Stair-Climbing Assistive Robots

A major drawback of assistive robotic devices for the mobility-impaired, such as wheelchairs or the Segway, is their inability to negotiate stairs and steps. Wheel-based systems are advantageous compared to other motion mechanisms because of their energy efficiency, relatively high velocity, and simple design, but enabling them to climb or descend stairs without manual support is an outstanding challenge for control engineers.

A single step as an obstacle for the wheelchair driver (Source: www.bsk-ev.org)

Manually overcoming stairs (Source: M.J. Lawn, Study of stair-climbing assistive mechanisms for the disabled, PhD thesis, Nagasaki Univ., 2002)

Stair-Climbing Wheelchairs

The iBOT wheelchair provides some degree of automated support for wheelchair drivers to overcome stairs. Shifting the center of gravity triggers the rotation of the iBOT's lower body. The wheelchair supports the driver by providing power during climbing; however, the wheelchair is not actively stabilized and the climbing cannot proceed autonomously. This limits the stair-climbing function for drivers with a high degree of disability or in cases where no handrails are present.

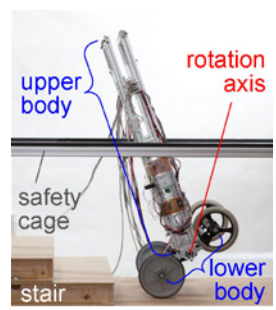
Stair climbing with the iBOT wheelchair (Source: D. Ding, R.A. Cooper, "Electric-powered wheelchairs—A review of current technology and insight into future directions," IEEE Control Systems Magazine, April, 2005)

Autonomous Stair-Climbing Device (SCD)

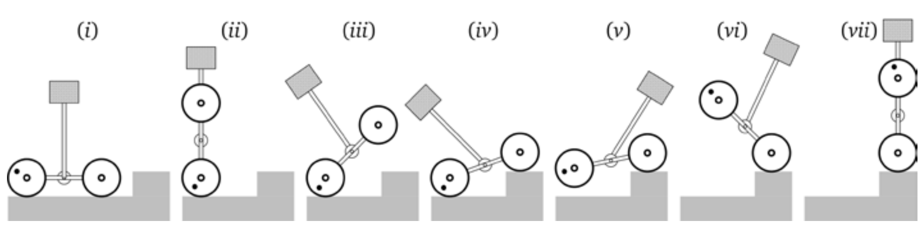
An autonomous stair-climbing device (SCD) could allow the mobility-impaired to manage stairs and steps without manual effort. One possible design is shown here. The mechanical system can be considered a double inverted pendulum. Motors are used to drive the wheels and to control the angle between the upper and lower body. The inclination angle can be estimated with high accuracy with an inclinometer and gyroscope. At least two different discrete states need to be considered:

- All wheels are in ground contact (see figure below, situations (i) and (iv)) and
- Two wheels are in ground contact (situations (ii) and (iii)).

Control action is needed to stabilize equilibrium points of the SCD in both states, enabling it to move on the ground in both states. Furthermore, stable state transitions must be achieved by the control to enable stair climbing.



SCD in balancing mode (Source: www.ims.tu-darmstadt.de)



A sequence of SCD configurations for stair climbing

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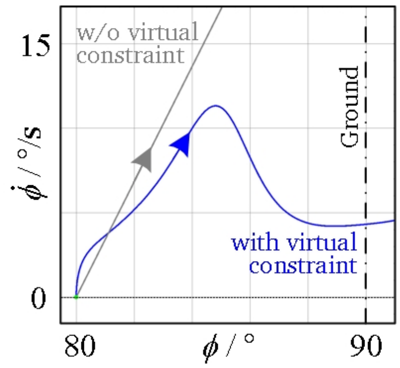
Control-Enabled Assistive Robotics

Control Characteristics

- **Hybrid nonlinear dynamics:** In a specific configuration, the SCD-like systems show nonlinear continuous-time dynamics with nonholonomic constraints due to wheel kinematics. In addition, discrete events such as the transition from two wheels to all wheels on the ground cause a discontinuous impact. Thus, the device exhibits hybrid nonlinear dynamics in its operation.
- **Unilateral constraints:** With the given mechanical structure, the wheel-ground contact exhibits a unilateral (non-negative) contact force, enabling wheel-ground contact activation and deactivation. These transitions should be realized by control actions that satisfy stability and performance criteria (e.g., soft landing). The degrees of freedom change during these transitions.
- **Underactuation:** Although the SCD is fully actuated when all its wheels are on the ground, this is not the case in configurations with two wheels in ground contact. Here the system is underactuated, with one more degree of freedom, namely, the inclination of the lower body.

Despite the wheel-versus-limb difference in motion mechanisms, these characteristics are shared by legged robots.



The transition from two wheels to all wheels in ground contact can be designed to achieve a soft landing using the "virtual constraints" framework. The upper-lower body angle (ρ, see figure below) and the lower body angle (ø) are coupled in the control system output function. The system zero dynamics of the SCD when falling to the ground are such that the upper-body motion causes a deceleration of the lower body as soon as the ground is close.

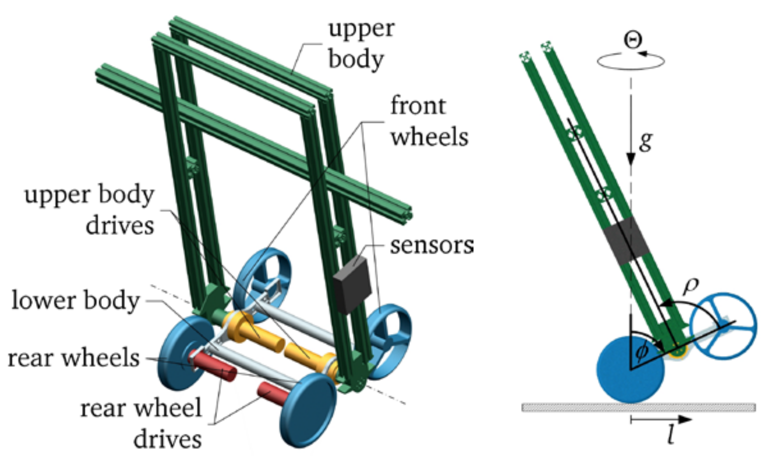
SCD Control Challenges

Stable motion and stable transition of configurations have been ensured using feedback linearization methods. In the underactuated state, the linearization can be achieved partially (input-output); in this case, the remaining internal dynamics have an unstable equilibrium, which can be stabilized with an additional linear full-state controller. A challenge for future research is to apply a full nonlinear control law, which could provide higher speed of motion across a broad amplitude range and disturbance compensation by (preferably) body motion instead of wheel motion.

Although the overall functionality has been achieved by considering motions in particular configurations and transitions, a further control challenge is to induce a limit cycle, causing a permanent lower-body rotation. Such a strategy could increase the stair-climbing velocity. A further advance would be to realize jumping to next steps. This capability could allow stair climbing in cases where the SCD lower-body and wheel geometry do not allow it. Furthermore, this control could mitigate the consequences of falling to the lower step in case of large disturbances.

Applications to Unmanned Service Robots

Stair climbing would be a useful capability not only for wheelchairs and other systems that mobility-impaired people can use for transport, but also for unmanned robots in service applications. Such robots are being developed for applications in homes, offices, museums, factories, and other facilities (www.doublerobotics.com).



CAD model of the SCD (above left) with main degrees of freedom (above right): position l, lower body angle (ø), upper-lower body angle (ρ), yaw angle (Θ), and gravitational acceleration g