Increasing Personal Mobility with a Powered Wheel-Track Hybrid Wheelchair

All-Terrain Wheelchair

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State-of-the-art technologies empower people with motor disabilities to carry out activities of daily living, thus enabling a better quality of life. Personal mobility is crucial for the well-being of individuals with motor impairments. In fact, studies have shown that, among people with motor disabilities, those having better mobility report greater satisfaction with their quality of life than those having lower mobility [1]–[3]. Motor functions can be improved, recovered, or partially substituted with various robot-based technologies, such as robotic prostheses, exoskeletons, and electric wheelchairs. Robotic wheelchairs allow those with motor disabilities practical and efficient electric mobility.

A team of students and mentors from the University of Ljubljana, Slovenia, developed the concept and prototype for a hybrid robotic wheelchair that allows the user to traverse obstacles, such as stairs and ramps commonly found in urban and rural environments, by utilizing both wheeled and tracked propulsion. Additionally, the team's prototype incorporates a wheel-drive system designed for enhanced maneuverability in indoor spaces. The prototype was put to test at the Cybathlon, a competition that promotes the development of advanced robotic devices for people with disabilities, in 2016. The team from the University of Ljubljana successfully finished the competition, winning a bronze medal in the powered wheelchair race.

While lost lower limb functions can sometimes be restored with intensive rehabilitation, wheelchairs are often the only practical means of transportation for disabled people who find it difficult or are unable to walk. The fundamental role of wheelchairs is to improve the mobility of users, thus enhancing their ability to participate in activities of daily life [4]. Because it is important for people with

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disabilities to regularly use their retained motor functions, the best solution is often a traditional, manual wheelchair [5]; however, if the upper limbs are also affected and operating a manual wheelchair is not possible, electric-powered wheelchairs provide a suitable solution.

Wheelchairs must fulfill three key user needs:

- basic transportation needs–controlling direction and speed
- functional needs–avoiding obstacles, going through doorways, and traversing ramps, curbs, and stairs
- community needs–allowing reasonably free interaction and cooperation with other people [3], [4].

A wheelchair should, therefore, be mobile, agile, and small enough to allow users to move in most common indoor and outdoor environments where unimpaired persons move freely. However, most manual and powered wheelchairs are quite limited when it comes to traversing rough terrain, street curbs, ramps, and stairs.

Wheelchairs can be categorized according to their ability to traverse uneven terrain in devices for indoor use or devices for outdoor use [2], [6]. Wheelchairs for outdoor use are usually specialized products that can cross rough terrain, curbs, lower-rise steps, and ramps. Such wheelchairs usually have wider, larger-diameter wheels. However, while such wheels are beneficial for outdoor use, they limit mobility and agility in indoor environments. Therefore, typical commercial wheelchairs generally have one pair of large-diameter wheels and one pair of smaller-diameter wheels, making them more suitable for indoor use and also for traversing low curbs and shallow ramps.

The most common way wheelchair users manage stairs is to be lifted by two people while remaining in the wheelchair. This obviously works only for manual wheelchairs, which are light enough to be carried, and requires that the wheelchair user depend on outside help, ultimately limiting freedom. Hence, the mechanisms and control strategies for stair climbing are at the forefront of research in the field of electrically powered wheelchairs. Three basic designs are used for wheelchairs intended to traverse stairs [6]–[9]:

- The most common type of stair-climbing electrically powered wheelchairs feature a wheel-based design. Typically, these wheelchairs have large-diameter wheels that allow them to climb over low-rise stairs. For higher steps, developers have experimented with articulated cluster-type wheels for stair climbing [10], [11].
- Leg-based designs for stair climbing typically use a linkage mechanism that features leg-like mechanisms with attached wheels. In normal driving mode, the wheelchair moves on wheels; in stair-climbing mode, the leg mechanism is used to raise or lower the wheels between the steps [12], [13].
- Track-based designs replace the wheels with tracks [14], [15]. Compared to wheel-based designs, track-based designs are more stable on stairs and are more suitable for different stair geometries. However, track-based designs are less suitable for flat ground, limiting the user's mobility and agility.

Developers have also experimented with two hybrid designs: the wheel–leg hybrid design [16]–[18] and the wheel–track hybrid design. In the wheel–track hybrid design, wheels are used for transportation on a flat terrain, and tracks are used for climbing stairs or traversing uneven terrain [9], [19]. This design combines the high efficiency of wheels with the advantages of tracks for stair climbing [6].

Wheelchair Design

Concept

Our wheelchair is based on a wheel–track hybrid design (Figure 1) comprising five main parts: a custom-designed steel–aluminum chassis, a main drive, steering system, tracks, and a seat system. The general requirements for the size and mass of the wheelchair were that it be small enough to maneuver in confined and indoor spaces. The Cybathlon rules stipulated that the wheelchair weigh no more than 200 kg, be fewer than 90 cm wide, and have a maximum height of 71 cm at thigh level.

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For our purposes, the design of the main drive system needed to allow for comfortable driving over obstacles, be compact, and feature a simple steering system. To comply with Cybathlon rules, the wheelchair had to be capable of surmounting obstacles 6 cm high. As a result, the team used four in-wheel motors with rubber tires.

The steering system must enable sufficient maneuverability for both indoor use in confined places and outdoor use in

Figure 1. A robotic wheelchair with a wheel-track design.

crowded streets. Steering has to allow a small turning circle and utilize a simple mechanical design that does not require a significant amount of space. For the wheelchair to slalom between poles placed 140 cm apart at the competition, the maximum turning circle must be 260 cm (taking into account that the poles have a 20-cm round base). The maneuverability has to be sufficient to drive through a 120-cm wide corridor. As steering with only one pair of wheels does not meet the aforementioned criteria, four-wheel steering is required. The team selected independent steering for each wheel via an electric motor because, unlike skid steering and Ackermann steering mechanisms, independent steering is precise and requires only a small implementation space.

The prototype was designed using a compact system that allows the seat to recline, moving the center of gravity backward while maneuvering obstacles.

During initial testing, the wheels proved inadequate for a safe and comfortable climb over the stairs, so the decision was made to add tracks. The track system must provide safe and comfortable climbing over any number of stairs, not just the three stairs used on the Cybathlon track. In addition, it needs to be compact enough to fit under the chassis between the wheels and retractable to allow driving over 15-cm-high obstacles. To comply with the Cybathlon rules, the wheelchair must climb three 17-cm-high stairs with a pitch of 31°. At the same time, the system must retract enough to allow the user to drive up a ramp with a 20° inclination. To meet these requirements, the team designed retractable rubber tracks with a dedicated Chebyshev mechanism.

In general, when driving over stairs or slopes, the wheelchair tilts more than 30°, which impacts the comfort of the driver and decreases the stability of the wheelchair. To solve this problem, the prototype was designed using a compact system that allows the seat to recline, moving the center of gravity backward while maneuvering obstacles. A limitation of the adopted approach is that it requires the wheelchair to face backward while climbing stairs. Based on this limitation, the wheelchair had to be turned 180° at the top of the stairs, which was possible due to the independent four-wheel steering.

The wheelchair consists of 15 degrees of freedom (DoF) actuated by 14 actuators: 4 active DoF with in-wheel motors, 4 active DoF with steering motors, 2 active and 1 passive DoF of the Chebyshev linkage, and 2 active DoF for the left and right tracks. The seat system uses two actuators connected in parallel that actuate 2 mechanically coupled DoF (the seat's inclination and translation).

The wheelchair is controlled by an off-the-shelf industrial controller: a joystick is used to govern the wheelchair's velocity and direction, and a touchscreen enables switching between the different driving and control modes. A LiFePo4 48-V battery pack powers the motors and electronics, while an auxiliary power unit supplies all critical electronics when the main battery is disconnected. The wheelchair is equipped with safety switches for powering off the system and a master switch for powering off the battery.

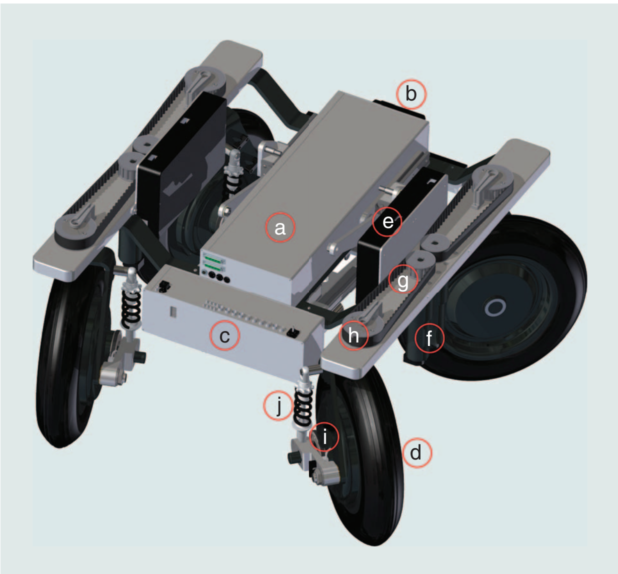

Figure 2. The power, control, and main drive system: (a) the power management box with a battery pack; (b) the electronic fuses; (c) the main controller box with the electrical connections; (d) the in-wheel motor with Hall sensors; (e) the controller for the in-wheel motor; (f) the steering motor with an incremental encoder; (g) the steering transmission; (h) the steering axis with an absolute encoder; (i) the wheel velocity sensor (magnetic encoder); and (j) the wheel suspension mechanism.

Systems

Drive System

The main drive system is depicted in Figure 2. Four active wheels with a 0.2-m radius, each with 2 DoF, one for traction (actuated by an in-wheel motor) and one for steering, provide the main driving capability. The interaxial distances are 0.58 m in the front/rear directions and 0.68 m in left/right directions. Each wheel is attached to the chassis via a passive spring-based suspension. Each in-wheel motor (Taizhou Quanshun Motor, China, Qs 10x3.0 inch 500 W 205 28 H; single-shaft hub motor, size Φ270 × 190 mm, weight approximately 13 kg) guarantees 60 N·m of peak traction torque at 48 V. The in-wheel motors are controlled through off-the-shelf motor controllers (RoboteQ MBL1660, United States) that receive commands from the main control unit via a CANopen bus and provide corresponding power to the in-wheel motors. The motor controller is equipped with several safety features, such as stall detection, speed limit, torque limit, and auxiliary power input. Safety limits are implemented on maximum velocity (2.5 m/s) and acceleration/deceleration (2.5 m/s^2). In case of a main power failure, electromagnetic braking is activated. Each traction motor is equipped with two position sensors: Hall sensors are embedded in the in-wheel motor, while magnetic encoders (LM13, RLS, Slovenia) are mounted externally. The two sensors enable smooth operation with sinusoidal control of the in-wheel motor and provide redundancy in case of sensor malfunction.

The prototype has individually steered wheels. Steering is actuated with a dc motor [Maxon Motor Switzerland, RE 50, Ø50 mm, graphite brushes, 200 W; planetary gearhead GP 62 A, ∅62 mm, 8–50 N·m, transmission ratio of 236:1; encoder HEDL 5540, 500 cycles per turn (CPT), three channels, with line driver RS 422] connected via a timing belt (transmission ratio of 32:22) to the wheel steering axis. The steering torque is limited to 100 N·m, the maximum steering angle is limited to ±45°, and the steering angular velocity is limited to 45°/s. Steering actuators equipped with a dc motor control module are directly controlled from the main control unit. Each steering actuator is equipped with two angle-measurement sensors. An incremental optical encoder attached to the dc motor is used to control the steering angle. The additional absolute magnetic encoder (RMB20V, RLS, Slovenia) is fixed to the wheel steering axis for system initialization and as a redundant safety measure.

The main drive system provides 240 N·m of total torque. With an assumed mass of 250 kg for the wheelchair and the user, the wheels provide more than enough torque for climbing ramps of over 20° inclination, and, with a good grip, the wheelchair can overcome steeper obstacles.

Track System

Two parallel rubber tracks (Thistle Special Belting, United Kingdom) are attached to an adjustable Chebyshev linkage mounted in the middle of the wheelchair (Figure 3). During wheel-based driving, the tracks are retracted and lifted from the ground. They can be lowered when driving over steep obstacles and rough terrain to provide additional traction. In this mode, the tracks are leveled with the wheels. This configuration enables the synchronous actuation of the wheels and rubber tracks, guarantees safety, and prevents the wheelchair from rolling over even on steep and uneven terrain.

Each rubber track is actuated independently (Beckhoff servomotor AM8131-0F21-0000, gearbox with a transmission ratio of 40:1). Therefore, the wheelchair can also be steered while driving on tracks. The motor torque is transmitted to the rubber track via a chain (transmission ratio of 28:16). The total rated traction force on each rubber track is 1.4 kilonewtons (kN) (peak force of approximately 3 kN). With the combined tracks' traction force, the wheelchair can climb obstacles of up to 35° of inclination (the safety limit related to system stability). Motors are equipped with velocity sensors and brakes that are released automatically when power is disconnected. Track actuators are controlled and powered by the main control unit via a servomotor controller module.

The adjustable Chebyshev linkage is actuated with two linear actuators (carts) running on the same rail. This enables the tracks' position adjustment in 2 DoF: the distance from the ground and the forward–backward position (Figure 4). The tracks' inclination relative to the wheelchair chassis is passively adjustable, allowing the tracks to follow the configuration of the terrain below. The tracks' basic position (when the tracks are parallel to the chassis) is defined by cart positions p_1 and p_2 (see Figure 4):

$$p = p_2 - p_1$$

$$h = \sqrt{r^2 - \frac{1}{4}(p+q)^2} + h_1 + h_2,$$

where h is the distance from the chassis to the tracks. A threaded spindle (SKF SD 14X4R, 4-mm pitch) actuated with the same dc motor (Maxon motor RE 40 ∅40 mm, graphite brushes, 200 W; planetary gearhead GP 42 A ∅42 mm, transmission ratio 26:1; encoder HEDL 5540, 500 CPT, three channels, with line driver RS 422, Maxon Motor,

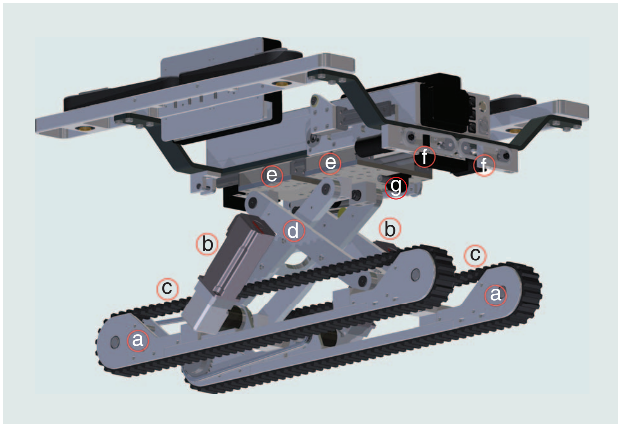

Figure 3. The track system: (a) the tracks' guiding mechanism; (b) the tracks' actuator with an absolute encoder; (c) the rubber tracks; (d) the Chebyshev-like tracks' height adjustment mechanism; (e) the rail and cart mechanism for the tracks' height and position adjustment; (f) the tracks' position adjustment actuator with an incremental encoder; and (g) the cart wire potentiometer.

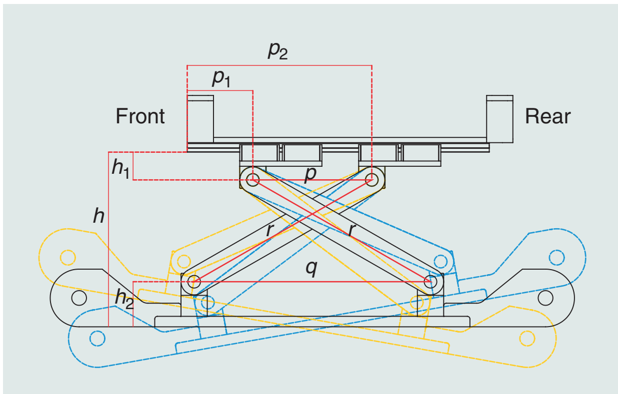

Figure 4. The adjustable Chebyshev linkage kinematics.

Figure 5. The seat system: (a) the seat, (b) arm rest, (c) footrest, (d) seat position linear guide, (e) seat inclination mechanism and coupling with position adjustment, and (f) seat position and inclination actuator.

Switzerland) moves each linear actuator. The actuator generates 5 kN of peak force with a maximum movement speed of approximately 20 mm/s. The actuator is equipped with two position sensors. An optical encoder is mounted directly onto the dc motor, and a wire potentiometer measures the displacement of the cart for initialization and redundancy. All active DoF of the tracks' mechanism are directly controlled from the main controller.

Seat System

The pilot's seat, with integrated user interface in the armrest for control of the wheelchair, provides comfort and safety for the user (Figure 5). The right-side armrest is equipped with a joystick and a touchscreen, while an emergency button is inserted into the left-side armrest.

The seat can be actively moved via two mechanically coupled DoF that enable simultaneous backward translation and reclining of the seat relative to the chassis. The backward translation shifts the overall center of gravity to the rear of the wheelchair when ascending and descending steep obstacles (the user faces in a downward direction while traversing obstacles with inclinations steeper than approximately 20°). In most circumstances, the reclining seat keeps the user leveled. Seat kinematics is defined as follows (see Figure 5):

$$\varphi = \alpha - \beta - \arccos\frac{l_1^2 + l_5^2 - (s_0 + s)^2}{2 l_1 l_5}$$

$$\vartheta = \arcsin\frac{l_2 \sin\varphi - l_4}{l_3}$$

$$d = l_3 \cos\vartheta - l_2 \cos\varphi - d_0,$$

where ϑ is the seat inclination and d is the change of seat position. The seat is actuated with two parallel nonbackdrivable linear actuators (Timotion series TA2, Taiwan). Each motor generates 750 N of thrust force at the maximum speed of 11 mm/s. The motors are equipped with Hall-based position sensors having a resolution of 0.1 mm/count. The parallel configuration provides 1,500 N of force and mechanical as well as sensory redundancy. Both actuators are directly controlled from the main control unit equipped with a dc motor control module.

Power Management

All wheelchair systems are powered from a power pack, which is capable of outputting several different voltage levels: 48 V (maximum current 120 A), 24 V, 5 V, and 12 V for auxiliary power source. The power pack is contained in an aluminum housing mounted beneath the chair system and includes the main power battery cells, the auxiliary battery cells for the low-power uninterruptible power supply (UPS), the battery management systems, the dc–dc converters, the power relays, the fuses, a liquid crystal display status indicator, the thermometer, and the current sensors. The main power source is a battery pack, which contains 14 LiFePo4 cells (AMP20M1HD-A, A123 Systems) with 3.3-V nominal voltage per cell, resulting in a battery nominal voltage of 46.2 V. The cell capacity is 20 Ah at nominal voltage. The battery of the main power supply is charged with an external charger through a battery management system module programmed to limit the maximum battery voltage to 49.7 V. All wheelchair motors are powered with the main power supply. The main controller requires a 24-V power supply source, and most sensors operate at 5 V; hence, the battery voltage is converted to lower voltage outputs by two dc–dc converters. The battery system also includes power relays for switching off the battery pack subsystems. The dead man's switch and emergency buttons are connected to the main power relay and switch the power on/off for all motors. A low-power UPS powers the wheelchair electronics when the main power supply is disconnected. The UPS specifically provides power to the in-wheel motor controllers. In case of a main battery failure, the UPS enables magnetic breaking by short-circuiting all three phases in the motor controllers.

Control System

The wheelchair control is implemented on a standard industrial controller (Beckhoff CX5130-0120) with expansion modules for analog/digital inputs/outputs and motor control. The control system block diagram is shown in Figure 6. The blue blocks in Figure 6 represent the controller modules, the gray blocks represent various motors, the light red blocks represent the power system, the dark red blocks represent the safety system, and the orange blocks represent user interfaces.

The main inputs from the user controlling the wheelchair come from a joystick and a graphical user interface (GUI). The analog values from two potentiometers, of the 2-DoF joystick connected to the Beckhoff EL3068 analog inputs terminal, represent a reference for the direction and velocity of the wheelchair. The GUI is displayed on a touchscreen display mounted beside the armrest. By selecting the appropriate mode, users can initialize different wheelchair components, select driving modes, select modes for stair climbing, adjust the seat or track pose, and change the values of various parameters.

The four in-wheel motors are controlled with dedicated RoboteQ motor controllers that receive velocity references from the main controller. Closed-loop velocity control of the in-wheel motors is implemented on the RoboteQ controllers, which receive position signals from Hall sensors embedded into the wheels and magnetic encoders mounted externally on the wheels. Other motors are controlled directly from the main controller through dedicated modules.

Two Beckhoff EL3068 modules enable sampling of 2 × 8 single-ended analog voltages (0–10 V) with 12-b resolution. The modules enable signal acquisition of four absolute encoders for steering, two wire potentiometers for positioning of the carts of the Chebyshev linkage, and the 2-DoF joystick. Four steering motors are position-controlled and receive references from joystick inputs. The dc motors are powered and controlled via four Beckhoff EL7342 dc motor driver modules, each controlling two dc motors (four steering motors, two Chebyshev linkage actuation motors, and two seat linear actuators). The Beckhoff EL1008 module enables sampling of eight digital inputs with a nominal voltage of 24 V dc. The battery status signal and four seat motor limit switches are connected to this module. Furthermore, to change the current control mode into initialization mode, the dead man's switch and emergency buttons are also connected to this module so that information about the state of the shut-off mechanisms is also available to the main controller. Two Chebyshev linkage actuation motors and two seat linear actuators are position-controlled and receive automatically generated references from the main controller. References are generated depending on the drive mode selected by the user on the GUI. To control the left and right tracks independently, the wheelchair uses two Beckhoff EL7211 servomotor EtherCAT modules with integrated resolver interfaces. The tracks are velocity-controlled, with the velocity references generated by the user through the joystick.

As a safety precaution, two emergency stop buttons are mounted on the wheelchair. Both buttons are easily accessible; one is integrated on the pilot's left side arm rest and the other on the left side of the wheelchair, which is also easily accessible for an accompanying person. The buttons are connected in series; in case of emergency, the power relay is triggered, disabling the main power for the motors and activating the brakes.

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Driving Modes

The high-level control scheme is organized into several driving modes [8], [9], which can be selected through the GUI. The driving modes are organized based on the selected main driving system: wheels or tracks. Figure 7 shows the stateflow of the high-level control and the driving modes.

The user can select different driving modes on the GUI through the touchscreen display. This enables the user to freely select and fully control the behavior of the wheelchair and thus adequately respond to a given task. The joystick is used as a reference input that provides intuitive and natural control of the wheelchair. The touchscreen and joystick proved to be a useful combination for control of the multimodal system.

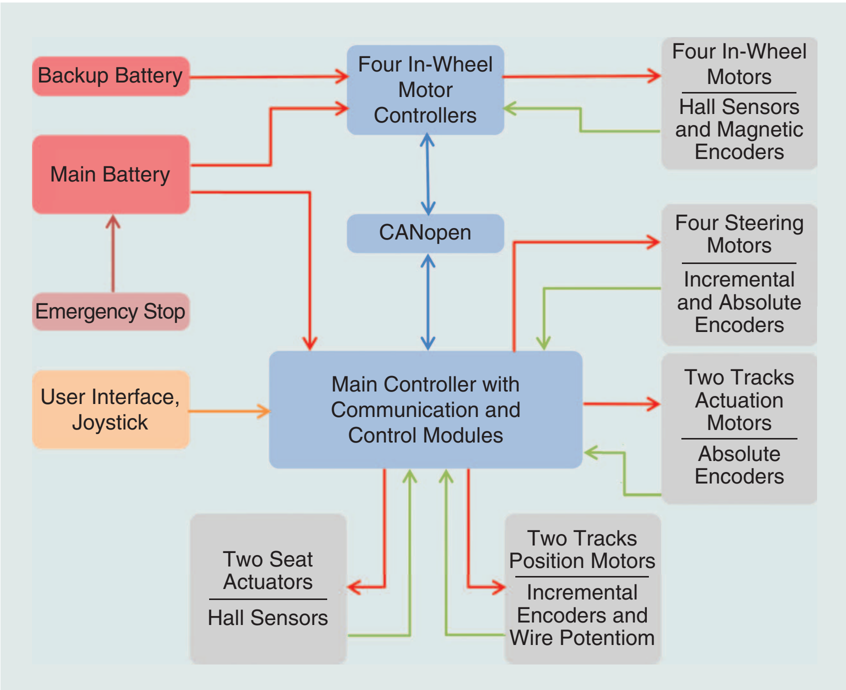

Figure 6. A block diagram of the power and control system.

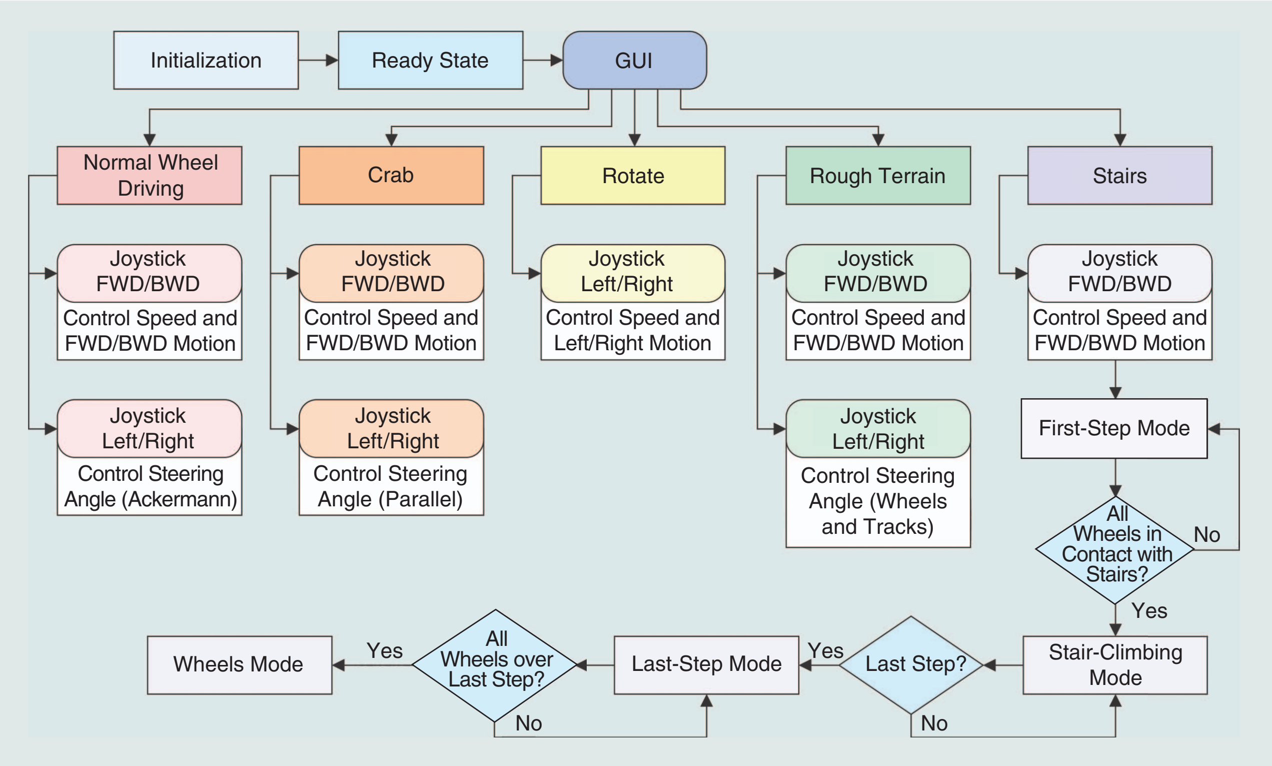

Figure 7. A stateflow diagram showing the driving modes of the high-level control. The stateflow starts with the initialization state, which is followed by the ready state. In the ready state, a GUI allows the user to select an appropriate driving mode (listed in rectangular blocks in the second row of the stateflow). After selecting the driving mode, the user then uses the joystick to control the relevant DoF. FWD: forward; BWD: backward.

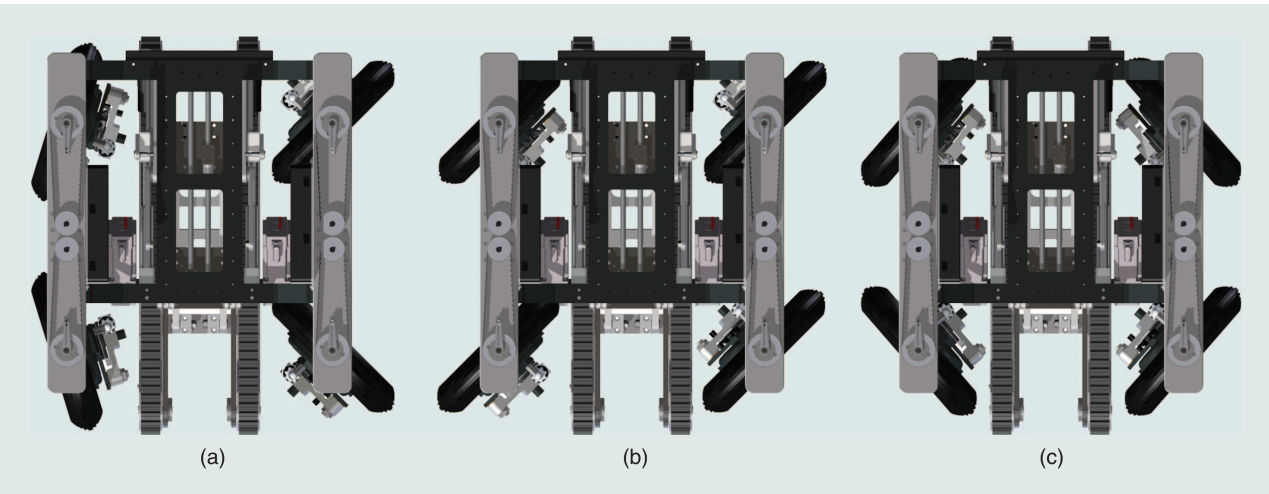

Figure 8. The different configurations for steering the wheels: (a) four-wheel steering with a small turning radius (Ackermann geometry), (b) crab steering, and (c) turning in place.

Wheel-Based Driving Modes

With four individually steered wheels, the user can choose between several driving modes (the options shown in Figure 7). The most common mode is the normal wheel driving mode [see Figure 8(a)], with wheels that provide traction torque and wheelchair maneuvering implemented as a four-wheel steering based on the Ackermann principle [20]. The wheels' relative velocities depend on the steering angle. Such a configuration enables steering with the smallest turning circle of 1.83 m (the outer diameter of the full turn). Two-wheel steering concepts are simplifications of the four-wheel steering. In this case, steering can be implemented on the front or rear wheels only. An analog value from left/right movement of the joystick is used as a turning circle reference, while the forward/backward movement of the joystick serves as a velocity reference [6]. The user can also choose low speed (top speed 4 km/h) or high speed (top speed 8 km/h) via the GUI.

In crab mode [see Figure 8(b)], all four wheels are rotated in the same direction and at an equal steering angle, which enables a crab-like motion. With the same speed from all wheels, the wheelchair drives in a straight line but at an angle relative to the front-rear axis. The control is designed in a way that the left/right movement of the joystick represents a reference for the wheels' steering angle (the maximum angle is 45°), while, for the velocity reference, the forward/backward DoF of the joystick is used. This type of motion is useful when the wheelchair's position needs to be changed while the orientation is already set and enables an easier approach to objects such as tables and walls, e.g., while driving up a loading ramp.

The third mode is the rotate mode [see Figure 8(c)]. In this mode, the steering mechanism rotates the wheels diagonally in parallel (steering angle of ±40.5°) so that all four wheels are set tangentially to a circle with its center in the middle of the wheelchair. The left/right movement of the joystick represents a reference for direction and velocity of rotation. This mode is very useful for maneuvering in a tight space, e.g., in elevators or narrow hallways.

Stairs Mode

The most demanding obstacle in the everyday life of wheelchair users is stairs. Stairs are problematic because they are steep and uneven, making it difficult to find a solid point of stability and provide the power/friction necessary for safe, effective climbing. The first and the last step represent the transition from flat ground to steep inclination and vice versa; as such, the stair-climbing protocol consists of five stages. The position of the tracks is preprogrammed at each stage, ensuring a safe and stable transition. The user can select the proper stage via the GUI.

The wheelchair climbs stairs backward [10], [11], while descending is performed forward. Figure 9 shows the procedure for stair descending; for ascending, the procedure is reversed. First, the user approaches the stairs and selects the stairs mode, which couples the tracks and wheels [see Figure 9(h)]. At the same time, the front of the tracks is lowered, enabling the user to set the end of the track on the first stair. The seat is moved to the reclined position, which shifts the center of mass to the back of the wheelchair. Then, the user drives the wheelchair backward until the rear tire is in contact with the first step. At this point, the position of the tracks is changed so that they are lowered, while the back of the wheelchair is raised and the rear wheels are over the first step [see Figure 9(g)]. The platform is moved backward until both wheels are in contact with stairs when the normal stair-climbing mode is selected. In this step, the position of the tracks is adjusted so that the seat is parallel with the ground. The tracks are in full contact with the stairs, providing sufficient grip for stair climbing. The additional DoF in the Chebyshev

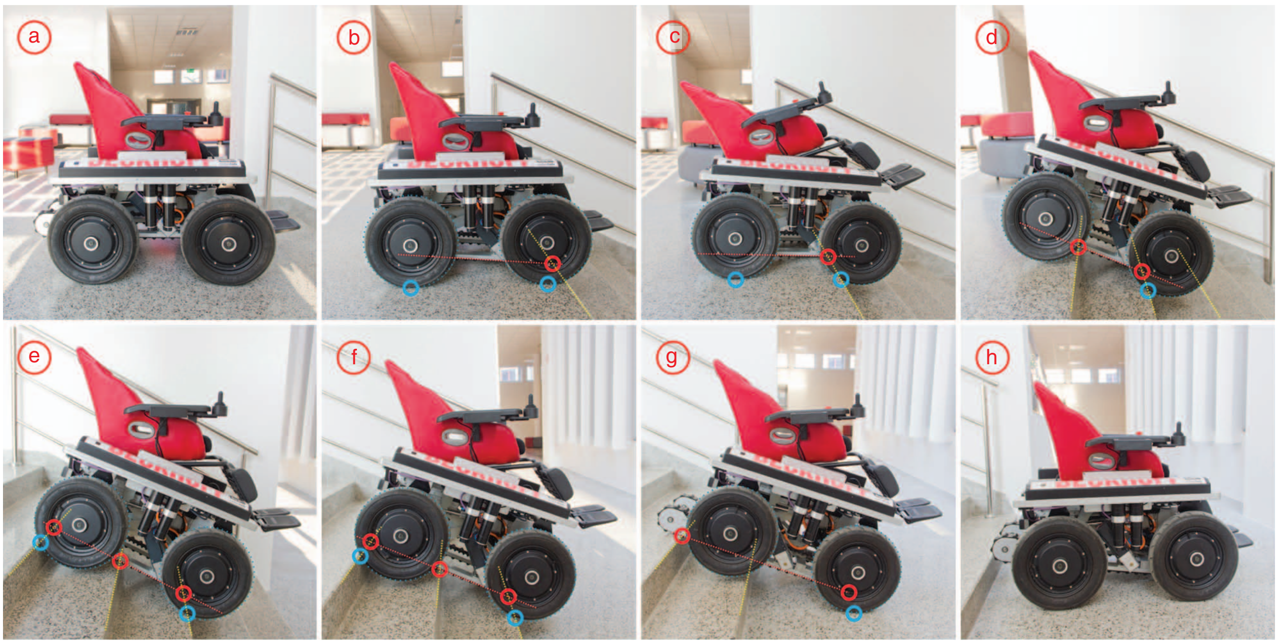

Figure 9. The stair descent. The blue circles represent the contact between the wheels and the stairs; the red circles represent the contact between the tracks and the stairs; the yellow dashed lines represent the stair edges; the red dashed lines show the right track surface; and the dashed circles represent the right wheels. The drive stages for stair descent are as follows: (a) The user drives the wheelchair to the stairs; (b) the tracks are lowered and coupled with the wheels; (c) the seat inclination is changed to move the center of mass backward, and the front wheels are driven to the first stair; (d) after the first stair, the pose of the tracks is modified to ensure good contact between the wheels, tracks, and stairs; (e) a free rotation in the track pose mechanism ensures soft transfer over stairs, and the wheels are in contact with the stairs at all times for additional stability. When the front wheels are over the last step, the tracks are moved (f) and (g) backward and upward to enable a soft transfer from the stairs to flat ground; (h) when the wheelchair is over the stairs, the tracks are raised, and the seat is moved to the initial position, at which point the wheelchair is ready for driving.

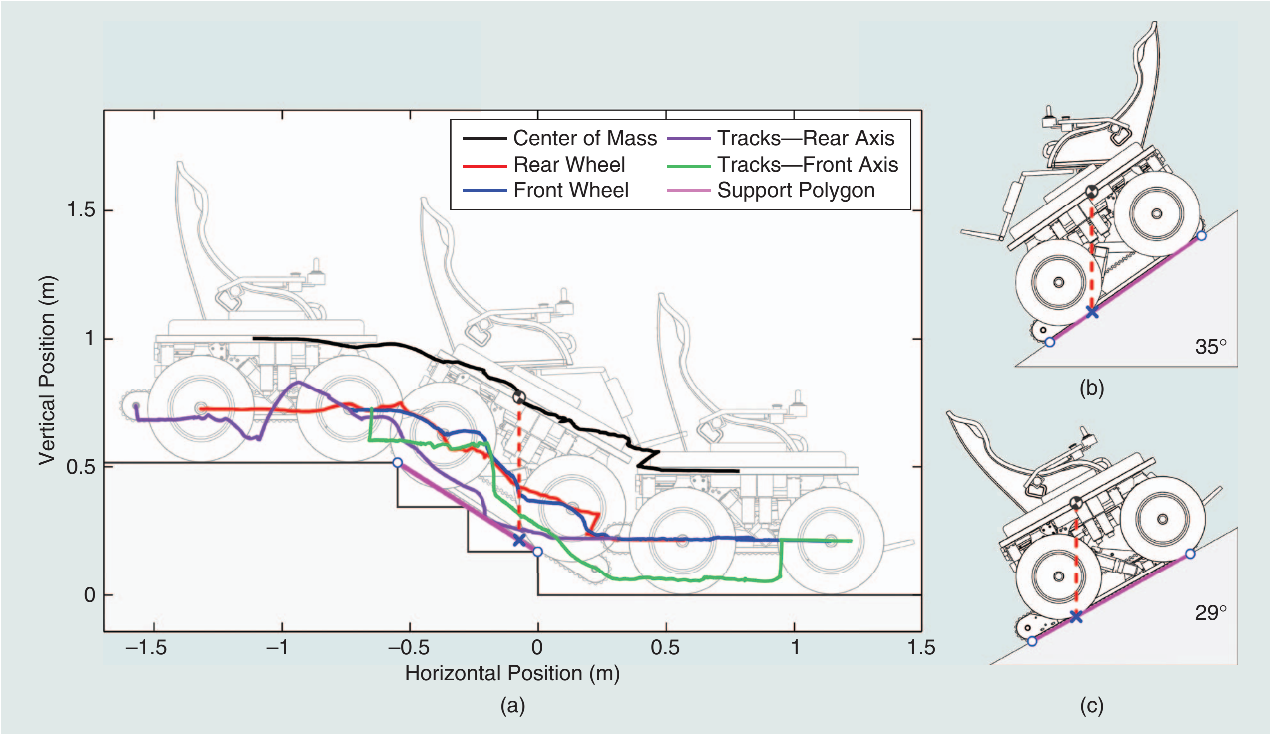

Figure 10. (a) The typical courses of the wheelchair and the user center of mass, front/rear wheel axes, and front/rear track axes during stair climbing. The middle position of the wheelchair presents the case with minimum stability margin (approximately 7 cm), where the blue cross denotes the projection of the center of mass on the support polygon. The maximum tested inclinations for (b) backward (35° of inclination) and (c) forward (29° of inclination) driving are also shown.

mechanism enables the platform to automatically adjust to the inclination so that the wheels are in constant contact with the stairs to provide additional safety. In this mode, the user can climb any number of stairs [see Figure 9(e) and (f)]. At the last step, the back of the wheelchair is lowered to ensure a smooth transition from inclined to level driving, while additional rotation transfers the tracks parallel to the ground [see Figure 9(c) and (d)]. Once over the stairs, the user lowers the seat to the initial position and can use the rotate mode to reorient the wheelchair and continue his or her driving [see Figure 9(a) and (b)].

The wheelchair development was organized as a student project, during which students could gain experience under the supervision of senior mentors (professors and teaching assistants).

Experimental Results

Figure 10 shows the trajectories of the wheelchair's center of mass, wheels, and tracks during stair climbing. A set of stairs with the same parameters as in the Cybathlon competition was built in the laboratory for testing and training. Data were measured using an Optotrak optical tracking system. Optical markers were attached to the tracks and the wheelchair chassis. Markers were also attached to the stairs to calculate the exact relative position between the wheelchair and the stairs. The trajectories shown in Figure 10(a) were then calculated from the marker trajectories. In addition to the stairs, a ramp with an adjustable inclination was built to test the chair's stability and traction on an incline. Experiments on the ramp have shown that the maximum inclination is 35° for backward driving and 29° for forward driving. In both cases, the stability margin is approximately 25 cm, indicating high stability of the wheelchair. Higher inclinations were not tested due to insufficient traction on steeper inclinations.

Rough Terrain Mode

While driving on a rough or demanding terrain, the tracks are lowered to ground level to provide additional support and traction. The velocity of the wheels is synchronized with the tracks' velocity. The combination of wheels and tracks provides maximum friction and power to move the wheelchair over an obstacle.

Competition

Team Organization/Structure

The wheelchair development was organized as a student project, during which students could gain experience under the supervision of senior mentors (professors and teaching assistants).

The student group typically consisted of around 15 students (overall approximately 30 students participated in the project). Students, who took responsibility for assigned tasks under the oversight of a student project leader, were organized into teams. Tasks were divided into three groups:

- *Administrative and management tasks:* A Gannt chart was devised to help the students maintain a specific schedule, and several important milestones were defined at the start of the project. The student leader was responsible for the administrative work and coordinating tasks among the other students.
- *Design and development tasks:* The wheelchair was divided into subcomponents, and students organized themselves into smaller teams responsible for the design, construction, assembly, and development of the control of the individual components and mechanisms of the wheelchair.
- *Fundraising tasks:* The development of the wheelchair was funded by sponsors, and funds were raised by students. The students managed communication with sponsors, produced promotional materials, and managed website and social media pages.

Figure 11. The wheelchair on a tilted path obstacle at the 2016 Cybathlon competition. (Photo courtesy of ETH Zürich/ Alessandro Della Bella.)

Competition Experience

While development of the wheelchair began in 2014, the system design was partially aligned with the requirements for the international Cybathlon competition, which took place in Zürich, Switzerland, in October 2016. The competition's goal is to demonstrate the latest assistive technologies that help people with physical disabilities in everyday life.

The competition and its challenging track served as a good test of wheelchair performance. The wheelchair had to meet the competition requirements, such as safety regulations, maximum mass, and dimension limitations, but at the same time it had to overcome the competition obstacles. The competition race track consisted of the most common obstacles found in the everyday lives of people with physical disabilities: driving with half the driver's thigh under a table, a slalom course around poles, driving up and down a ramp with the door opening and closing, driving over rough terrain, driving over a tilted path (Figure 11), and traversing three stairs up and down.

Experimental tests performed prior to the competition on a testing track built at the Laboratory of Robotics confirmed that the wheelchair can safely traverse most common obstacles and all of the obstacles on the Cybathlon track. In fact, the large-diameter (40-cm) wheels allow traversing obstacles 10-cm high (e.g., curbs). Nevertheless, the wheelchair is low enough that the user can fit with his or her thighs under a table. For additional accessibility, a joystick is mounted to a passive mechanism and can be rotated to the side of the armrest so that the user can move as close to the table as possible. The center of mass of the wheelchair without the user is 30 cm from the ground, and it is 48 cm with a user weighing 80 kg. This results in excellent stability on sloped terrain and stairs. The theoretical stability margin for driving sideways on a sloped terrain is 38°, while the theoretical limit for driving with lowered tracks and a nonreclined seat is 29° up the slope and 35° down the slope. However, in practice, driving on a slope of more than 20° in a nonreclined seat becomes uncomfortable. Therefore, in practical experiments, the wheelchair was tested driving sideways on a slope of 20°; due to the four in-wheel motors, it can safely climb a slope of 20° even without the tracks being lowered. Furthermore, using the tracks, the wheelchair can climb most common public stairs (17-cm high, 28-cm long, with a pitch of 31°). The theoretical stability margin for climbing stairs backward with a fully reclined seat is 41° (stairs' pitch). Due to the independent steering of all four wheels, the wheelchair can turn around in a very confined space, such as in a corridor 120-cm wide. The wheelchair also has a small turning circle, so it can slalom around obstacles positioned 110 cm from each other. The total mass of the wheelchair without the user is approximately 160 kg.

Our team overcame all obstacles and won a bronze medal in a timed wheelchair competition.

Conclusion and Future Work

Electric-powered wheelchairs are practical and efficient assistive devices for people with movement disabilities. However, architectural barriers, such as curbs, ramps, and stairs, present a major challenge for users of electric wheelchairs. We have presented the concept of a hybrid wheelchair with efficient mobility and maneuverability in both indoor and outdoor environments using large-diameter in-wheel motors with independent steering mechanisms for each wheel. The wheel-drive concept was augmented with tracks for stair climbing, which allows the climbing of an arbitrary number of steps. A Chebyshev-based linkage mechanism was designed for lifting and lowering the tracks. Finally, a seat with 2 coupled DoF allows safe and comfortable stair climbing by moving the center of gravity backward for better stability on the stairs and by reclining the seat so that the user is comfortably level with the ground. The wheelchair won the bronze medal at the Cybathlon competition, demonstrating its capabilities and effectiveness.

However, there are limitations to our approach that will need to be addressed in future development of the wheelchair. Currently, the wheelchair is fully controlled by the user without any autonomy. Therefore, we plan to implement algorithms for autonomous stair climbing and obstacle avoidance. Also, in the current state of our wheelchair design, the user still needs to possess sufficient cognitive, neuromuscular, sensory, and perceptual capabilities to safely control the wheelchair in a complex environment with a joystick. Users who are not capable of doing this require an assistant to help them. In this regard, future work will be focused in two directions: 1) the development of more natural and intuitive interfaces and 2) shared/collaborative control between the user, smart wheelchair control algorithms, and an accompanying person.

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