JCSE International Journal of Computer Sciences and Engineering Open Access
Research Paper **Volume-4, Issue-10** **E-ISSN: 2347-2693**

Improved of Stair Climbing Wheelchair for Differently Abled People

Arun Jose[1]*, Leneesh N Gopal[2], Jishnu M[3], Harikrishnan A R[4]

[1,2,3,4]Department of Mechanical Engineering, Mangalam College of Engineering, Kerala, India.

Available online at: www.ijcseonline.org

Received: 25/Sep/2016 Revised: 30/Sep/2016 Accepted: 22/Oct/201 Published: 31/Oct/2016

Abstract: This paper presents a new version of Wheelchair's, a wheelchair with stair climbing ability. The wheelchair is able to climb single obstacles or staircases thanks to a hybrid wheel- leg locomotion unit with a triple-wheels cluster architecture. The new concept presented in this work represents an improvement respect to previous versions. Through a different arrangement of functional elements, the wheelchair performances in terms of stability and regularity during movement on stair have been increased. In particular, attention has been paid to ensure a regular and comfortable motion for the user during stair climbing operation. For this reason, a cam mechanism has been introduced and designed with the aim to compensate the oscillation generated on the wheelchair frame by the locomotion unit rotation. A design methodology for the cam profile is presented. Moreover, a para- metric analysis on the cam profile and on the mechanism dimensions has been conducted with the aim to find a cam profile with suitable dimensions and performances in terms of pressure angle and radius of curvature.

Keywords: Stair-climbing wheelchair, Triple-wheels, Cam mechanism, Mechanism design, Architectural barriers

I. Introduction

Nowadays, architectural barriers represent an unsolved problem for disable or people with reduced mobility. According to [1] there are around 1.2 million wheelchair users in the UK, roughly 2% of UK population. As regard U.S.A. population, about 3.3 million people (1.4%) use a wheelchair or similar devices and 10.2 million (4.4 %) use a cane, crutches, or walker [2]. Only 28% of wheelchair users are under 60. Disability is strongly related to age: 2.1% of 16–19 year olds; 31% of 50– 59 years; 78% of people aged 85 or over [1]. This means that the number of wheelchair users will increase according to the aging society, thus the architectural barriers problem will become even more important. Moreover, the most common barriers to access buildings for adults with impairments are related to physical obstacles [3]. From these data, it is evident that providing autonomy to disabled people is an unsolved challenge.

Problems related to architectural barriers can be faced in two ways. From one side, governments try to introduce stan- dards in order to remove architectural barriers from buildings. From the other side, disable people can be provided with devices able to climb obstacles when architectural barriers cannot be removed for technical or economic reasons.

Some commercial stair-climbing devices already exist but most of them are complex, bulky, heavy, expensive and/or they require a great number of sensors and actuators. Thus, in the research field, several architectures have been proposed with the aim of improving the performances of existing stair-climbing wheelchairs in terms of efficiency, simplicity and stair climbing effectiveness. Stair-climbing mechanisms for wheelchair can be classified according to [4] in the same way as obstacle climbing mobile robots: wheel, leg, track and their hybrid combinations.
Finally, another typology of locomotion system is represented by wheel clusters. In [18,19], a two-wheels cluster mech- anism is presented. This architecture is not statically stable but should be balanced through a stability controller based on an inverse pendulum model. The high control requirements necessary to maintain the dynamic stability and safety issues are the main drawbacks of this kind of solution. In [20,21] a two-wheels cluster solution is presented. In these cases, the static stability is guaranteed by the introduction of additional articulated mechanisms. Finally, [22] presents a triple-wheels cluster solution with a hybrid wheel-track architecture. The wheel cluster is the locomotion unit and ensures the climbing ability while the tracks allow the wheelchair static stability.

The two contact points are the locomotion unit (on the rear) and the idle track (on the front). The front contact force is oriented as the normal of the track surface at the contact point. In order to avoid slippage, the friction force (Tcp) on the wheel must be almost equal to the horizontal component of the track contact force (Nca). In general, especially for stairs with high slope, the contact force on the track can be high, compromising the static stability. In order to avoid this condition, most of the wheelchair weight must be loaded on the locomotion unit. A possible solution to this problem could be an inverted architecture with the locomotion unit on the front, carrying most of the wheelchair weight, and the idle track on the rear.
The second issue is related to wheelchair oscillation during stair climbing. The use of a rotating leg locomotion is the source of the wheelchair oscillation. During steady state step climbing, the locomotion unit center advances with a not straight trajectory similar to a cycloid, represented in Fig. 1.

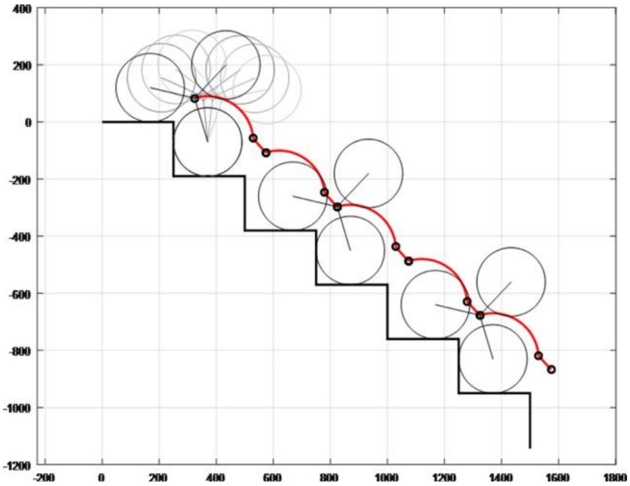


Fig. 1. Trajectory of the locomotion unit center during steady state stair climbing.

No active mechanism to control the seat orientation is expected on the wheelchair so the oscillating movement is trans- mitted to the user reducing the comfort. In early wheelchair concepts, the problem has been faced trying to minimize the oscillation amplitude by choosing appropriately the relative position between locomotion units and track [28]. However, the oscillation cannot be totally canceled and their minimization imposes important constraints to wheelchair design.

A complete compensation of the seat oscillation could be obtained with the introduction of a cam mechanism between the wheelchair frame and the seat that could completely compensate the oscillation related to the locomotion unit motion, at least in a nominal condition. For these reasons, a new wheelchair structure has been designed.

The paper is organized as follow: in Section 2 the new wheelchair architecture is presented. The functional elements are shortly described and the cam mechanism is introduced. Section 3 shows the cam mechanism design process. The methodology for obtaining the correct cam profile, starting from the description of the locomotion unit motion is illustrated. In Section 4 a parametric analysis on the cam mechanism is proposed. The effects of the mechanism parameters on the performances of the cam profile are shown and a procedure to identify the best dimensions for the mechanism is proposed. Finally, in Section 5 conclusions are stated and future developments of the project are considered.

II. Functional design

In this section, the new wheelchair architecture is presented.

II.1. Functional elements

All the wheelchair architectures developed till now are made by three functional elements plus the transmission group. Also the new concept presented in this paper has the same components even if they are arranged in a different way ac- cording to the considerations done in the introduction. In Fig. 2 a comparison between old and new wheelchair versions is given. The wheelchair functional elements are: locomotion unit (element 1 in Fig. 3), seat (2), track (3) and transmission group (4).

The characteristic element of all wheelchair versions and also of all mobile robots presented in [23–25] is the triple-wheels locomotion unit. It is composed of a triangular shaped frame with an internal epicyclical transmission as represented in Fig. 3.

This structure has two degrees of freedom: the rotation of the solar gears and the revolution of the planet carrier. This feature has been used to develop a smart architecture for mobile robots able to climb obstacles in an autonomous way

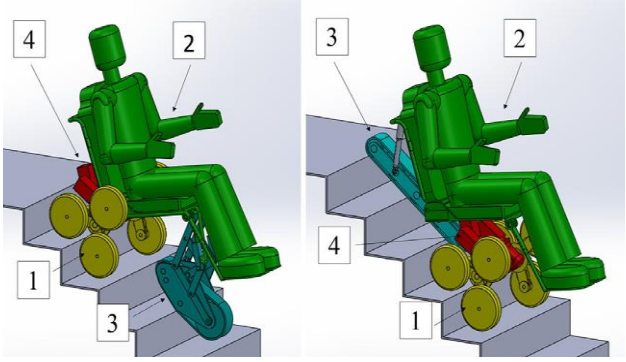
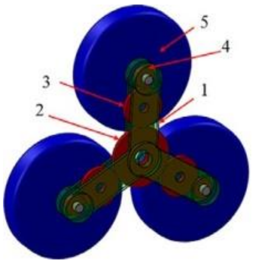


Fig. 2. Wheelchair functional elements in old (left) and new (right) wheelchair versions.



Label	Component
1	Planet carrier
2	Solar gear
3	First planet gear
4	Second planet gear
5	Wheel

Fig. 3. Detail of the locomotion unit structure.

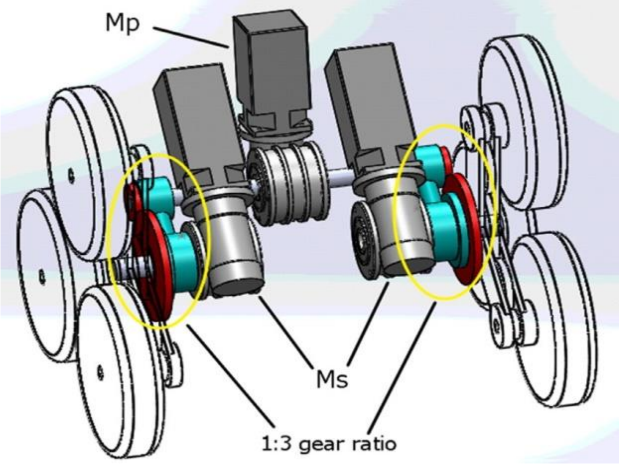


Fig. 4. Detail of the actuation and transmission system.

[23–25]: only one motor is used to control each locomotion unit which behavior is determined by dynamic conditions. The adopted architecture is represented in Fig. 4. Both planet carriers are connected to the same motor (Mp) in order to have a synchronous rotation while two different motors (Ms) are used to control the solar gear rotation of each locomotion unit.

II.2. Wheelchair structure

The wheelchair behavior is affected by the relative positions and connections between the functional elements previously introduced. Indeed, starting from the same functional elements and keeping in mind the considerations done at the end of the introduction, several structures can be designed. The innovation presented in this paper is the introduction of the cam mechanism between the wheelchair frame and the seat in order to filter the oscillation introduced by the locomotion unit motion.

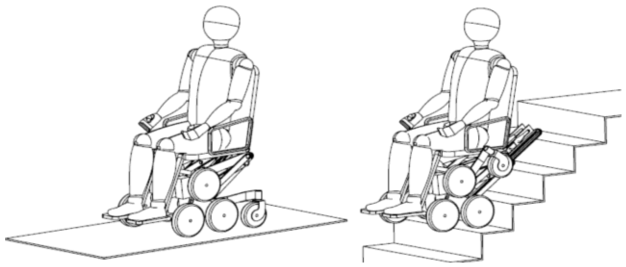


Fig. 5. Wheelchair configurations for movement on flat ground and on stair.

Independently from the specific structure adopted, some preliminary considerations can be done:

- cam mechanism should be integrated into the wheelchair structure in order to minimize the number of link and coupling;
- cam follower should be swinging to avoid sliding movement;
- structure must be as simple as possible with the lower number of moving parts and actuators.

In the architecture for the wheelchair structure is proposed. The cam is fixed with respect to the locomotion units. While the locomotion units rotate performing the step climbing sequence, the cam controls the distance between points R and P according to the designed profile and allows to keep a constant orientation for the seat. The seat moves with a translational motion along a straight line parallel to the line connecting the step edges if the cam mechanism completely compensates the oscillation generated by the locomotion unit motion. The velocity vectors of remarkable points of the wheelchair structure are presented.

In Fig. 5 the wheelchair is represented in the flat ground and stair-climbing configurations. A couple of caster wheels are the rear footholds for the wheelchair during flat ground motions. Moreover, a reconfiguration mechanism is required to set the wheelchair in a configuration proper to stair-climbing. The relative position between the track and the locomotion units should be changed and the caster wheels must be moved in order to avoid contact with step edges.

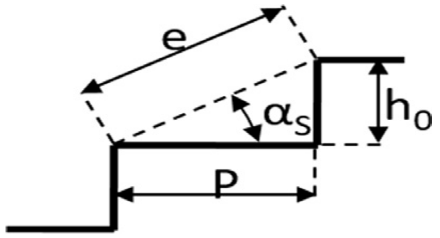


Fig. 6. Schematic representation of a step.

Table 1 Standard stair dimensions.

	h_0 [mm]	P [mm]	α_S	e [mm]
Low slope	145	350	22.5°	378.8
Medium slope	170	300	29.5°	344.8
High slope	190	250	37°	314

The detailed analysis of these aspects is not the goal of this paper and it will be discussed in future works.

III. Cam mechanism design

In the following paragraph, the design of the cam mechanism will be presented. As stated in the previous paragraph, the design process will be developed for the nominal stair and the proposed methodology is valid only under this hypothesis. The cam profile must be designed such that the distance between point P and R changes properly in order to maintain a constant orientation of the seat (i.e. a constant orientation for the element RC). According to this hypothesis, the point C moves on a straight trajectory parallel to point S trajectory. At the same time, the locomotion unit rotates around the fixed wheel (point W) and its center (point P) moves on a circular trajectory.

For a generic locomotion unit rotation θ_P, the wheelchair frame (PC) rotates of $\Delta\alpha = \alpha - \alpha_0$. Angle β is the angle that must be controlled by the cam mechanism in order to compensate the seat oscillation. Starting from the initial value β_0 that will be chosen properly, for each position of the locomotion unit, $\Delta\beta = \beta - \beta_0$ must be equal and opposite to $\Delta\alpha$ to maintain a constant orientation of the seat. From the scheme of Fig. 7, the relation between α and θ_P can be obtained: Eqs. (7) and (8) can be derived by applying the cosine and the sine theorem on triangle WPC. Finally, by considering triangle WHC, the value of α can be obtained as

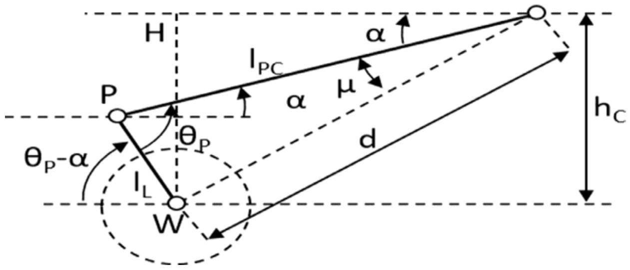


Fig. 7. Schematic representation of the mechanism during locomotion unit rotation on stair (detail).

A first consideration deals with the proper choice of the relative position between points P and C. The wheelchair os- cillation (represented by $\Delta\alpha$) can be minimized with a proper choice of the position of point C. The synthesis of the cam profile will be easier with small values of $\Delta\alpha$ because the resulting angular displacement for the cam ($\Delta\beta$) will be smaller. The two parameters that affect the wheelchair oscillation are l_{PC} and h_C. It can be observed that the smaller values of $\Delta\alpha$ can be obtained with:

The first statement can be justified observing that a higher value of l_{PC} brings to a lower rotation $\Delta\alpha$, starting from the same variation of h_P. The second statement can be understood by observing. During step climbing the point C move along a straight line. By choosing a generic initial position C_0 (i.e. choosing a value for h_C) the oscillation $\Delta\alpha$ can be evaluated in By drawing the line CP^{rr} that represents the initial configuration (C_0P_0) with respect to CP^{r}. The minimum value of oscillation $\Delta\alpha$ is obtained when the distance P^{r} P^{rr} is minimum. This condition is represented by the configuration and occurs when $h_C^* = h_{Copt}$.
Each step climbing can be modeled as a 120° rotation of the locomotion unit. In Fig. 17 the initial, final and intermediate configurations are represented with the parameter h_C chosen at its most favorable value. With this hypothesis, the total wheelchair oscillation is $\Delta\alpha = 2\alpha_0$ and a qualitative trend for $\alpha(\theta_P)$ is represented in Fig. 18. An important observation can be done on the asymmetric shape of the function. The maximum value for h_P (minimum value for α) is obtained after a rotation of 60° of the locomotion unit.

The initial value β_0 is a parameter that should be chosen properly because it affects the shape and the dimension of the cam profile. A first observation can be done on the minimum acceptable value for β. In order to have a positive radius of the cam, β must be greater than zero for any values of θ_P. This affects the choice of β_0 that must be greater than $\Delta\alpha$.

Once these preliminary concepts have been fixed, the procedure for the cam design can be described. In Fig. 8 two different configurations for the mechanism are showed in the kinematic inversion in which the locomotion unit and the cam connect with it are fixed. Variables with subscript zero refer to the initial configuration of the climbing sequence. The notation with apostrophe indicates variables values in a different and generic configuration of the mechanism.
According to this kinematic inversion, during the locomotion unit rotation, the wheelchair frame PC moves around P with a rotation of $\Delta\theta_P = \theta_P^{r} - \theta_{P0}$. Meanwhile the seat RC rotates around P and moreover the relative orientation between PC and RC changes according to the desired angle $\beta(\theta_P)$, in order to remove the oscillation of the seat. The trajectory of point R around P describes the desired cam profile.

The cam profile can be described in polar coordinates (h_{CAM}, δ) with respect to a reference frame fixed on the locomotion unit and centered in P. By applying the cosine and the sine theorems on triangle $P_0C'R'$.

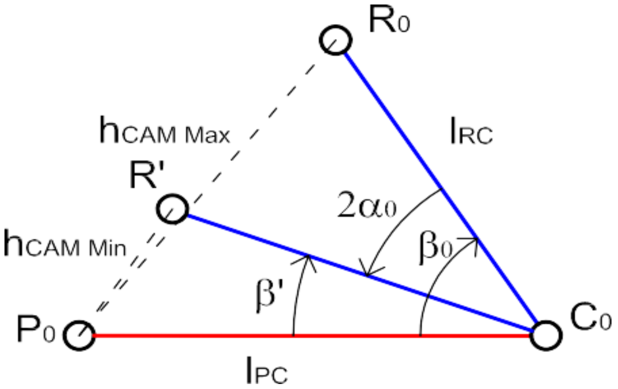


Fig. 8. Generic representation of a cam mechanism with swinging follower in two reference configurations.

IV. Parametric analysis on the cam mechanism

The procedure described in the previous paragraph defines a cam profile capable of removing the seat oscillation at least for the nominal stairs. Different profiles can be obtained changing the mechanism parameters. By following the proposed procedure, it is possible to obtain a constant orientation for the seat during stair-climbing for any combination of parameters. However, the resulting cam profile will be different and thus different performances should be expected. In this section, a parametric analysis on the cam mechanism will be conducted with the aim of analyzing the relations of the different parameters with the cam dimensions and the mechanism performances. The results can be used to properly choose the best cam mechanism. In Fig. 8 the mechanism is represented in another kinematic inversion in two different configurations: the initial one (P_0 C_0 R_0) and the configuration associated with the maximum value for h_P (P_0 C_0 R'), that corresponds to the maximum value of $\Delta\alpha$ and to the minimum values of β and h_{CAM}. The wheelchair frame PC is fixed, the seat RC rotates around C and the cam and the locomotion unit rotate around P. This representation can be associated with the generic representation of a cam mechanism with swinging follower.

A complete analysis of the cam mechanism cannot be done only focusing on the dimension and geometry of the cam profile. Important quantities that must be taken into account are the pressure angle (θ_{PRESS}) and the radius of curvature (ρ). These equations are known from the cam mechanism synthesis theory and can be understood referring to Fig. 8. The computation of the pressure angle of the cam profile from the geometry of the mechanism. The angle β represents the angle between the frame PC and the rocker arm RC, while K is the center of curvature of the pitch curve. Then, further parameters can be introduced: the radius of curvature (ρ), of the pressure angle (θ_{PRESS}) and the value of the radius of curvature of the cam profile (ρ) describe the performances of the cam and will be used to evaluate the quality of the profiles designed through the parametric analysis.

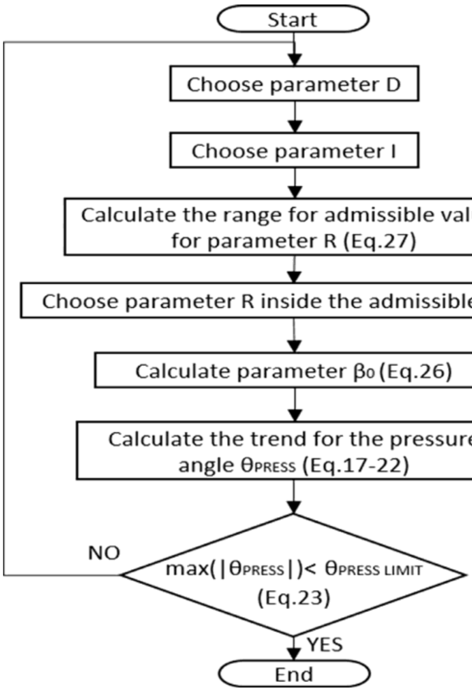


Fig. 9. Flowchart for the choose of a proper cam profile.

The desired cam dimension cannot be obtained with any choice of parameters D, R and I. Indeed, Eq. (26) imposes a constraint on the acceptable values for R because the argument of the arccosine function must be included between −1 and 1. Moreover, according to Fig. 18, in order to have a positive cam radius, the minimum acceptable value for β_0 must be greater than $2\alpha_0$. A proper cam profile satisfies the requirement for the pressure angle and it is suitable as regard the maximum dimension. In order to perform a reasonable choice for the free parameters (D, I and R) a parametric analysis must be conducted. The first choice regards the parameter D. It has been observed that greater values allow reducing the pressure angle. A first attempt can be done choosing D = 1. This means that the maximum radius of the cam is equal to the locomotion unit arm length. After this preliminary choice, the other parameters can be evaluated according to the proposed flow chart.

The dimensionless pitch curve and the pressure angle (θ_{PRESS}) as a function of θ_P for different choices of I, R and β_0. These allow having a general overview of the influence of the mechanism parameters over two fundamental aspects in the cam design: profile shape and pressure angles. This happens because the input for the cam synthesis is the single step climbing that requires a 120° of locomotion unit rotation. This means that the corresponding pitch curve will be developed in 120° and the complete shape is the juxtaposition of three identical profiles that correspond to a 360° of locomotion unit rotation and three steps climbing.

Moreover, it appears that the geometrical parameters of the mechanism strongly affect the designed cam shapes and its orientations. Thus, it is fundamental to verify that the chosen parameters are such that no interferences with step edges occur during stair-climbing. The changing in the mechanism parameters (I, R and β_0) causes significant modifications in the curves. Even if the shape of the curves is almost similar, their positions about the horizontal axis change considerably, affecting the maximum and minimum values for the pressure angle.

Table 4 Comparison between the best mechanism parameters for the profile obtained after the first iteration and after the complete design process.

Parameter	D	l_{PC} [mm]	R	l_{RC} [mm]	β_0 [°]	max($\lvert\theta_{PRESS}\rvert$) pitch curve [°]	max($\lvert\theta_{PRESS}\rvert$) smoothed cam profile [°]	I
First iteration values	1	800	0.96	768	11.5	43.0	54.14	5
Final values	1.13	800	0.95	760	13.1	38.64	50	5

to curve $\alpha(\theta_P)$ in the initial and final parts for an interval that is the 20% of the total $\Delta\theta_P$. The curve smoothing can be improved by increasing this interval, but the error done in the approximation will rise as a drawback. Considering the function $\alpha^*(\theta_P)$ instead of $\alpha(\theta_P)$ generates oscillation on the wheelchair seat even on nominal stairs because the cam profile is no longer able to completely compensate the locomotion unit movement in its initial and final section. In Fig. 28(b) the amplitude of the seat oscillation due to the proposed cam profile smoothing is shown and it can be observed that it is lower than 1°. The benefits that the use of a smoothed function introduces in the dynamics of the mechanism prevail on the small error generated on the compensation of the frame oscillation.

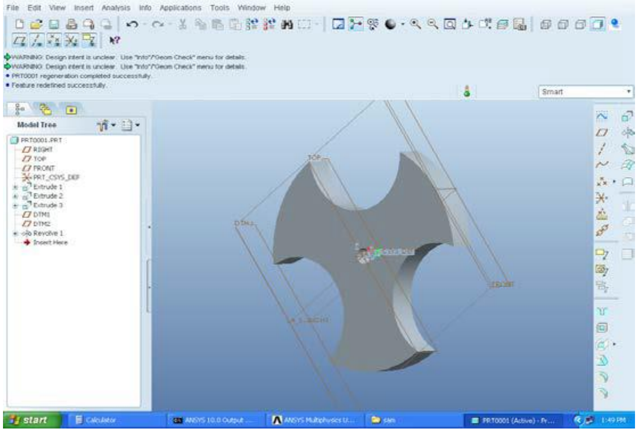
The $\alpha^*(\theta_P)$ function is composed of two fifth order polynomial curves with different coefficients. The fifth order is necessary to allow choosing six coefficients and imposing the curve continuity, the first and second derivatives continuity both in the external and internal boundary for each interval. The approach is identical for both intervals and it will be shown just for the first section. As regard pressure angle, its maximum value is increased with respect to the unsmoothed profile due to the local growth of the derivative of $\alpha^*(\theta_P)$ compared to the derivative of $\alpha(\theta_P)$. The maximum pressure angle is a bit higher than 50°, that can be considered as an upper limit. In order to reduce the maximum value for pressure angle, all the algorithm described in this paragraph should be repeated starting from a higher dimension for the cam. In other words, the design procedure should be repeated using a parameter D greater than 1 that was the value used for the first iteration.

A final analysis has been conducted in order to assess the influence of parameter D over the max($\lvert\theta_{PRESS}\rvert$) value of the smoothed cam profile. This analysis is necessary in order to identify the proper value for D with which repeat the cam synthesis algorithm. The maximum pressure angle decreases with the increase of the cam dimension as can be observed. In order to obtain a maximum pressure angle equal to 50°, it is necessary to impose a dimensionless size of the cam D = 1.135.

With this value of D, the procedure explained in this section can be repeated. The smoothed cam profile obtained with the most favorable values for I, R and β_0 it is showed in and the mechanism parameters are summarized in Table 4 in comparison with the parameters obtained from the previous iteration. It can be observed that the cam dimension is adequate to avoid interferences with step edges and so this profile can be considered verified under all the design requirements. In a step climbing sequence with the best cam mechanism is presented.

V. ANALYSE THE FOOT STEP WHEEL

First we draw the 2D view of stair climbing wheelchair in Au-to-CAD software and implement in the PRO-E / CRE-O soft-ware. And finally foot step wheel is analyzed in the ANSYS software as shown. Applying boundary conditions & von mises stress; then the deformation, maximum & minimum stress values are obtained.



WARNING: Design intent is unclear. Use "Info"/"Geom Check" menu for details.
WARNING: Design intent is unclear. Use "Info"/"Geom Check" menu for details.
- PRT0001 regeneration completed successfully.
- Feature redefined successfully.

Fig 10 3D VIEW OF FOOT STEP WHEEL

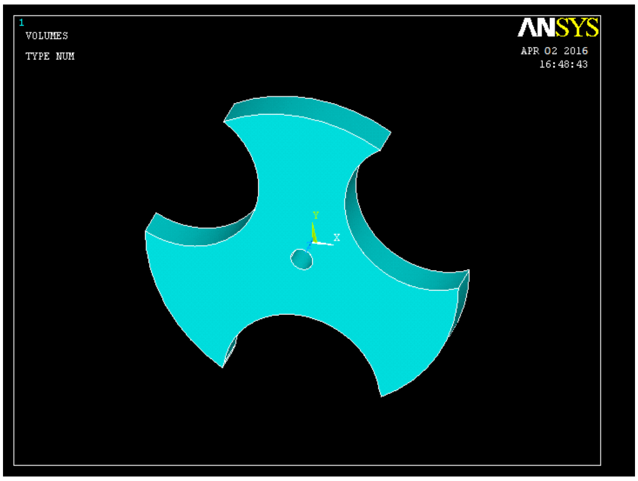


Fig 11. Foot step wheel in ANSYS

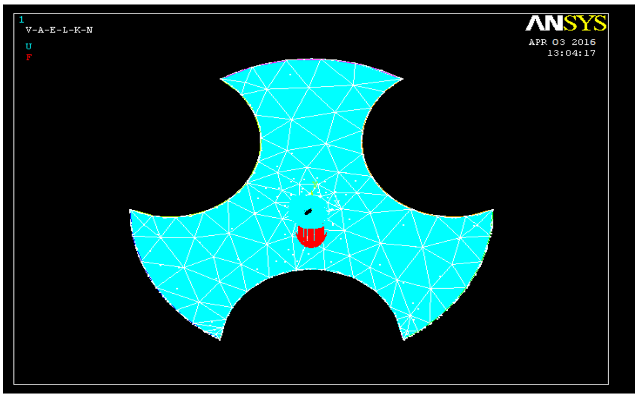


Fig 12. Force analysis

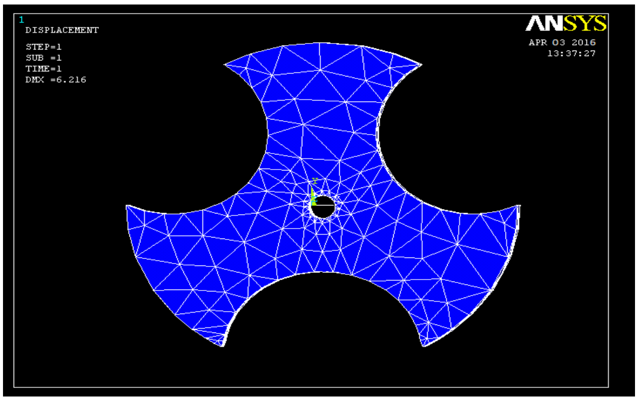


Fig 13. Minimum deform position

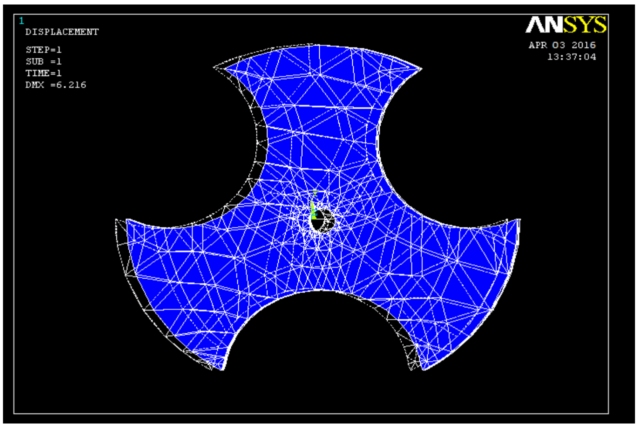


fig 14. Fully deform position

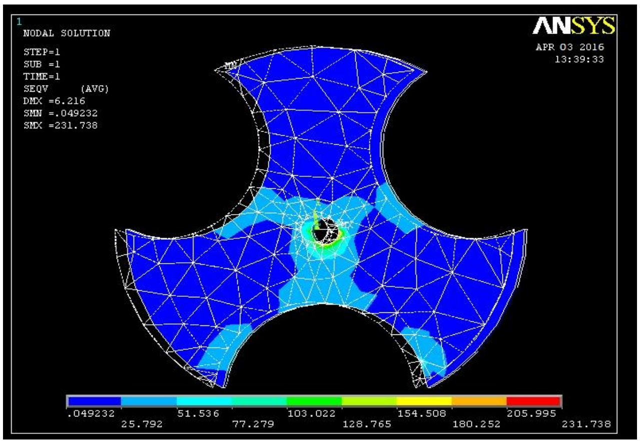


Fig 15. Entire analysis

VI. RESULT & DISCUSSION

S.No	Analysis	Values
1.	Deformation (MIN)	0.13 mm
2.	Deformation (MAX)	6.216 mm
3.	Stress (MIN)	0.0492 N/mm^2
4.	Stress (MAX)	231.73 N/mm^2

The foot step wheel has considerable deform only due to heavy loading conditions. The elonagtion in the wheel due to central axial load, tractional force and gravity force is allowa-ble. These are compared to existing result in the journal. The vibrational & deformational level is much better than the other conventional manual type wheelchair as shown in the table no.1. So, the foot step wheel is emerging method of stair climbing wheelchair through lever & ratchet mechanism. In order to develop further technology where will be used for changing the foot step wheel to normal wheel for riding in the straight path.

VII. CONCLUSION

In this paper, a new version of the stair-climbing device Wheelchair.q has been proposed. This new concept tries to over- come the unsolved problems related to previous versions through a different wheelchair architecture. The main idea was to define a smart mechanical structure, able to reduce as much as possible the number of the actuators and mechatronic subsystems, in order to guarantee lightweight, safety, comfort, and reduced costs. The idle track that represents the rear foothold for the wheelchair during stair-climbing is moved to the rear with respect to previous versions. This innovation allows to increase the static stability and to reduce the seat oscillation during stair-climbing activity. In particular, the reduction of the seat oscillation has been the focus of this new design. A cam mechanism with a swinging follower has been added to the wheelchair structure with the aim to passively compensate the oscillation introduced on the device frame by the locomotion unit rotation. Thanks to the cam mechanism action, the wheelchair seat moves with a translational motion along a straight line, increasing the user comfort. The main topic of this paper has been the description of the design process that has brought to the choice of a proper cam profile. In the first part, the locomotion unit motion has been described and the algorithm necessary to obtain the cam profile has been presented. In the second part, a parametric analysis on the mechanism has been conducted. The results have been used to choose the most favorable parameters in order to have the smallest cam with acceptable values for pressure angle and curvature radius.

Future works will regard the design and optimization of the other parts of the wheelchair structure that are not already completely defined. In particular, the reconfiguration mechanism that should modify the wheelchair configuration before stair-climbing must be analyzed. Once the design process will be completed, a multibody analysis of the vehicle should be conducted in order to finalize the design process before starting with an experimental activity on a prototype.

References

[1] Papworth Trust, Disability in the United Kingdom 2014: Facts and Figures, 2014.

[2] U.S Census Bureau, Americans with Disabilities: 2005, 2008.

[3] Disability Statistics Center Institute for Health and Aging, Mobility Device Use in the United States, University of California, 2000.

[4] L. Bruzzone, G. Quaglia, Review article: locomotion systems for ground mobile robots in unstructured environments, Mech. Sci. 3 (2012) 49–62.

[5] Y. Sugahara, et al., Walking up and down stairs carrying a human by a biped locomotor with parallel mechanism, in: Proceeding of International Conference on Intelligent Robots and Systems (IROS), Edmonton, Alberta, Canada, 2005, pp. 1489–1494.

[6] S. Yu, T. Wang, et al., A tip-over and slippage stability criterion for stair-climbing of a wheelchair robot with variable geometry single tracked mecha- nism, in: Proceeding of International Conference on Information and Automation (ICIA), Shenyang, China, 2012, pp. 88–93.

[7] S. Yu, T. Wang, et al., Configuration and tip-over stability analysis for stair-climbing of a new-style wheelchair robot, in: Proceeding of International Conference on Mechatronics and Automation (ICMA), Xi'an, China, 2010, pp. 1387–1392.

[8] H. Wang, W. Zhang, et al., Research on a kind of leg-wheel stair-climbing wheelchair, in: Proceeding of International Conference on Mechatronics and Automation (ICMA), 2014, pp. 2101–2105.

[9] Y. Bang, C. Lee, et al., Two-legged stair-climbing wheelchair and its stair dimension measurement using distance sensors, in: Proceeding of Interna- tional Conference on Control, Automation and Systems (ICCAS), Gyeonggi -do, Korea, 2011, pp. 1788–1791.

[10] J. Yuan, S. Hirose, Research on leg-wheel hybrid stair-climbing robot, Zero Carrier, in: Proceeding of International Conference on Robotics and Biomimetics (ROBIO), Shenyang, China, 2004, pp. 654–659.

[11] M.J. Lawn, T. Ishimatsu, Modeling of a stair-climbing wheelchair mechanism with high single-step capability, Neural Syst. Rehab. Eng. 11 (3) (2003) 323–332.

[12] J. Liu, Y. Wu, et al., High-order sliding mode-based synchronous control of a novel stair-climbing wheelchair robot, J. Control Sci. Eng. (2015).

[13] A. Gonzalez, R. Morales, et al., Improving the mechanical design of new staircase wheelchair, Ind. Robot 34 (2) (2007) 110–115.

[14] A. Gonzalez, E. Ottaviano, M. Ceccarelli, On the kinematic functionality of a four-bar based mechanism for guiding wheels in climbing steps and obstacles, Mech. Mach. Theory 44 (8) (2009) 1507–1523.

[15] J. Chocoteco, R. Morales, V. Feliu, Improving the climbing/descent performance of stair-climbing mobility systems confronting architectural barriers with geometric disturbances, Mechatronics 30 (2015) 11–26.

[16] R. Morales, V. Feliu, et al., Coordinated motion of a new staircase climbing wheelchair with increased passenger comfort, in: Proceeding of Interna- tional Conference on Robotics and Automation (ICRA), Orlando, Florida, USA, 2006, pp. 3995–4001.

[17] R. Morales, V. Feliu, A. González, Optimized obstacle avoidance trajectory generation for a reconfigurable staircase climbing wheelchair, Rob. Autom. Syst. 58 (1) (2010) 97–114.

[18] S. Motoki, N. Tomokuni, et al., Wheeled inverted pendulum type robotic wheelchair with integrated control of seat slider and rotary link between wheels for climbing stairs, in: Workshop on Advanced Robotics and its Social Impacts (ARSO), Evanston, Illinois, USA, 2014, pp. 121–126.

[19] N.M.A. Ghani, A.N.K. Nasir, M.O. Tokhi, Optimization of fuzzy logic scaling parameters with spiral dynamic algorithm in controlling a stair climbing wheelchair: ascending task, in: Proceeding of International Conference on Methods and Models in Automation and Robotics (MMAR), Mie̜dzyzdroje, Poland, 2014, pp. 776–781.

[20] C. Chen, H. Pham, Design and fabrication of a statically stable stair-climbing robotic wheelchair, Ind. Robot 36 (6) (2009) 562–569.

[21] Y. Sugahara, N. Yonezawa, K. Kosuge, A novel stair-climbing wheelchair with transformable wheeled four-bar linkages, in: Proceeding of International Conference on Intelligent Robots and Systems (IROS), Taipei, Taiwan, 2010, pp. 3333–3339.

[22] Kenneth Ray Cox, “Battery Powered Stair-Climbing Wheelchair”, U.S. Patent No. 6484829, Nov. 26, 2002.

[23] G. Quaglia, et al., The Epi. q-1 hybrid mobile robot”, Int. J. Rob. Res. 29 (1) (2009) 81–91.

[24] G. Quaglia, L. Bruzzone, et al., A modular approach for a family of ground mobile robots, Int. J. Adv. Rob. Syst. 10 (2013).

[25] G. Quaglia, M. Nisi, Design and construction of a new version of the Epi.q UGV for monitoring and surveillance tasks, Proceeding of the International Mechanical Engineering Congress & Exposition (IMECE), 2015. Houston, Texas.

[26] G. Quaglia, W. Franco, R. Oderio, Wheelchair. q, a motorized wheelchair with stair climbing ability, Mech. Mach. Theory 46 (11) (2011) 1601–1609.

[27] G. Quaglia, W. Franco, R. Oderio, Wheelchair.q, a mechanical concept for a stair climbing wheelchair, in: Proceeding of International Conference on Robotics and Biomimetics (ROBIO), Guilin, China, 2009, pp. 800–805.

[28] G. Quaglia, W. Franco, M. Nisi, Design of a reconfiguration mechanism for an electric stair-climbing wheelchair, Proceeding of the International Me- chanical Engineering Congress & Exposition (IMECE), 2014. Montreal, Quebec, Canada.

[29] G. Quaglia, W. Franco, M. Nisi, Evolution of wheelchair.q, a stair-climbing wheelchair, Proceeding of the 14th World Congress in Mechanism and Machine Science, 2015. Taipei, Taiwan.

[30] R.L. Norton, Design of Machinery: An Introduction to the Synthesis and Analysis of Mechanisms and Machines, McGraw-Hill Professional, 2004.

[31] P.L. Magnani, G. Ruggieri, Meccanismi per macchine automatiche, Utet, 1986.