Stair-climbing wheelchair.q05: from the concept to the prototype

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Abstract. In this paper, an electric stair-climbing wheelchair, named wheelchair.q05, able to move on flat ground and to climb stairs, is presented. The proposed solution has been developed through a series of studies and designs, all based on a smart hybrid triple leg-wheel locomotion unit. The stability of the device is guaranteed by a rear support of a pair of pivoting wheels during motion on flat ground, and by the support of an idle track, when climbing on or going down stairs. By means of mechanisms and actuators, it is possible to change the configuration of the wheelchair, from the flat ground motion to the stair climbing configuration.

Keywords: stair-climbing wheelchair, mobile robot, sidewalks overcoming, mechanism design, architectural barriers.

1 Introduction

Steps and stairs represent an important restriction on the mobility of wheelchair users, whose number is growing rapidly [7]. The problem can be alleviated, on the one hand by breaking down the architectural barriers with structural modifications, on the other hand with the development of devices able to climb single steps or staircases.

Regarding the last approach, currently, few solutions are available on the market or among prototypes and patents. Moreover, most of them are bulky, heavy, complex, difficult to use, not appealing. From a mechanical point of view, different locomotion systems are used. In [1] and [20] wheelchairs with a legged locomotion are presented. Using legged locomotion allows the highest climbing capability but requires a complex control and high energy consumption. In [22] and [23] a hybrid wheel-track solution is proposed. It combines the effectiveness of wheels during flat ground motion and the regular motion of the track during stair-climbing. The main weakness is represented by the low efficiency of the track and, consequently, by the high energy consumptions. In [2, 5, 6] a hybrid leg-wheel locomotion is proposed. High performances in any working conditions are guaranteed by the efficiency of wheel motion on flat ground and the effectiveness of leg during obstacle climbing. Finally, in [3, 5, 21] a hybrid leg-wheel solution with a rotating leg locomotion system is presented. This solution allows obtaining an effective behavior with a reduced complexity in the control and sensing system. Starting from this analysis, the authors have developed a series of concept of stair climbing wheelchair [8-19], aimed at overcoming the weaknesses of the current solutions. In particular, efforts have been addressed to reduce the mechanical complexity, simplify the control system, and ensure a safe and comfortable climbing sequence.

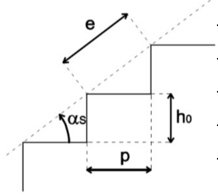
In the paper, the entire design process of the last solution (Wheelchair.q05), from the concept to the prototype, is presented. First, the design requirements are discussed. Then the concept of the wheelchair is described, the functional and detailed design is illustrated, and finally the prototype is shown.

2 The design requirements

The stair climbing wheelchair must be able to move in indoor and outdoor environments and climb stairs or single steps, for example sidewalks, in order to satisfy the mobility needs of people with walking problems.

The synthesis of the wheelchair mechanisms must be conducted with the aim of realizing a device according to safety requirements expressed in ISO 7176-28:2012, “Requirements and test methods for stair-climbing devices”, able to climb both stairs according to UNI10804 (types *public* and *main-private*, Table 1) and staircase with low slope, typical of outdoor environments. In addition, the wheelchair must be able to overcome sidewalks using forward motion, both during ascent and descent phases.

Table1. Stair dimensions according to UNI 10804.



	p	h_0	α_S	e
	mm	mm	°	mm
Low slope	350	145	22.5	379
Public	300	170	29.5	345
Main private	250	190	37	314
Nominal slope	221.3	166.8	37	277.1

Table2. Design parameters of the wheelchair.

Maximum transportable mass	80-100 kg
Maximum Wheelchair mass	80 kg
Maximum width	0.65-0.7 m
Maximum length	1.3 m
Maximum velocity on flat ground	10 km/h
Maximum slope of ramp	10°
Maximum velocity on ramp	5 km/h
Stair climbing time	5 s/step
Maximum height of the staircase step	240 mm
Maximum height of the step moving forward	200 mm

Other design parameters, concerning masses, dimensions and performances are summarized in Table 2. The maximum length of the wheelchair must be limited, in order to allow effective indoor motion and easy pass through the doors. The maximum velocity during motion on flat ground must be comparable with that of current commercial solutions, ensuring adequate mobility in outdoor environments. The maximum velocity during motion on ramp is reduced compared to that on flat ground.

3 Concept and functional design of the wheelchair

The wheelchair (Figure 1) is composed by four main functional elements: a locomotion group and traction system (1); a sub-frame connected to the seat with actuation system (2); an idle track with actuation system (3); the pivoting wheels group with actuation system (4). During motion on flat ground, the stability of the wheelchair is guaranteed by the contact to the terrain of the wheels of the locomotion group and of the pivoting wheels group (Figure 1a). In the stair climbing configuration, the stability is assured by the contact of the wheels of the locomotion group to the step tread, and of the idle track to the edge of the steps, along to the pitch line of the stairs (Figure 1b).

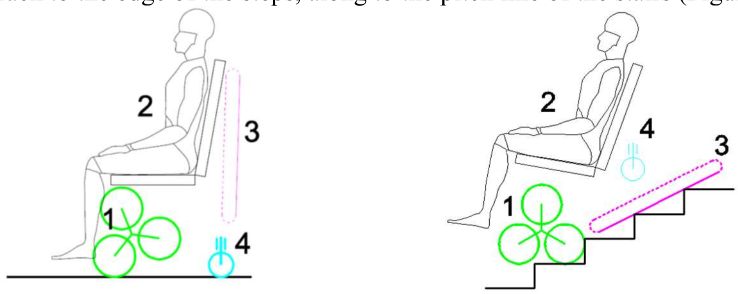


Fig. 1. wheelchair's functional elements configurations: a) on flat ground; b) stair climbing

The relative positon of the functional elements must therefore be changed, depending on whether it is in the flat ground configuration or in the stair climbing configuration. For this purpose, the kinematic architecture depicted in Figure 2 has been chosen: two sub-frames, PCD (red) and CER (blue) are connected by a hinge in C.

The locomotion group PW (green), hinged in P, and the arm supporting the pivoting wheels DU (cyan), hinged in D, are linked to the first sub-frame PCD.

The second sub-frame CER supports the chair, and in E is hinged the arm ES (fuchsia), in turn hinged to the idle track in S.

The choice of the kinematic architecture with two sub-frames is due to two main functions. First, to compensate the oscillations transmitted to the user by the rotation of the locomotion group when overcoming the step, like widely discussed in [17]. Secondly, to ensure the correct position of the center of mass with respect to the ground-step contact points and so to guarantee the stability, in all the using conditions.

The wheelchair is equipped with mechanisms and actuators, able to regulate the angle between the sub-frames (Figure 3), the position of the idle track respect to the sub-frame CER (Figure 4), the position of the pivoting wheels group respect to the sub-frame PCD (Figure 5), whose detailed design will be summarized in the next section.

The planar linkages synthesis addressed to relative motion generation has been conducted considering on the one side the requirement of the stability of the wheelchair in all operating conditions, and on the other side the requirement of the relative positioning of the functional elements in the reconfiguration operations of the wheelchair (motion on flat ground or stair climbing configuration).

For the sake of brevity, the Figures 3-5 show the extreme positions of the range of motion, and an intermediate position commonly used. In the Table 3 the values describing the range of motion, calculated considering the reference frames shown in Figure 6, are listed.

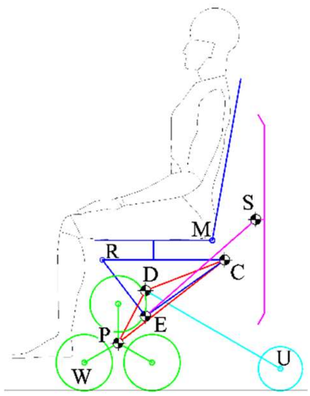


Fig. 2. Architecture of the wheelchair. Locomotion group PW (green); sub-frame PDC (red); sub-frame ECR (blue); idle track group ES (fuchsia); pivoting wheels group DU (cyan).

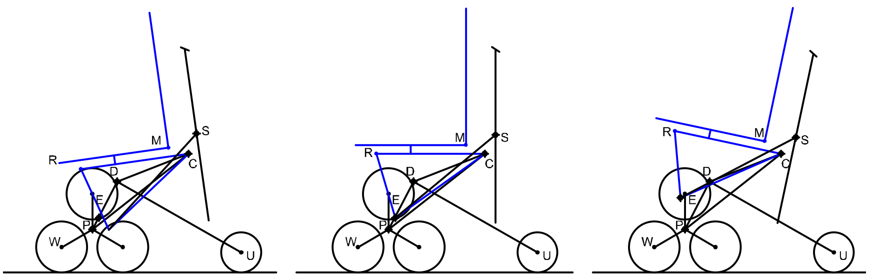


Fig. 3. Range of motion of the sub-frames

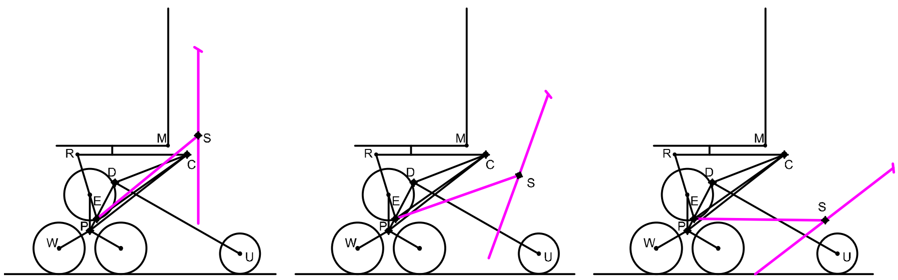


Fig. 4. Range of motion of the idle track group

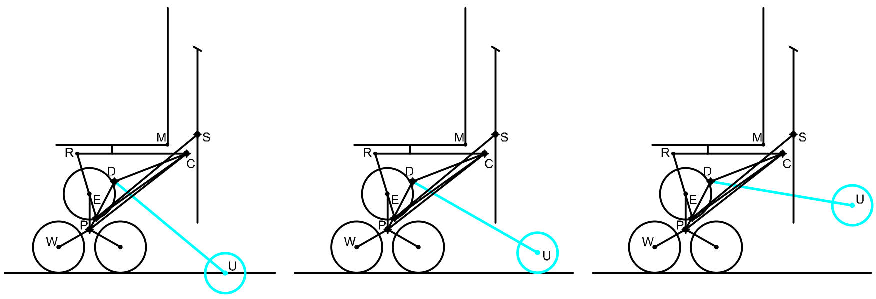


Fig. 5. Range of motion of the pivoting wheels group

Table3. range of motion.

d.o.f.	description	range of motion
$\boldsymbol{\beta}$	sub-frame PCD /sub-frame CER	29 ÷ 47 °
$\boldsymbol{\vartheta_{DU}}$	sub-frame PCD / link DU	10 ÷122 °
$\boldsymbol{\vartheta_{ES}}$	sub-frame CER / link ES	-4 ÷ 30 °

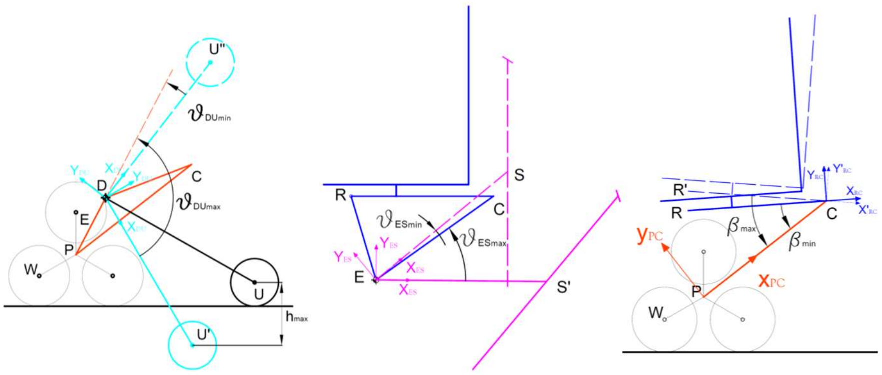


Fig. 6. Reference frames and ranges of motion

The stair climbing wheelchair is based on a smart hybrid leg-wheel locomotion group [9], consisting of two locomotion units, equipped with three rotating legs each with a wheel at the end (Figure 7a). The arms of the tripod constitute the planet carrier (1) of an epicyclical mechanism, in which the central solar gear (2) transmits the motion, by means of three idle gears (3), to three planet gears (4) coupled to the three wheels (5).

Each locomotion unit has two degrees of freedom (d.o.f.): the rotation of the planet carrier with respect to the sub-frame PCD and the rotation of the wheels with respect to the planet carrier. The first d.o.f. corresponds to the steps-climbing motion, the second d.o.f. is related to motion on flat ground .

In order to control all d.o.f. of the locomotion group in all conditions, the solution depicted in Figure 7b has been chosen.

Two independent gear motors (M_{SR}-R_{SR} and M_{SL}-R_{SL}) actuate the solar gears respectively of the right and left locomotion units, while the planet carrier of both tripod are driven by a further gear motor (M_P-R_P), by means of a toothed belt transmission. During the stair climbing motion, i.e. in the execution of the most difficult task, the three gear motors cooperate, allowing the limitation of the maximum power required for each actuator, and then reducing weight and dimensions.

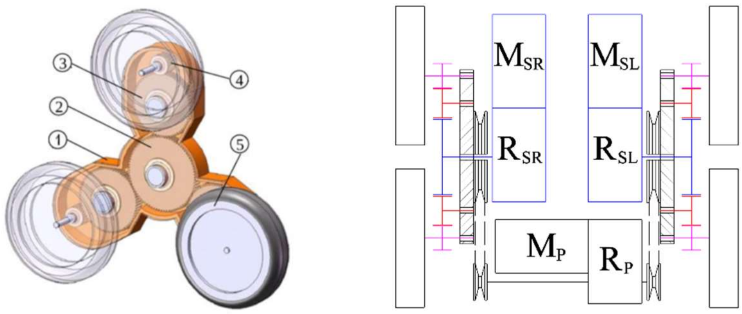


Fig. 7. Functional scheme of the locomotion group: a) the single locomotion unit; b) general arrangement drawing

4 The detailed design

Starting from the concept and the functional design of the wheelchair, described in the previous sections, the detailed design of the device has been developed (Figure 8).

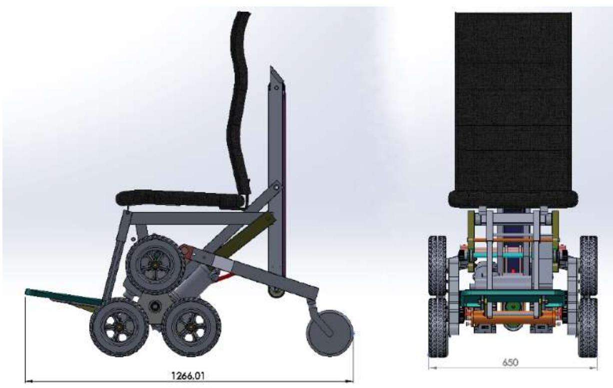


Fig. 8. Detailed design of the wheelchair.q05

In Figure 9a the detailed design of the locomotion unit is shown. Two identical locomotion units where assembled in order to realize the locomotion group, as shown in Figure 9b.

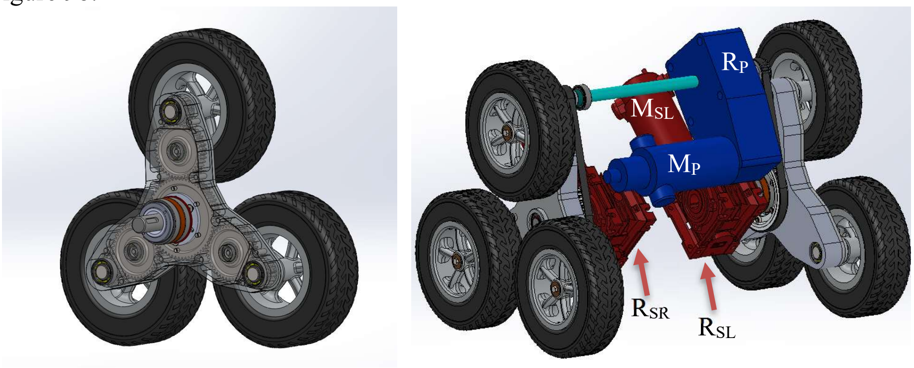


Fig. 9. Detailed design of the locomotion group: a) locomotion unit; b) general arrangement drawing

The detailed design of the sub-frames PCD-CER and relative actuation mechanism is reported in Figure 10a. For sake of clarity, the right side of the sub-frame PCD is not represented. The transmission mechanism scheme is shown in Figure 10b.

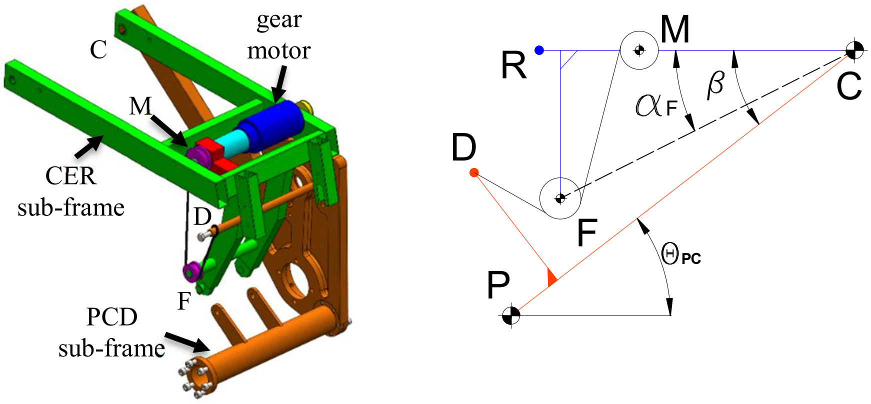


Fig. 10. Sub-frames and movement mechanisms: a) Detailed design b) Kinematic scheme

The detailed design of the idle track group actuation mechanism is reported in Figure 11a. The track is free to rotate around the hinge S of the SE link. The rotation of the SE link around the hinge E is actuated by means of a linear motor hinged to CER and SE sub-frames.

Finally, in Figure 11b is depicted the detailed design of the pivoting wheels group. In this case has been employed a ball screw and nut transmission mechanism, actuated by a gear motor.

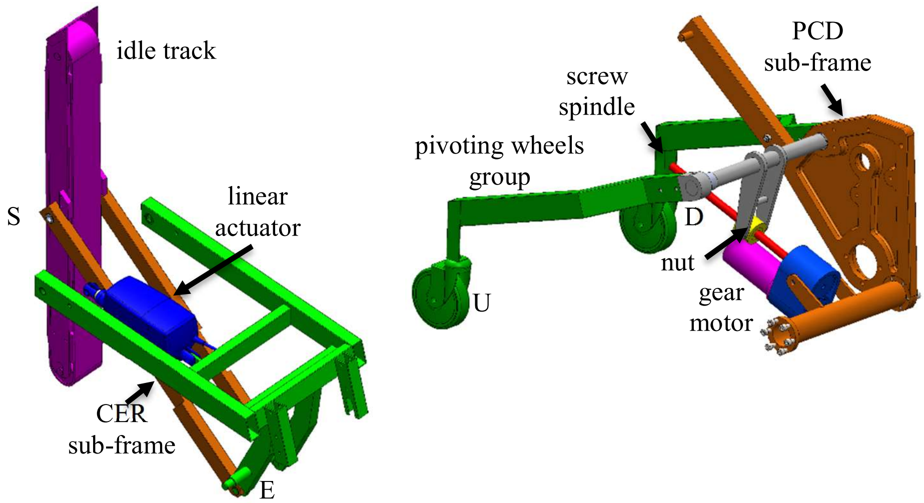


Fig. 11. Detailed design: a) idle track group; b) pivoting wheels group

5 The prototype and preliminary experimental tests

Starting from the detailed design described in the previous section, a first prototype of the wheelchair has been realized. The functionality of the prototype has been evaluated in preliminary experimental tests.

Figure 12 shows the sequence of a single step climbing: 1) the wheelchair, in flat ground motion configuration, advances until the front wheels of the locomotion unit (L.U.) reaches the riser of the step; 2) the rotation of the L.U. begins; 3) the front wheels of the L.U. touch the tread of the step; 4) the rotation of the L.U. is stopped; 5) the wheelchair advances on the new tread; 6) the center of mass of the wheelchair is repositioned in such a way that its projection falls between the wheels of the L.U. in contact with the ground, then the pivoting wheels group is lifted; 7) the wheelchair advances on the new tread; 8) the flat ground motion configuration is restored.

Figure 13 shows the stair climbing sequence: 1) the wheelchair approaches the staircase in backward motion; 2) the center of mass of the wheelchair is repositioned in such a way that its projection falls between the wheels of the L.U. in contact with the ground and the pivoting wheels group is lifted; 3) the idle track group is moved down, until it touch the edge of the steps, along to the pitch line of the stairs; 4) the center of mass of the wheelchair is repositioned in order to distribute the load between the locomotion group and the track, and the wheelchair advances until the rear wheels of the L.U. reaches the riser of the step; 5) the rotation of the L.U. starts; 6) the rear wheels of the L.U. touch the tread of the step; 7) the rotation of the L.U. continues; 8) the cycle of the step climbing is repeated.

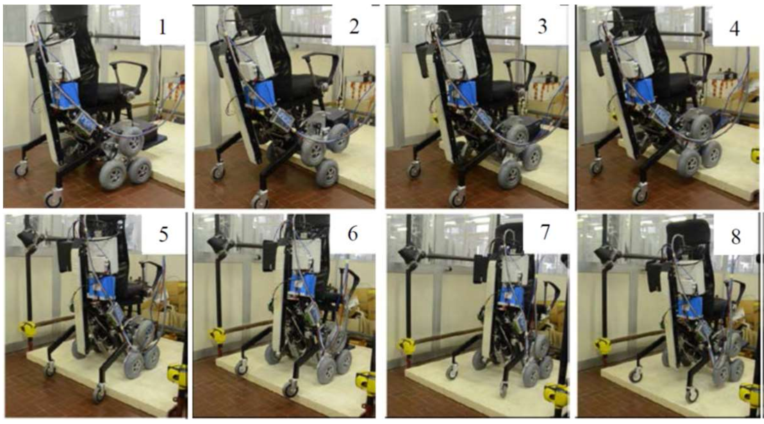


Fig. 12. Single step climbing sequence

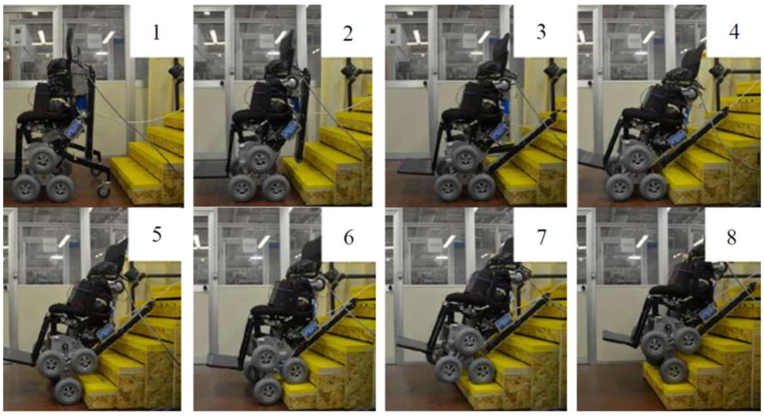


Fig. 13. Stair climbing sequence

6 Conclusions

A new stair climbing wheelchair, named Wheelchair.q05, has been conceived, designed and realized. The preliminary tests conducted on the prototype allowed to validate the functionality of the solution. The next phases of the wheelchair development will include full sensorization and automatic control setting of the device.

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