Virtual prototype of a climbing electric wheelchair.

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Abstract
This paper presents the development of an electric wheelchair, which is able to climb straight and spiral staircases. A virtual prototype of the wheelchair has been developed at Forschungszentrum Karlsruhe (Karlsruhe Research Centre, Germany). The virtual prototype uses the simulation programs ADAMS and MATRIXx in co-simulation. ADAMS is used to model the wheelchair mechanics and MATRIXx is used for implementation of the control algorithms. Additionally, the CASE-tool Rhapsody is used for object-oriented software design and code generation. Rhapsody has been integrated in our co-simulation environment, which enables us to test and debug our C++ algorithms in the simulation of the virtual prototype.

1 Introduction

Staircases are hard to negotiate for people in wheelchairs. Currently available tools are limited in their use:

- Fixed installations can only be used for a specific staircase and are complex and expensive. In rented houses, they can often not be installed because of existing rules.
- Mobile tools require the help of a strong, experienced and brave person. In theory, curved stairs can be climbed. In practice however, they are only used for straight stairs.
- Vehicles with belt-mechanisms often damage the surface of stairs and floor, which is usually not acceptable, especially in rented houses.

The objective of this project is to make the user more independent and to extend his range of operation. This is done by the development of an autonomous wheelchair which can be used indoors and outdoors as a conventional electric wheelchair and with which the user is able to climb straight and spiral staircases without any external help.
Climbing is possible without any fixed installation. The user should have all cognitive abilities and needs at least one hand to steer the vehicle. Climbing is done semi-automatically; the user navigates towards the first step and after a start-command the wheelchair will climb automatically by means of sensor systems and control algorithms.

2 Technical description

The wheelchair which is being developed at Forschungszentrum Karlsruhe is a complex mechatronic system consisting of the mechanics, motors, sensors and control system. Various principles have been considered. The structure has 16 moving parts, resulting in 8 degrees of freedom, 15 electromechanical actuators for normal motion, ascent and descent, and a total of 25 sensors, including staircase detection sensors and safety systems. The control system comprises axis control, user interface, power management and safety systems.

2.1 Mechanics and actors

The wheelchair has 4 wheels, each of which is mounted on a wheelbase. The angle between the wheelbase and axle can be varied. A special frame, in the shape of a parallelogram, connects front and rear axle and maintains an upright seat position during climbing. The axle can be rotated around this frame and the frame length can be adjusted to the various staircase geometries. The rear axle has a maximum rotation of about 50°, the front axle can be rotated almost 90°. In this way, the structure is mechanically stable in all positions and can still be steered with a small turning circle.

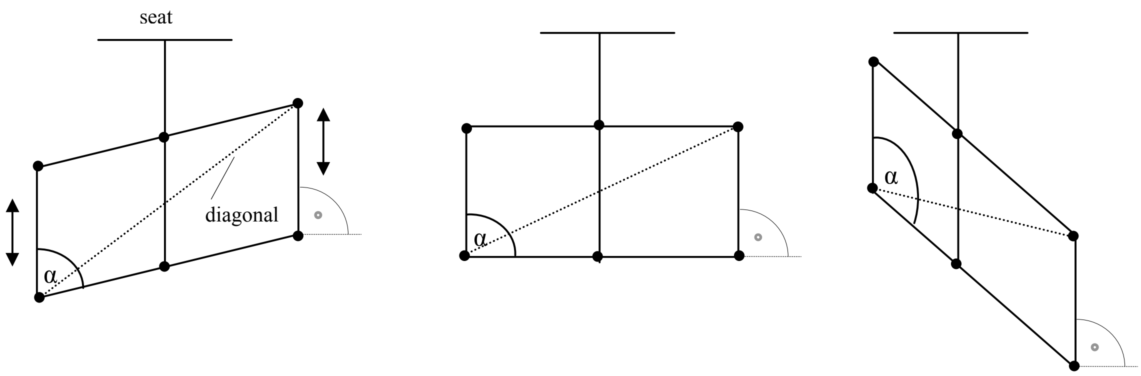

Fig. 1: Wheelchair frame with parallellogram

Battery lifetime is an important factor in the design and selection process. All axes are driven by brushless dc-motors because of their good characteristics and low weight and power consumption. Credit card size servo amplifiers are used to power the motors, in order to save valuable weight and space.

2.2 Sensors

All axes require sensors for positioning. Optical encoders and potentiometers are used. Additional sensors are required for detection of staircase geometry and for safety systems. Step detection is done with sonar sensors and light switches. All sensors with safety-critical functions are implemented with redundancy so that sensor defects can be detected and system safety can be guaranteed at all times.

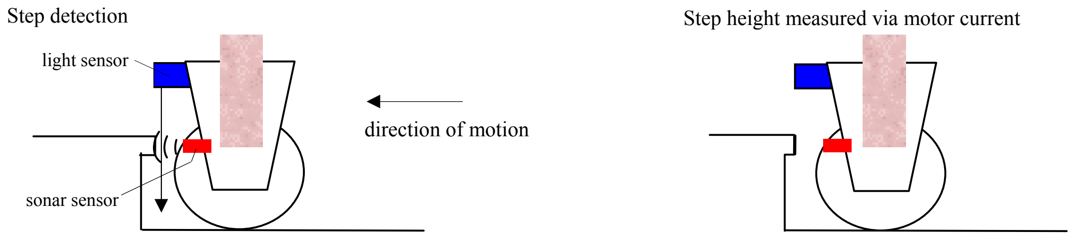

Fig. 2: Sensors for staircase detection during ascent

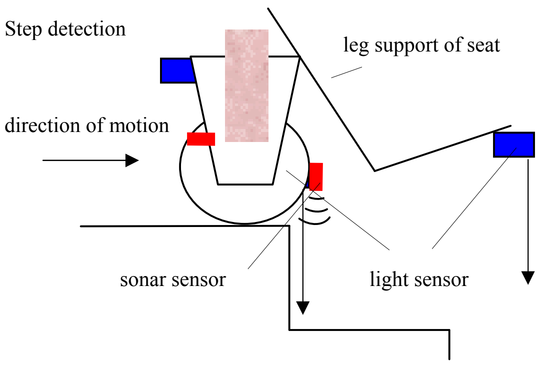

Fig. 3: Sensors for staircase detection during descent

A warning sensor is mounted under the leg support of the seat. This light sensor can detect a staircase so that speed can be reduced in time.

2.3 Control system

A powerful control system is needed for control of all axes of motion, staircase detection and safety checks. The controller hardware consists of three PC104 modules, one for front axis control, one for rear axle control and one for supervision, MMI and safety systems. Hardware watchdogs guard correct operation and are directly connected to an emergency relays.

The real-time operating system VxWorks is used. This operating system has many features for safety-critical applications. The control software is written in C++. For the design of the software, object oriented design methods and CASE tools are used. Below, an example class diagram for the control structure is shown.

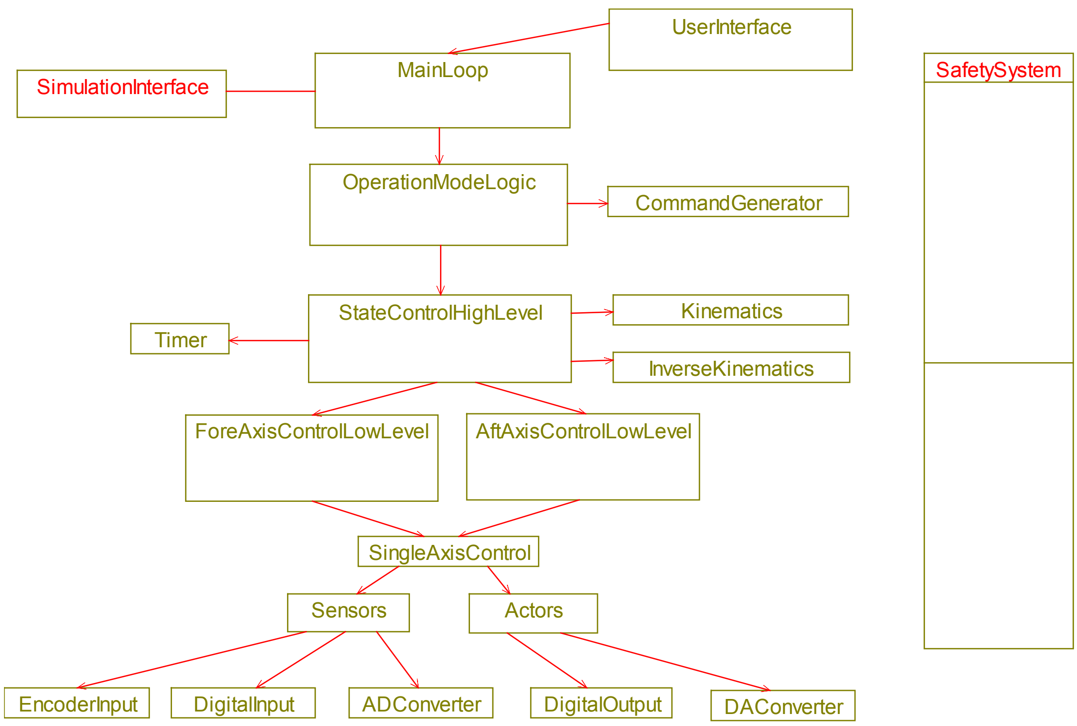

Fig. 4: Example class diagram for control

The software comprises: man-machine interface, power management, trajectory generation for autonomous climbing, control of 15 axes of motion, environment information (e.g. staircase database) and safety checks.

3 Simulation model

In the design phase of the project, a simulation model has been built to prove that the chosen design concept is able to fulfil the functional specifications. The mechanical part of the system has been modelled in ADAMS and the control system has been modelled in MATRIXx. The complete system can be studied in closed-loop in co-simulation with the ADAMS/CONTROLS package

3.1 ADAMS mechanical model

The ADAMS model includes a fully functional model of the wheelchair with all its moving parts, sensors and actors.

To the active joints a MOTION-command is applied with a VARVAL-function. The state-variables for these MOTION-commands are the servo amplifier setpoints which are calculated by the control system.

Sensors are:

- Position sensors for all axes of motion
- Sonar sensors for staircase detection and environment information

The sensor values are saved in state-variables and sent to the control system.

The staircase is generated as a shell. A Fortran USER-function which was written by MDI is used to calculate the contact forces between the staircase and all four wheels and between the staircase and all four support arms. Friction, elasticity and damping characteristics have been taken into account.

3.2 MATRIXx control system

The MATRIXx control system consists of a setpoint-generator, controller logic in the form of finite-state machines, high-level control functions such as trajectory-control for autonomous motion and a number of position and velocity control loops which control the movement of each axis. Also, control loops concerning seat inclination and centre of gravity have been implemented.

The first design of the controller logic has been implemented in the form of Blockscript blocks. As the complexity of the models increases, finite state machines can be used to keep the controller logic modular and comprehensible. It is possible to use MATRIXx AutoCode functionality to generate C-code for the control system automatically.

3.3 Co-simulation

The ADAMS/CONTROLS package is used for co-simulation of the mechanical model and its control system. In this way, realistic scenarios can be simulated and the behaviour of the wheelchair on various staircase geometries can be studied. Step height, width and depth, as well as radius of spiral staircases can be easily modified. Kinematics, control algorithms and the choice of sensor systems can be verified without having to build a prototype in this early design phase of the project.

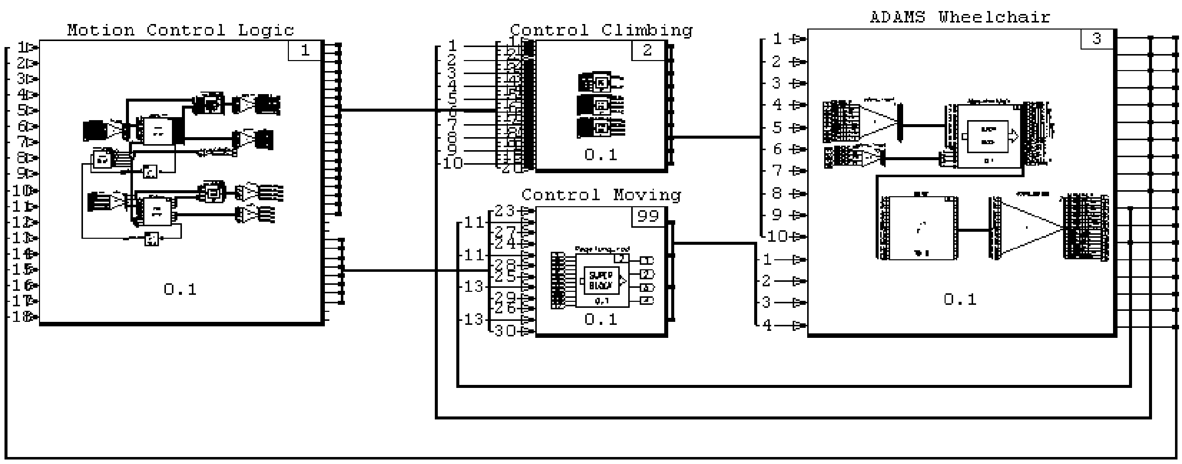

Fig. 5: Closed loop simulation model (Co-Simulation)

4 Virtual prototype

In order to be able to test our operational software in simulation, we have integrated our CASE tool in the co-simulation environment described above.

Rhapsody is a CASE-tool which is based on the UML. It can be used to design object-oriented software for real-time embedded systems and produces C++ code which is tailored to our real-time operating system. The combination of Rhapsody with MATRIXx and ADAMS enables us to test our operational software with the virtual prototype immediately. The main advantage is the possibility to debug at design level, single-step through the messages which are sent between objects and single-step through the states of the state machine of a single object.

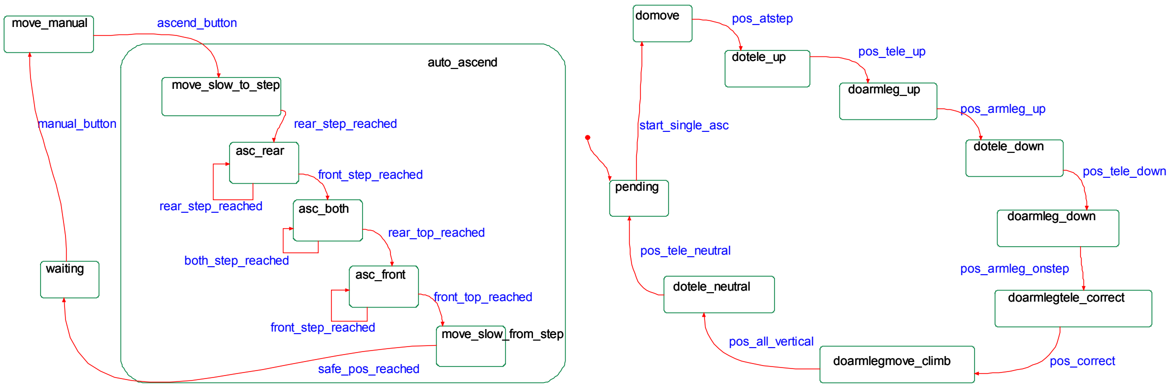

Fig. 6: Statechart ascent and single step ascent

The figures above show the statecharts for staircase ascent. During development and debugging, these statecharts can be animated so that it is immediately clear in which state the system is pending.

The process of virtal prototyping is shown below.

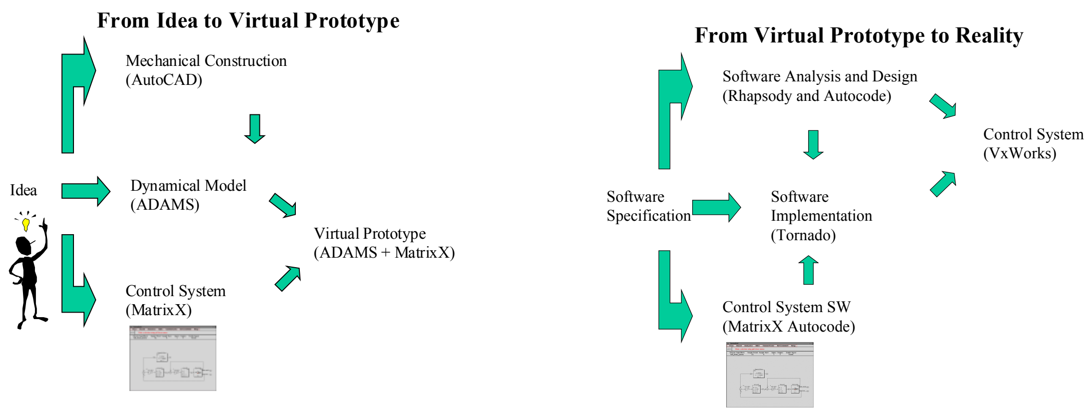

Fig. 7: The process of Virtual Prototyping

The next figure shows our software development cycle. The main advantages of such a closed development tool chain are:

- Early detection of design flaws
- No introduction of new errors during transitions to new design phases
- High quality code
- High quality documentation which is coupled to the design and code
- Reduced development times, shorter time to market

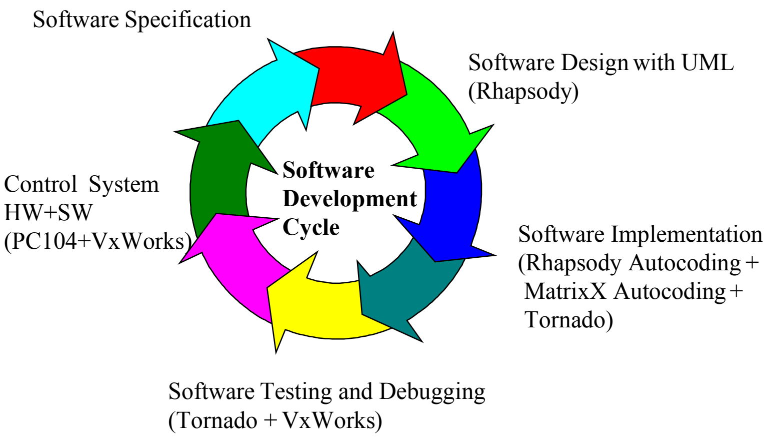

Fig. 8: Software development cycle

5 Conclusion

The co-simulation of MATRIXx and ADAMS enabled us to prove that our design concept can fulfil the functional specifications. The wheelchair is able to climb staircases with varying geometry. The main control algorithms have been tested.
The integration of Rhapsody with the combination of MATRIXx and ADAMS enables us to test our operational software in the simulation of our virtual prototype. This allows us to detect design errors early in the development process and results in a reduction of development time and higher quality software.
In the next phase of the project, a fully functional prototype of the wheelchair will be developed.

Note:
This project "Treppensteiger" (step-climbing robotic device) is being developed by Forschungszentrum Karlsruhe (Karlsruhe Research Centre, Germany) in co-operation with the German companies MIT and AST. The project is funded by the Bayerische Forschungsstiftung (Bavarian Research Association), nr. 240/97.

ITK-Consulting is an engineering and consulting company, specialised in modelling, simulation, control systems and real-time embedded systems. ITK is the subcontractor for Forschungszentrum Karlsruhe which is hired to develop the ADAMS and MATRIXx simulation models, the virtual prototype and all control algorithms and software for the prototype.