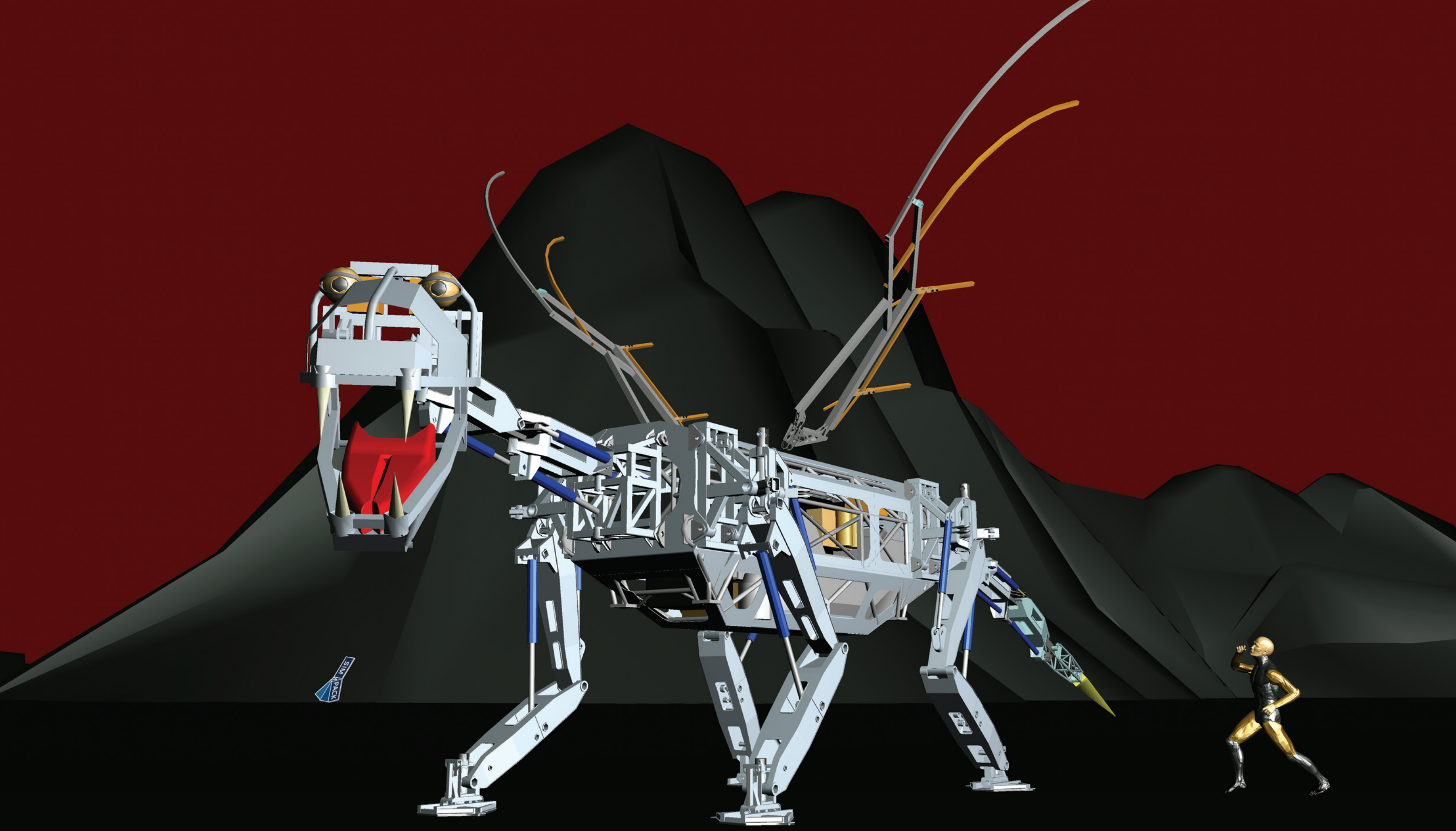

Fig. 1: The new dragon (SIMPACK model)

Rise of a Monstrous Robot, called "Tradinno", in SIMPACK

In 2010, a new high-tech mechatronical dragon will be put into operation and is going to be the headliner of an ancient German folk festival, Further Drachenstich (www.drachenstich.de). This unique, autonomous and remote-controlled four legged dragon, with a total mass of about 11 tons, is being designed at Zollner Electronic AG in Zandt, Bavaria. To guarantee the success of this highly ambitious project, extensive dynamic simulations in SIMPACK are essential.

THE DIMENSIONS AND ABILITIES OF THE MECHATRONICAL SYSTEM

The robot under development will have a total length of 16 meters and will be powered by a 100 kW Diesel-engine. A total of 50 closed-loop controlled axises are moved by carbon fibre laminated (CFK) hydraulic-cylinders (about 50 % lighter than conventional cylinders). The maximum speed of the system, while "walking" autonomous on its own four feet, will be about 2 km/h. For moving over large distances, a custom built transporter will be used.

The dragon will handle some special effects too, for example fire-breathing and flapping, with its 12 m wingspan and it must assume several pre-programmed positions in the festival. The entire system will be remote-controlled by five operators.

The large mass and high number of degrees of freedom result in extremely high dynamic forces on the individual components. Furthermore, the highly complex redundant controllers may interact and generate an uncontrollable situation.

SIMULATION OF THE JOINT- AND CONTACT-FORCES GENERATED DURING THE STEP-CYCLES AND ACTIONS OF THE FOUR-LEGGED MONSTER

After importing the CAD geometry (well over 100 subassemblies) and the mass properties to SIMPACK via ProSIM and setting up the topology through joints and constraints, the next step was to model contact and friction forces between the four feet and the ground. This was realized via the force elements FE 018: Unilateral spring damper and FE 100: Non-linear friction. The biggest problem in this case was to find suitable stiffness and damping values. Various assumptions were made via a realistic penetration depth of foot and ground. The forces obtained this way were essential for the design process and the FEM-analysis of the systems' components, for example body and legs (see Fig. 2).

To receive more realistic results, the system's wobbling masses had to be considered, e.g. motor and hydraulic pumps (total mass: 500 kg), mounted on spring-dampers. Furthermore, the variable compression of the oil quantity enclosed in the cylinder, depending on the piston stroke, could not be neglected. This coefficient was implemented by a force expression in the hydraulic cylinders. It showed that the simulation

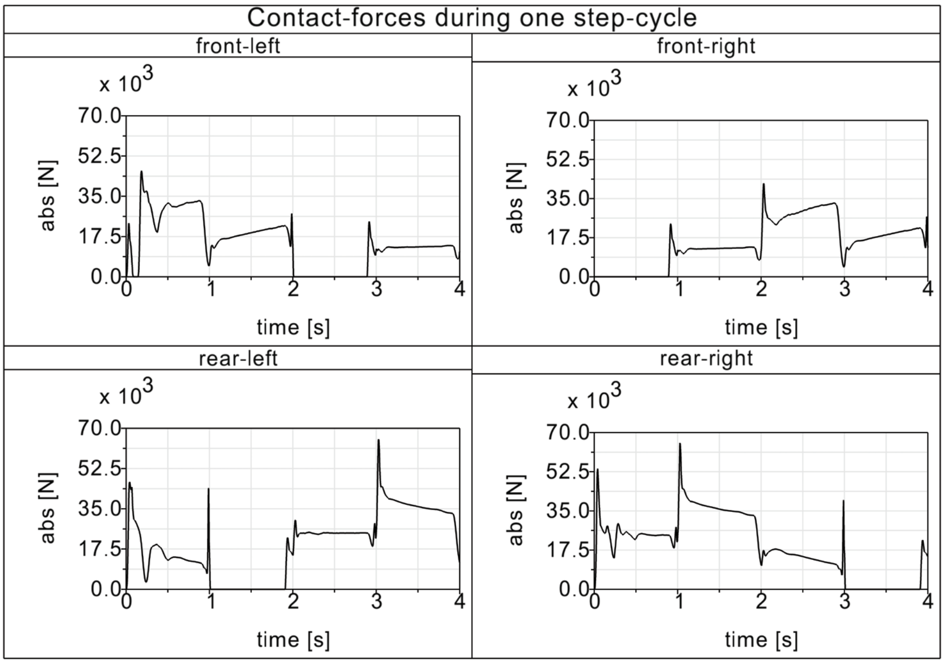

Fig. 2: Contact forces of the four feet during one step-cycle

results varied considerably depending upon the flexibility of the single subassemblies and the values of stiffness and damping of the contact forces.
The impact when stepping on solid ground could be considerably reduced by optimising the trajectory of the single legs.

"A reliable closed-loop control was essential"

Simulating the step-cycles also delivered information about the stability of the walking system with regard to the lateral buckling. Observing the robot's total centre of mass made it possible to optimise both the placement of the single components in the torso and the equations of motion of neck and tail. The walking and movement tests were made repeatedly under different conditions:

- moving straight forward on a flat plane
- moving on a slope (the system has to handle inclinations up to 10 %)
- walking an arc
- turning on the spot

As aforementioned, the system has to readily assume special positions necessary for the theatrical play. This often has to happen very fast and thus results in high component stresses. The wings, acting independently in three directions, were also tested to find out the best possible agreement of weight and stability.
The rare event of a complete front leg failure (either mechanical or hydraulic), was investigated in detail. The simulations helped to find ways to stabilise the dragon in order to eliminate any potential risk to human beings. A lot of simulation work showed

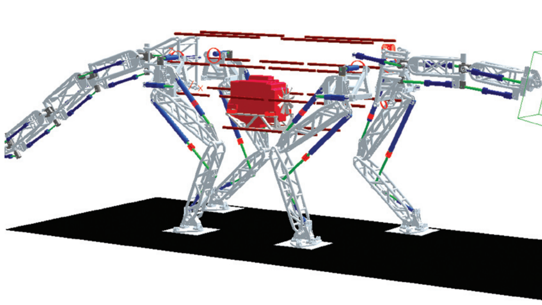

Fig. 4: Flexible torso

that a fast lowering of the complete system after detecting the leg failure helped to ease the situation. Other possible scenarios, such as quickly lowering the dragon's head or swinging both head and tail rapidly to the opposite side of the damaged leg, proved not to be as effective. Nevertheless, various possibilities to avoid system damage, and to ensure the safety of people standing around the robot, were found.

CLOSED-LOOP CONTROL TESTS WITH THE MATLAB CO-SIMULATION TOOL SIMAT

The first walking simulations were made with fixed input function splines steering the acting cylinders. These splines were generated by using inverse kinematics. That method was sufficient for predictions respecting the resulting forces and torques. The steadiness of the closed-loop control was also checked. In particular, the sophisticated hydraulic system had to be reviewed in order to find out if control could be lost. The intention was to ensure that the human supervisor could push the button

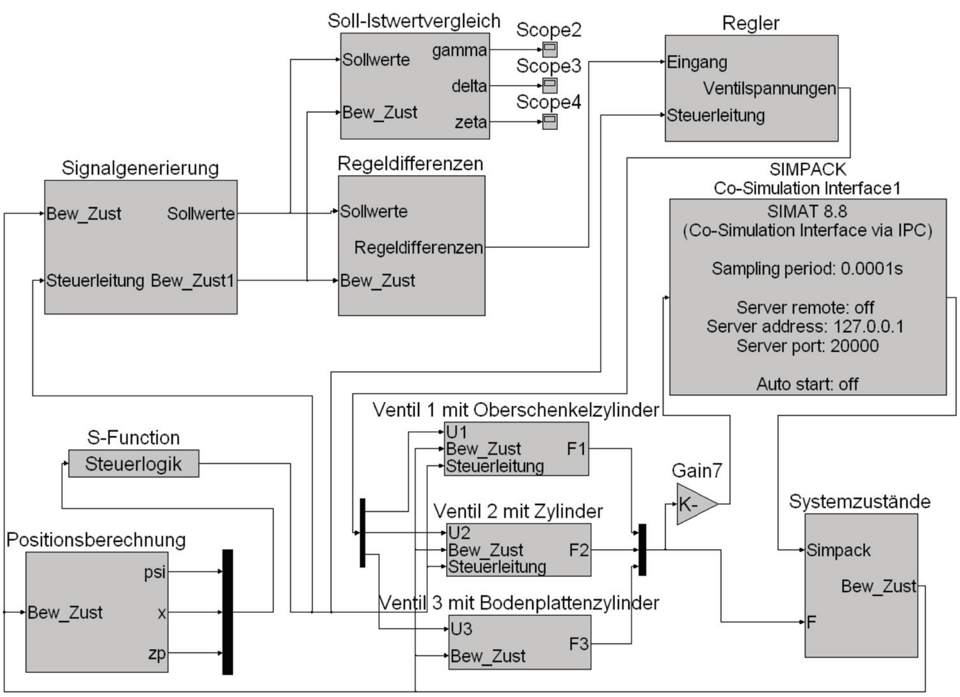

Fig. 3: Closed-loop control of a leg

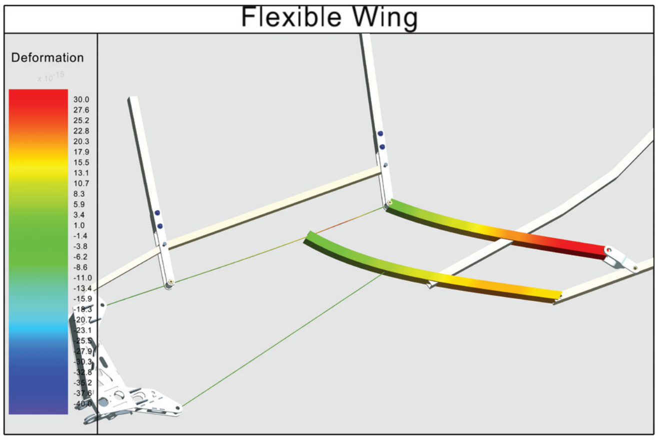

Fig. 5: Flexible dragon-wing

on the remote control and have the dragon perform all moves automatically. A reliable closed-loop control was essential for that purpose.
The first control test with realistic geometry and mass properties was performed using SIMPACK and the MATLAB-interface SIMAT.
The big advantage of SIMAT is that SIMPACK delivers MATLAB with all geometrical data in real-time making the interface very effective.
The basic question as to what kind of control was the best for the overall system had to be clarified. Would force control, position control or a mixture of both control types give best results? Several co-simulations showed that position control was more stable. Therefore, it will be used for moving the dragon.
When lifting a leg for stepping forward, an additional subordinated force controller was used, minimising the reaction speed of the entire system.
The first simulations using SIMAT handled only the interaction of the hydraulic cylinders of one foot. After observing that the controller was able to handle the flexibility of the system, the whole system was implemented in the co-simulation.
It was found that the closed-loop control, in extracts shown in Fig. 3, produced reasonable results concerning the "drilling" of the dragon. The control circuit shown in Fig. 3 is at about 90 % of its final state and requires only fractional improvements before testing it with the real dragon hardware.

MODELLING FLEXIBLE SYSTEM COMPONENTS VIA SIMBEAM AND FEMBS

In order to simulate a complex system such as the mechatronical dragon in a realistic manner, it is essential to model the physical characteristics in as much detail as possible. In addition to joint types, mass properties, trajectories and compressibility of the hydraulic system, attention had to be paid to the flexibility of the mechanical components. The torso had to absorb huge deformation energies that had an influence on the quality of the simulation. On the one hand, the load of the complete system was lowered by absorbing the stress peaks received in earlier simulation. On the other hand, designing a reliable closed-loop control was hindered.

"SIMPACK played a very significant role in the success of the project"

In order to check the influence of a flexible geometry, SIMBEAM and FEMBS were used to create a rudimentary flexible torso. The torso was chosen because it is the largest part of the whole system and all the other components are attached to it. When it is deformed, the complete machine is affected. By modelling the torso with flexible components, the results of former FEM analyses could be exploited for the SIMPACK model. As SIMPACK offers the possibility to apply dynamic loads, the emerging forces could be calculated (something that had not been feasible in the original FEM software used).
Because the torso is quite a huge sub-assembly, a simple model involving about 100 flexible components to get first impressions of the possibilities of the SIMPACK modules was set up (see Fig. 4).
The simulation results showed good correlation to the values obtained in FEM, taking both loads and deformations into account.
After the successful simulation of the elastic trunk, other parts of the system were built up in SIMPACK and made flexible. For example, the wings which are statically overdetermined are subject to high dynamic loads. It is an arduous task to get reasonable results in classic FEM and so, this case was a prime candidate for SIMPACK simulation. As shown in Fig. 5, it was possible to get the deformations and loads from SIMPACK and use them for further strength calculations.

CONCLUSION

Since Zollner Elektronik AG started perfoming simulations with SIMPACK in 2007, essential knowledge was gained on what is important when dealing with highly dynamic complex systems. SIMPACK played a very significant role in the success of the project.
There is still a lot of work to do before the real dragon-robot will finally rise in 2010, but Zollner is confident it will complete the project on time.

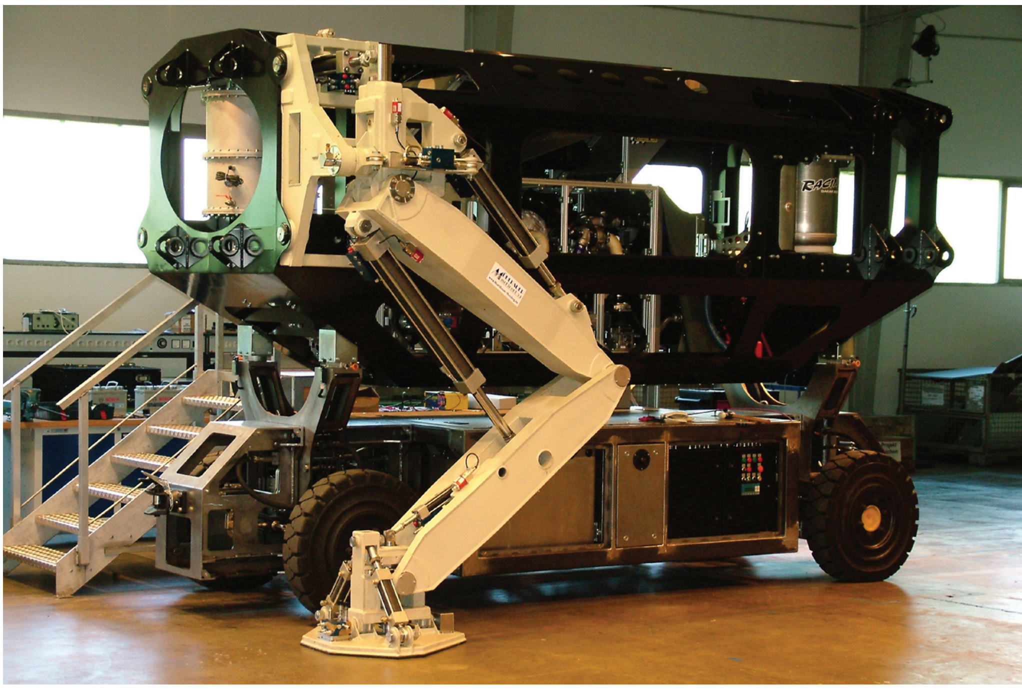

Fig. 6: Status quo, May 2009