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## WHEELCHAIR MECHANISM FOR NEGOTIATING OBSTACLES

Moving with the wheelchair can be a serious problem, especially when the obstacle occurs on its way. An alternative solution would be to equip the wheelchair with appropriate mechanical device, thanks to that it becomes possible to overcome barriers such as kerbs or doorsteps. In this paper, the authors present an idea of mechanism overcoming barriers by the wheelchair. Type and geometrical synthesis have been presented. The mechanism is modelled in a multibody computer analysis system and sample simulation research results are reported.

### 1. Introduction

Efforts to increase the independence of disabled persons with paraparesis are made in the fields of social sciences, transport, construction and architecture [1]. One of the basic problems which disabled persons have to cope with is covering short distances, such as the way to a car park, a bus/tram stop, a shop and so on, in a wheelchair. This problem is currently being addressed by removing architectural barriers, i.e. removing entrance thresholds, installing lowered kerbs at zebra crossings, wheelchair ramps, lifts, etc. Unfortunately, this is usually done in highly urbanized areas and only to a small extent. Despite the measures taken, disabled persons still have to daily negotiate a considerable number of small architectural barriers.

An alternative solution is to equip the wheelchair with a proper mechanical device enabling the wheelchair user to negotiate the most common obstacles: low thresholds and kerbs. The kinematic system to be designed is to lift the wheelchair's front wheels to a proper height, move them over the obstacle and lower them to the ground. In the second phase, the rear wheels should be lifted and drive onto the obstacle. For this purpose, an additional

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drive allowing the wheelchair whose large rear wheels have lost contact with the ground to move on is required. A schematic diagram of such a kinematic system is shown in Fig. 1.

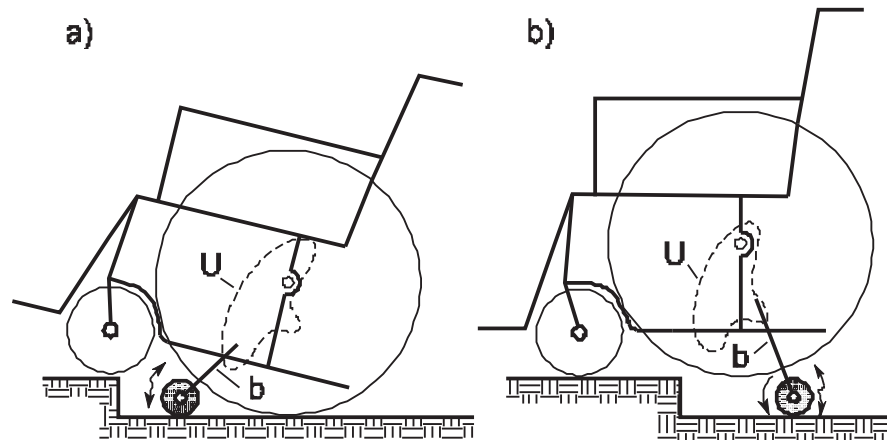


Fig. 1. Idea of mechanism enabling wheelchair to negotiate obstacles

## 2. Structure of mechanism

First, the structure of the mechanism should be designed, i.e. the number of links  $k$  and kinematic pairs  $p_i$  connecting the links should be determined. The method of chain  $U$  of intermediate links can be used to search for possible solutions [5]. As a result, a full set of possible solutions is obtained. Depending on the assumptions and constraints, systems with more or less complex structure are obtained. The mechanism should have a possibly simple design and its manufacturing cost should be low. Taking the requirements into consideration, it was assumed that both the front and rear wheels will be lifted by a flat mechanism with mobility  $W = 1$  (a single motor). The task will be performed by two driven links with rollers mounted on them. In order to avoid elaborate (expensive) designs, the number of links ( $k < 6$ ) and that of class two pairs ( $p_2 < 3$ ) were reduced. Generally, the mobility of the mechanism can be written as:

$$W_T = W_C + W_B + W_U \quad (1)$$

where:

- $W_B$  – the mobility of the driven link,
- $W_U$  – the mobility of the intermediate chain,
- $W_T$  – the mobility of the mechanism.

The mobility of chain U can be expressed by the following relation:

$$W_U = 3k - 2p_1 - p_2 \tag{2}$$

where:

$k$  – the number of chain U links,

$p_i$  – the number of  $i$ -th class pairs.

By transforming equations (1) and (2) under the above assumptions, the following relation describing the structure of the chain of intermediate links was obtained

$$3k + 1 = 2p_1 + p_2 \tag{3}$$

Table 1.

Structure of the chain of intermediate links

No.	1	2	3
Symbol	0.2.2	2.6.0	4.8.2

Taking into consideration the basic quality factors [4] and the specific application of the system, the design denoted as 2.6.0. (Fig. 2) was chosen for further analyses. By substituting the specified forms of (sliding, rotational) pairs a full set of schemes is obtained. One of them is a doubled four-bar linkage whose connecting links are driven links. The kinematic diagram of the adopted design is shown in Fig. 2.

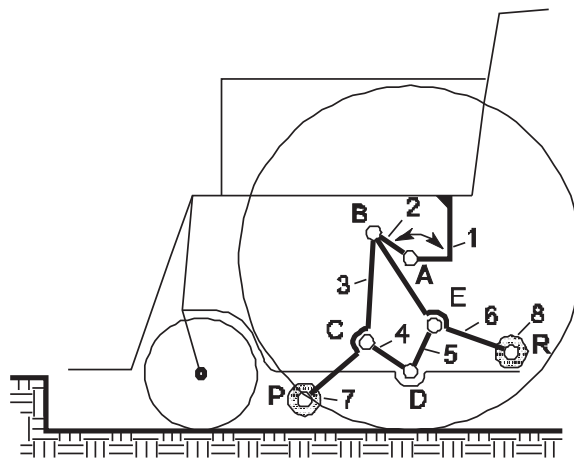


Fig. 2. Design based on four-bar linkage

### 3. Geometric synthesis

In the search for a design of a system which would aid the wheelchair in negotiating obstacles, it was assumed that the disabled person will use a standard (everyday) wheelchair. It was also required that the mechanism be designed as optional wheelchair equipment and so be easily assembled and disassembled (e.g. for transporting the wheelchair). The assumptions to a large extent determine the geometric features of the obstacle negotiating aiding mechanism. It was assumed that kinematic excitation is effected between crank 2 and frame 1. The full work cycle of such a mechanism can be divided into the following phases:

1. The lowering of wheel 7 mounted on link 3, until it touches the ground. In this phase of motion, the mechanism is a classic four-bar linkage whose base is the wheelchair frame. The requirements which the particular links should meet are: wheel 7 must reach the desired point of contact with the ground, and the mechanism links cannot collide with the wheelchair frame components (fig. 3a).
2. The lifting of the wheelchair front wheels (fig. 3b), which starts when wheel 7 touches the ground. Then, the wheelchair frame revolves around the axis of the large wheels (which constitute the base in this kinematic system). The structure of the lifting mechanism has already changed. In this phase, rear wheel 8 is required only to prevent the wheelchair from overturning.
3. The return of the mechanism to the starting position relative to the wheelchair's frame (after the wheelchair's front wheels have driven onto the obstacle).
4. The lowering of wheel 8 until it touches the ground.
5. The lifting of the wheelchair rear wheels and driving with them onto the obstacle, using a rotary drive applied between links 6 and 8.
6. The return of the lifting mechanism to the starting position.

For known diameters of wheels 7 and 8, the system operates so that points P and R trace respectively trajectories  $\mu_P$  and  $\mu_R$ . In each of the trajectories, one can distinguish segments responsible for the particular work mechanism phases during obstacle negotiation. Theoretically, for the lifting alone of the wheelchair wheels to the desired height it is enough to ensure proper displacements of points P and R. However, this solution does not satisfy the functional needs specified by disabled persons. The main quality criteria are: wheelchair frame movement without sharp changes in speed, effort as small as possible, and protection against wheelchair overturning as the wheels are being lifted. Therefore, prior to designing the mechanism, it is necessary to determine the motion (calibrated trajectories) of points P and R.

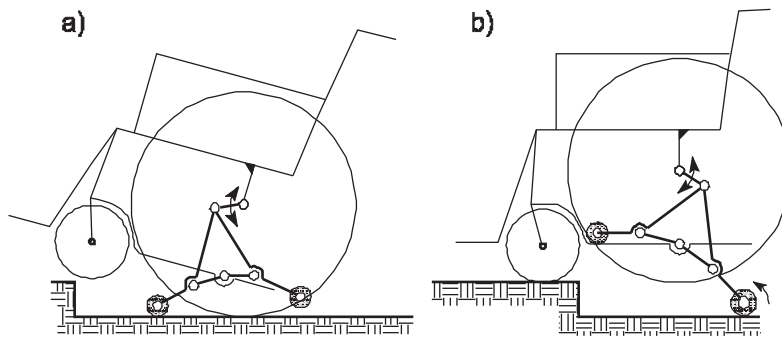


Fig. 3. Work phases of obstacle negotiation aiding mechanism

### 3.1. Determination of coupler curve

Before designing the mechanism's dimensions one should define the coupler curve for the four-bar linkage during the lifting of the wheelchair. For this purpose, (assuming the diameter of wheel 7) one can use a substitute mechanism (Fig. 4) in which the upper pair between wheel 7 and the ground has been replaced with a slide.

In the proposed kinematic system, the rotation of the frame is forced by the simultaneous change of length  $AP$  and angle  $\angle PAD$ . The determination of proper interdependencies between the quantities constitutes the first stage in the geometric synthesis. For this purpose, for the defined substitute mechanism structure the start point and the end point of path  $s$  of slider  $7'$  were assumed. Thus, the desired angle of rotation  $\alpha$  of the wheelchair frame corresponds to the defined displacement  $\Delta s$ . The boundary values of the length  $AP$  and the angle  $\angle PAD$  are obtained from the basic geometric relations. In addition, a requirement was set that the motion of frame 1 during lifting be characterized by a constant angular velocity and the motion of slider  $7'$  along path  $\Delta s$  be uniform.

Under the above assumptions, for the lifting phase it is required that the four-bar linkage realizes the desired pattern of changes in length  $AP$  and angle  $\angle PAD$ . For the needs of this stage of synthesis, wheelchair arm 1 was assumed to be fixed while base 0 was allowed to revolve around point A (Fig. 5). Thanks to this measure, one can easily obtain a part of the calibrated trajectory of point A during the lifting of the front wheelchair wheels.

A similar procedure can be used to generate a part of the trajectory of point R, responsible for the lifting of the wheelchair rear wheels, but only as a function of the negotiated threshold's height (the frame's centre of rotation changes relative to the base – the axis of the small wheels). Analyzing the motion of the frame, we assumed that the wheelchair's rear wheels would be

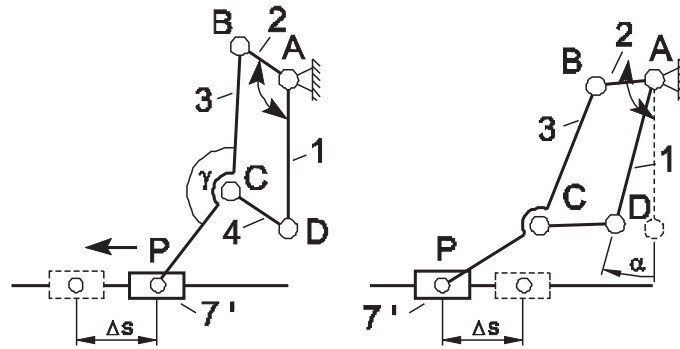


Fig. 4. Substitute mechanism for wheelchair lifting phase

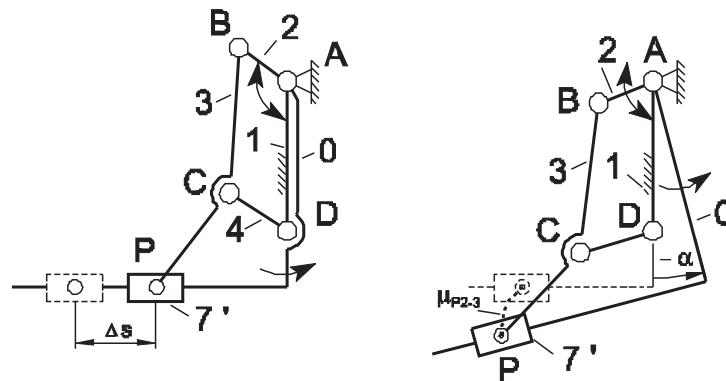


Fig. 5. Shifts in mechanism base

lifted using the same trajectory as the one used for lifting the front wheels. Thanks to this assumption, a symmetric system could be sought for, which is of immense importance as regards mechanism costs. Then, the other parts of the trajectories of points P and R had to be determined. In addition, it was assumed that as the front wheelchair wheels were being lifted, rear wheel 8 of the mechanism should perform an anti-tip-over function. Thus, a part of trajectory  $\mu_R$ , corresponding to a part of curve  $\mu_P$ , is determined. The only requirement which the other parts of trajectories  $\mu_P$  and  $\mu_R$  must meet is to ensure that there will be no collision between the mechanism links and the wheelchair frame.

### 3.2. Synthesis of mechanism basic dimensions

Having trajectories  $\mu_P$  and  $\mu_R$  (in the form of a set of points), what remains to be done is to determine the basic dimensions of the four-bar linkage for the above assumptions. Major requirements include: geometric and

structural constraints, gear angles, design compactness and constant angular velocity of crank 2. Despite the wide capabilities of the four-bar linkage in shaping coupler curves, an exact solution exists for, at the most, five positions of the point on the coupling link [4]. In order to obtain satisfactory approximate solutions on the basis of contour equations [5], one must specify the initial conditions. Hence, a procedure consisting in adopting dimensions for four-bar linkages until their coupler curves get close to the expected ones was employed. Then, the dimensions were corrected, as shown in Fig. 6a. The coordinates of points A and D were assumed. It was also assumed that the lengths of the respective links of both four-bar linkages are identical. As a result, a considerable number of solutions were obtained. The solutions can be ordered according to the following index:

$$w = \sum_{i=1}^n \left( (x_{ass} - x_{obt})^2 + (y_{ass} - y_{obt})^2 \right). \quad (4)$$

The index is a measure of the fit of trajectories  $\mu_P$  and  $\mu_R$  traced by a given four-bar linkage to assumed trajectories  $\mu_P^*$  ( $\mu_R^*$ ). In the sought system, the assigned trajectories in segment  $\mu_{2-4}$  can be achieved with a much lower accuracy than in segments  $\mu_{2-3}$  and  $\mu_{4-5}$ . Taking this fact into account, we adopted the index with weight coefficients  $k$  as the criterion of solution quality:

$$\begin{aligned} w_P^* &= k(w_{P1-2} + w_{P1-4} + w_{4-5}) + w_{P2-3}, \\ w_R^* &= k(w_{R1-2} + w_{R2-3} + w_{R1-4}) + w_{R4-5} \end{aligned} \quad (5)$$

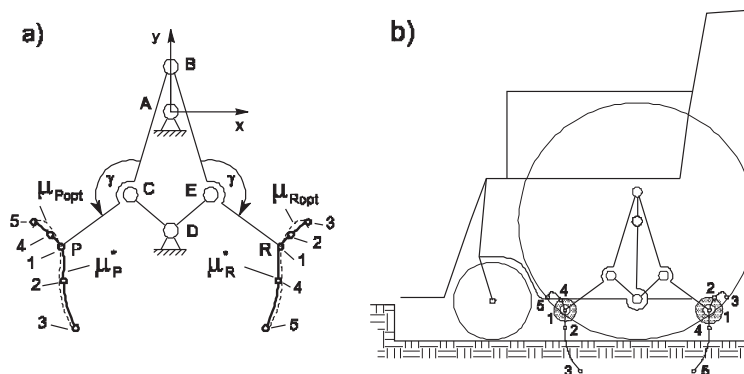


Fig. 6. Geometric synthesis of four-bar linkage mechanism separated from system (a) and basic dimensions of lifting mechanism mounted on a wheelchair (b)

The solutions obtained from the search were ordered according to the value of  $w^*$ . The solution with the lowest value of  $w^*$  was subjected to

optimization aimed at lowering index  $w^*$  [3]. The fit was improved by correcting length CP (ER) and angle  $\gamma$ . The solution (shown in scale in Fig. 6b) for which index  $w^*$  has the lowest value (as well as meeting all the other requirements) was adopted as the final solution.

#### 4. Simulation studies of kinematic system motion

Once the basic dimensions were known, a solid model of the mechanism with the wheelchair was built. Also a geometric model of a standard wheelchair, reflecting the dimensions and mass parameters of the actual object, was created. The aim was to obtain the mass parameters of the particular members of the kinematic system and to validate the determined basic parameters. The data from the geometric model were used to roughly model the target system in ADAMS (Fig. 7). The purpose of creating the numerical model in the program for multilink system analysis was to exclude possible collisions and to determine the dynamic parameters of the mechanical system being designed.

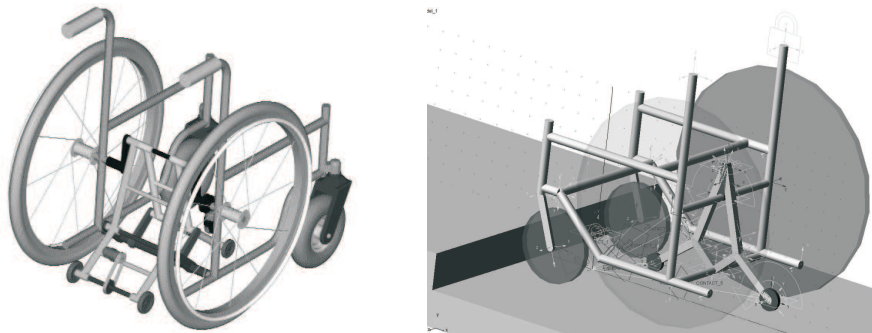


Fig. 7. Geometric 3D model and numerical model of kinematic system in ADAMS

The model was used to verify the geometry adopted for the system. Then, kinematic excitation  $\omega_1 = \pi/6$  [1/s] was applied between link 1 and 4 and the wheelchair frame was loaded with additional mass  $m = 80$  [kg] imitating the weight parameters of a person sitting in the wheelchair. The contact of the wheels with the ground was modelled using a contact force [6], according to the relation:

$$F = \begin{cases} \max(k_s(x_1 - x)^e - c\dot{x}) & \text{for } x \leq x_1 \\ 0 & \text{for } x > x_1 \end{cases}, \quad (6)$$



where:

- $c$  – a damping coefficient,
- $k_s$  – a stiffness coefficient,
- $x - x_1$  – the interlink distance.

Linear kinematic excitations were used to model motion in the drive. A numerical dynamic analysis was used in the simulations. The influence of friction in the couples of rotation was not taken into account. The angular displacement of the wheelchair frame is presented in Fig. 8. The numerical model was used to trace the contact forces between the ground and the mechanism's wheels (Fig. 9), and the driving torque (Fig. 10). The angular velocity of the frame changes very little, which is very beneficial as regards the wheelchair's dynamics.

The obtained results corroborate the previous theoretical considerations. The obtained active torque trace warrants the use of a battery-powered electric motor for driving the designed mechanism.

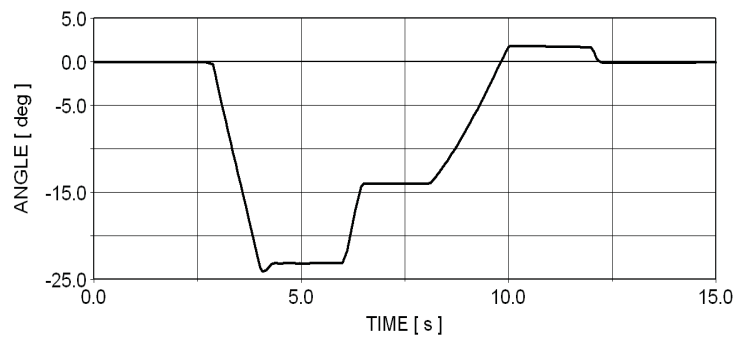


Fig. 8. Changes in wheelchair frame angle

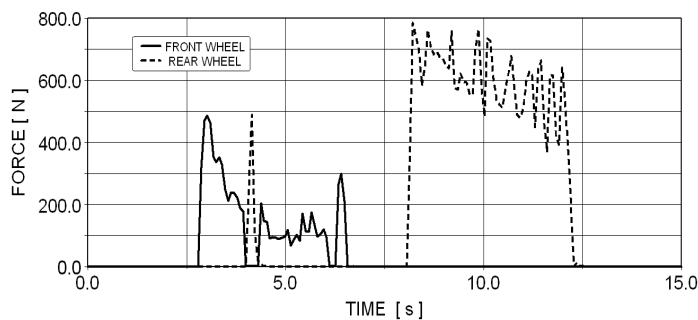


Fig. 9. Contact forces between ground and the mechanism wheels

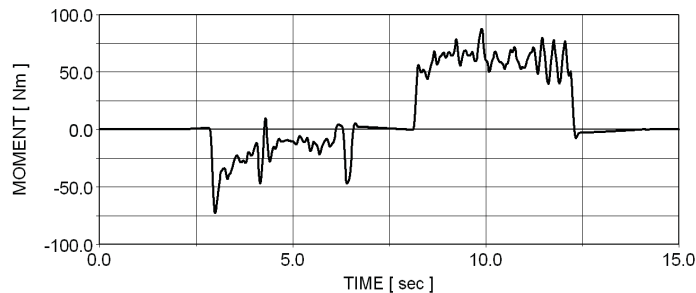


Fig. 10. Results of numerical analysis of driving torque

## 5. Conclusion

The method of synthesis used in this research guarantees that a design consistent with all the assumptions, free of singularities, having the assumed gear angles and at the same time compact is obtained. Both analytical and numerical methods were used in the synthesis. The changing structure of the kinematic system was modelled using contact forces [6]. The results of the computer analyses proved the geometric synthesis to be correct. The results of the simulations of the kinematics and the driving forces showed them to be achievable by means of an electric drive (with a gear) powered by a conventional car battery. When a sensor and steering system is added, the operation of the system aiding the wheelchair in negotiating obstacles can be controlled fully automatically.

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**Mechanizm wózka inwalidzkiego do pokonywania przeszkód**

## S t r e s z c z e n i e

Problem przemieszczania się osoby korzystającej z wózka inwalidzkiego jest obecnie rozwiązywany głównie poprzez likwidowanie tzw. barier architektonicznych. Niestety takie rozwiązania stosowane są jedynie na obszarach silnie zurbanizowanych. Pomimo podejmowanych działań niepełnosprawni wciąż borykają się z koniecznością codziennego pokonywania znacznej ilości przeszkód architektonicznych. Alternatywnym rozwiązaniem jest wyposażenie wózka inwalidzkiego w odpowiednie urządzenie mechaniczne, dzięki któremu możliwe staje się pokonywanie najczęściej występujących przeszkód. W pracy zaprezentowano koncepcję układu mechanicznego, który ma za zadanie wspomagać pokonywanie przeszkód przez osoby niepełnosprawne poruszające się na wózkach inwalidzkich. Przedstawiono koncepcję syntezy geometrycznej wybranego układu kinematycznego. Przeprowadzone badania symulacyjne pozwoliły na zweryfikowanie poprawności otrzymanego rozwiązania, oraz uzyskanie danych niezbędnych do opracowania konstrukcyjnego.