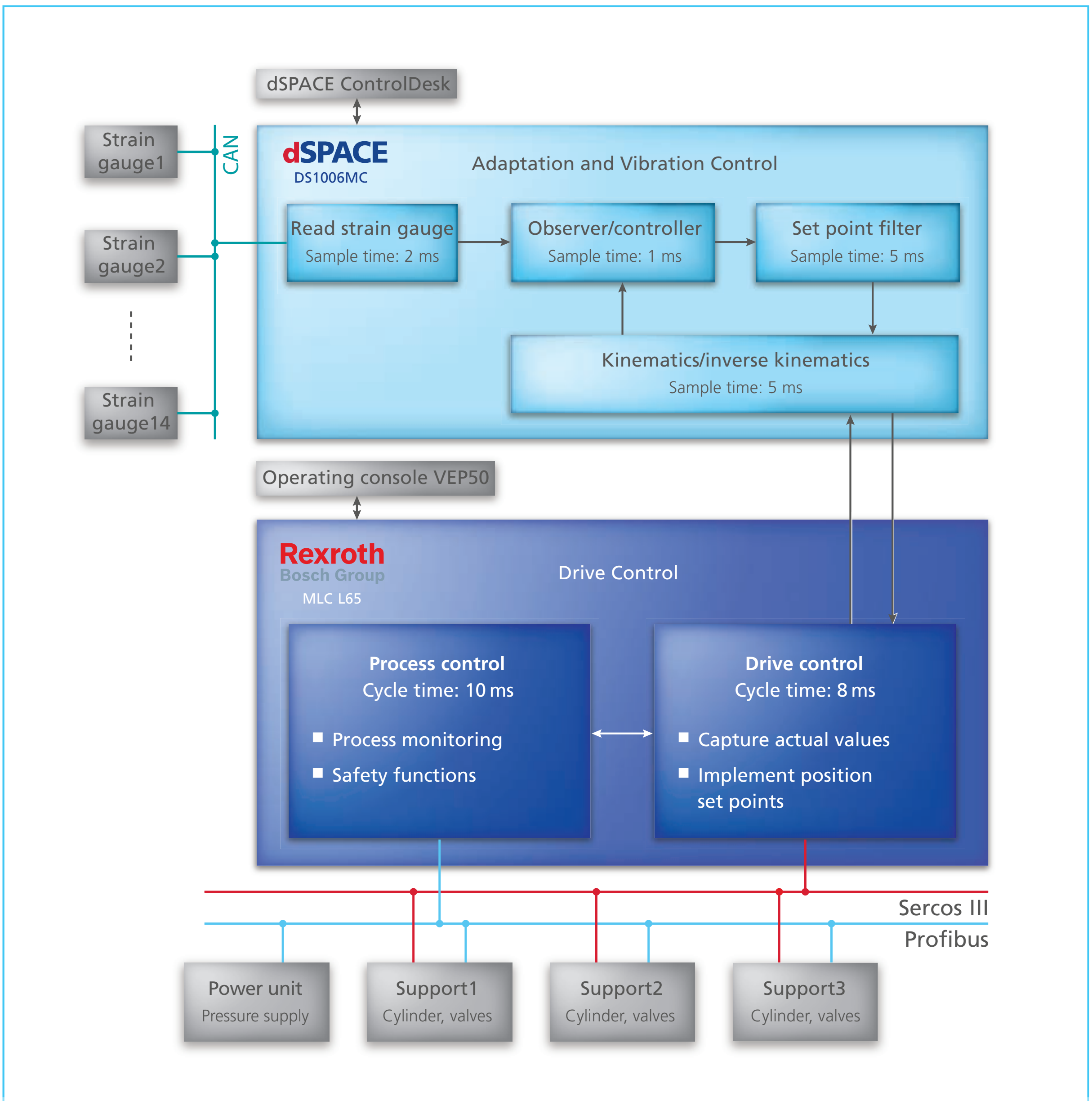
Figure 4: Comparison between undamped vibration (blue curve) and actively controlled vibration (red curve). The damping control is activated at 3 s and reduces the duration of vibration by 80%.



Supporting structure for assembling the Stuttgart SmartShell.

> "With the dSPACE prototyping-system, adaptivity concepts for ultra-light-weight structures can be implemented in a short time."
>
> *Martin Weickgenannt, University of Stuttgart*

Figure 5: Software and hardware structure for implementing the static and dynamic adaptation.



Conclusions

Using a dSPACE controller board together with a Rexroth Motion Logic Control (MLC) combines the advantages of a rapid prototyping system and a process ECU. This means that the tasks of the Stuttgart SmartShell – generating static and dynamic set points, plus process control – can be implemented efficiently.

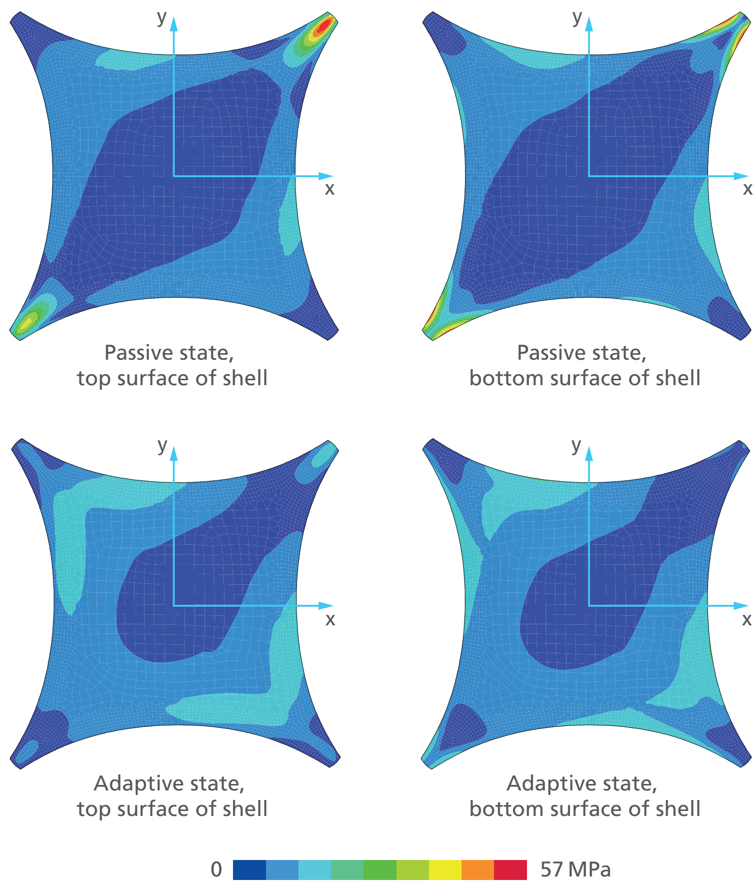


Figure 6: Stress distribution due to an exemplary external load. Adaptation reduces peak stress by 66%.

positions and forces into local set points for the drives. The current values for the positions and forces at the support points are obtained from the local measurements, which are then transformed into the global coordinate system. The high complexity of the kinematic calculations and the short cycle time of 5 ms involve a large computation load. The convenient configuration options of the DS1006 are particularly helpful here, as the computation processes can easily be distributed across its processor cores to ensure optimum use of the processing capacity. The Profibus connection between the DS1006 and the MLC allows the high-frequency exchange of the set points, measurement values and control commands at a rate of 12 MBit/s. The strain sensors are connected to the DS1006 via three separately controlled CAN networks, providing a sampling rate of 200 Hz. The CAN interface can be set up quickly and conveniently by means of the RTI CAN MultiMessage Blockset. Finally, with the experiment software

Snow, wind and traffic are typical forces that structures have to withstand.


The shell structure is only 40 mm thick.

ControlDesk, it is easy to specify items such as set points for the individual drives and to switch between different control strategies. ■

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Watch this video to see the Stuttgart SmartShell in action:
www.youtube.com/watch?v=vDb2h1-7LA0

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