Methods of Determining Trajectory for Wheelchair with Manual Pushrims Drive

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Abstract. The article describes a method of operation of wheelchairs with differential control, as well as elaborates a developed method that allows visualising the wheelchair motion trajectory on the basis of reading of road or linear velocity measured independently on both left and right drive wheel. The Method chapter describes a complete proceeding algorithm, which allows determining the trajectory of wheelchair rear wheel axle’s middle point by using only road value of rear wheels in regular intervals. The Measurement system chapter describes the used set of sensors, type of measured kinematic value, and method of transforming it into unit compliant with the method. The Results chapter shows exemplary values of measured wheelchair velocities and motion trajectory charts determined by transforming them.

1. Introduction
A wheelchair with manual drawdown drive is a part of the man-technical device anthropotechnical system that is responsible for the execution of locomotion function for a person with reduced mobility. A characteristic feature of this system is its propulsion method that consists of powering cycles [1] divided into propulsion phase, during which a propulsion force is generated and, return phase, during which hand returns to initial position [2]. The manual wheelchair drive system is characterised by its independence, which can translate to various drive torque values on both left and right drive wheel [3] that result from lack of symmetry in muscle strength of upper limbs [4, 5]. In addition, the difference in drive torque of drive wheels is also influenced by rolling resistance [6 – 9]. This is can be especially felt during the return phase because the system is not powered by impetus. The problem of increased motion resistances is also the result of utilising new technologies that support moving on a wheelchair [10]. Different values of drive torque on wheelchair’s wheel translate into various velocity values for left and right drive wheel, which in consequence influences the wheelchair’s trajectory. The familiarity of wheelchair’s trajectory is particularly important during bench testing [11, 12] because it constitutes as feedback informing the patient sitting in an immobile position about distance travelled. In addition, as it is shown by research from the field of manual wheelchair propulsion biomechanics, the wheelchair’s motion trajectory has an impact on other biomechanical parameters [13], such as centre of gravity location [14]. This impact results from dynamic changes in the position of human body during manoeuvring using a wheelchair [15, 16].

By observing the current trend consisting of development of manual drive systems by combining them with electrical drives [17], the familiarity of motion trajectory is also required during development of software controlling such hybrid drives. As a result, there occurs a necessity to elaborate a method of determining wheelchair’s motion trajectory in iterative sequences using commonly available sensors. Additionally, the said sensors should also enable their implementation in the wheelchair’s structure without excessively increasing its dimensions and mass.
2. Method

The developed method uses differential wheelchair control consisting of differentiating velocities independently of powered rear wheels \( v_L \) and \( v_P \). According to the differential control rule, the \( R \) turning radius depends on the difference between velocity vectors of wheels (Fig. 1).

![Figure 1](image1.png)

**Figure 1.** Determination of the \( R \) turning radius using geometric method on the basis of known velocity values of \( v_L \) left wheel, \( v_P \) right wheel, and \( L \) wheel spacing

In case of measuring kinematic parameters of a wheelchair, it is possible to measure an independent road for \( s_L \) left wheel and \( s_P \) right wheel within the same \( t \) time unit. Division of whole wheelchair motion into equal intervals allows to divide the motion into trapezoids, the basis of which is equal to \( L \) wheel spacing and the sides of which are equal in length to road travelled by \( s_L \) left wheel and \( s_P \) right wheel (Fig. 2 A, B).

![Figure 2](image2.png)

**Figure 2.** Diagram of distributing wheelchair motion trajectory into trapezoids (description in text)

According to the trapezoid method, first the whole motion should be divided into equal intervals for which the roads of \( s_L \) left wheel and \( s_P \) right wheel are known (Fig. 2 A, B). Next, the \( \alpha \) inclination angle in relation to level of straight line connecting the ends of \( s_L \) left wheel and \( s_P \) right wheel should be calculated (1).

\[
\alpha = \arctan\left(\frac{s_P^i - s_L^i}{L}\right) \tag{1}
\]
The wheelchair’s trajectory can be described as a change of position in space for a point constituting as the central point of wheelchair’s rear drive wheel axle. Because of this, a path of \( s_C \) axle central point, which constitutes as mean of roads travelled by \( s_L \) left wheel and \( s_P \) right wheel, should be determined for each trapezoid describing the road at regular \( t \) intervals (2).

\[
\frac{s_C^i}{2} = \frac{s_L^i - s_L^{i-1}}{2}
\]  

(2)

Determination of wheelchair’s motion trajectory according to the trapezoid method consists of building whole wheelchair’s road using specific trapezoid in compliance with several principles (Fig. 2 C, B). The first trapezoid framing the road of wheels and central axle point always has the \( L \) base parallel to the x axis describing the axis middle for time \( t=0 \), which constitutes as the start of coordinate system. Each subsequent trapezoid should be drawn in such a way that its \( L \) base will lie on the line inclined at the \( \alpha \) angle and will connect the ends of \( s_L \) left wheel and \( s_P \) right wheel road from the previous propulsion cycle. In addition, the central points of drive wheel axle from the end of previous and beginning of new time interval should overlap as it is shown in case of point B (Fig. 2 C).

In order to determine wheelchair’s trajectory, it is sufficient to determine the coordinates of drive wheel axle central point location for the end of each distributed propulsion intervals (Fig. 2 D). Coordinates \( x_0=0 \) and \( y_0=0 \) are adopted as the first point. Coordinates of the second point are \( x_1=0 \) and \( y_1=s_C^1 \). Coordinates of each subsequent point are determined using equations (3, 4):

\[
x_i = x_{i-1} + s_L^i \cdot \sin(\beta_i),
\]

(3)

\[
y_i = y_{i-1} + s_L^i \cdot \cos(\beta_i).
\]

(4)

Where the \( \beta \) angle is described with equation that is the sum of all preceding \( \alpha \) angles of the line connecting ends of roads for both \( s_L \) left wheel and \( s_P \) right wheel (5).

\[
\beta_i = \beta_{i-1} + \alpha_{i-1}
\]

(5)

3. Measurement system

The research was conducted using a measurement system consisting of two incremental encoders 1 connected with central unit 2 that transmits the measurement signal to in-house software (Fig. 3). The measurement system used Hohner 21-122-500 encoders with 500 impulse resolution. The angular velocity was determined using the \( \omega_L \) left and \( \omega_P \) right drive wheel. Next, the angular velocity was used to generate a histogram of wheelchair’s velocity progress. With known linear velocity of wheelchair, the \( v(t) \) for each of independently powered wheels was determined for road travelled by \( s_L \) left wheel (6) and \( s_P \) right wheel (7).

Figure 3. Wheelchair with test apparatus used to measure its motion kinematics, where: 1 - incremental encoder with 500 step resolution, central unit collecting measurement signal.
\[ s_L = \int_{t_{\text{start}}}^{t_{\text{end}}} v_L(t)\,dt = R \int_{t_{\text{start}}}^{t_{\text{end}}} \omega_L(t)\,dt \]  
\[ s_P = \int_{t_{\text{start}}}^{t_{\text{end}}} v_P(t)\,dt = R \int_{t_{\text{start}}}^{t_{\text{end}}} \omega_P(t)\,dt \]  

where: \( s_L \) – road travelled by left wheelchair wheel within adopted time interval, \( s_P \) – road travelled by right wheelchair wheel within adopted time interval, \( t_{\text{start}} \) – time of commencing a propulsion cycle, \( t_{\text{end}} \) – time of concluding a propulsion cycle, \( v_L \) – left wheelchair wheel linear velocity measured with regular time interval, \( v_P \) – right wheelchair wheel linear velocity measured with regular time interval, \( \omega_L \) – left wheelchair wheel angular velocity measured with regular time interval, \( \omega_P \) – right wheelchair wheel angular velocity measured with regular time interval, \( R \) – radius of wheelchair’s drive wheel.

4. Results

Method verification was conducted for laboratory measurements and measurements in real conditions. In case of laboratory measurements, the wheelchair was located on a stand equipped with traction rolls A (Fig. 4). Exemplary results of trajectories determined on the basis of known wheel velocities for bench testing were presented in Fig. 5 and 6.

![Figure 4](image)

**Figure 4.** Examined wheelchair on a test stand with indicated wheelchair inclination system B-F and system of traction rolls receiving drive torque of a wheelchair’s wheel.

![Figure 5](image)

**Figure 5.** Exemplary wheelchair trajectory charts, where trajectory is determined during bench testing on the basis of velocity measurement
In case of bench testing, the motion trajectory was determined only on the basis of road travelled by the wheelchair during propulsion phase and did not take into account road travelled during the phase of hand returning to initial position. This results from the construction of a stand, which does not allow to accumulate inertia force energy and as a result the wheelchair’s wheel stops rotating when the hand returns to initial position during return phase.

The effectiveness of developed wheelchair trajectory determination method was also tested during propulsion the wheelchair in real conditions. Exemplary results of wheelchair’s wheel velocity during travelling inside a building are shown in Fig. 7. Next, these results were used to visualise the wheelchair’s motion trajectory (Fig. 8).

Figure 7. Chart of left and right wheel velocity measured during propulsion the wheelchair in real conditions and used to determine the wheelchair’s motion trajectory

Figure 8. Exemplary trajectory charts for a wheelchair powered in real conditions
5. Summary

The developed method of determining wheelchair trajectory uses only measurement signal received from encoders. This translates into simple measurement system structure, which can be adopted in any wheelchair type and model equipped with manual drive. The described method proves itself as a tool that enables to draw trajectory in real time. Therefore, it is possible to create a feedback with user during operation in laboratory conditions. In addition, this method can constitute as a tool, which allows to analyse the wheelchair’s motion kinematics and inspect the motion trajectory influence on biomechanical parameters [14] accompanying the combination of a human with wheelchair.

The accuracy of calculated trajectory depends on the sampling time and resolution of used encoders. The term sampling time mean time interval utilised to measure velocity or road travelled by drive wheel. Lowering the sampling time value results in greater the accuracy of generated trajectory. However, this translates into increase of iterations, which the program executing presented mathematical model must performed. As a result, a delay in the presented trajectory chart may occur. This phenomenon is especially undesired in case of presenting trajectory in real time.

The influence of encoder resolution on measurement accuracy results from the number of impulses that the encoder can generate during on full rotation of measurement wheel. In case of a too small encoder resolution, it is possible that a phenomenon, in which an identical amount of impulses generated by the encoder will be measured for several subsequent sampling times (iterations), will occur. When designing a test procedure, the sampling time should be appropriately selected depending not only on the encoder resolution, but also the envisioned wheelchair velocity. At high wheelchair velocities it is recommended to reduce the sampling time. However, the sampling time can be increased at low velocities.

Conclusion

The method described in the article has been verified during numerous measurement trials in laboratory and real conditions. The correctness of its operation has been confirmed during the said tests. Therefore, it became a useful tool in visualisation of road travelled by a wheelchair and other vehicles that are controlled differentially [18, 19]. Despite this, it is recommended to conduct further studies that will allow to determine the influence of used encoder’s resolution and adopted sampling time as maximum wheelchair velocity ranges, for which the trajectory render accuracy is at a satisfying level.

Further plans include the development of this method, as well as its modification in order to enable trajectory visualisation in a three-dimensional system. For this purpose, it will be necessary to equip the measurement system with a gyroscope that will allow to measure the wheelchair inclination angle. Knowledge of this angle will enable the determination of changes in terrain height, on which the wheelchair moves. Another considered development direction for the measurement system is the method of coupling rotational velocity sensors with wheel. The utilised friction connection influences the deformation of wheelchair’s tyre while leaving a connection through a strand-type transmission can provide a connection, which will not require adjustment during wheelchair’s operation with various pressure in wheels or various wheelchair load conditions [20, 21].

References

[1] Van der Woude L H V Veeger H E J Rozendal R H and Sargeant A J 1989 Optimum cycle frequencies in hand-rim wheelchair propulsion European journal of applied physiology and occupational physiology 58(6) 625-32
[2] Shimada S D Robertson R N Bonninger M L and Cooper R A 1998 Kinematic characterization of wheelchair propulsion Journal of rehabilitation research and development 35(2) 210-8
[3] Kukla M Wieczorek B Warguła Ł and Berdychowski M 2019 An analytical model of the demand for propulsion torque during manual wheelchair propelling Disability and Rehabilitation: Assistive Technology 1-8.
[4] Morrow M M Rankin J W Neptune R R and Kaufman K R 2014 A comparison of static and dynamic optimization muscle force predictions during wheelchair propulsion Journal of biomechanics 47(14) 3459-65
[5] Kuśla M Wieczorek B and Warguła Ł 2018 Development of methods for performing the maximum voluntary contraction (MVC) test MATEC Web of Conferences 157 05015
[6] Warguła Ł Wieczorek B and Kuśla M 2019 The determination of the rolling resistance coefficient of objects equipped with the wheels and suspension system - results of pilot tests MATEC Web of Conferences 254 01005 https://doi.org/10.1051/matecconf/201925401005
[7] Pałasz B Waluś K J and Warguła Ł 2019 The determination of the rolling resistance coefficient of a passenger vehicle with the use of roller test bench method MATEC Web of Conferences 254 04007 https://doi.org/10.1051/matecconf/201925404007
[8] Pałasz B Waluś K J and Warguła Ł 2019 The determination of the rolling resistance coefficient of a passenger vehicle with the use of selected road tests methods MATEC Web of Conferences 254 04006 https://doi.org/10.1051/matecconf/201925404006
[9] Sawicki P Waluś K J and Warguła Ł 2018 The comparative analysis of the rolling resistance coefficients depending on the type of surface – experimental research Transport Means: Proceedings of the 22nd International Scientific Conference 434-41
[10] Warguła Ł Kuśla M and Wieczorek B 2020 The impact of wheelchairs driving support systems on the rolling resistance coefficient IOP Conf. Series: Materials Science and Engineering 776 012076 https://doi.org/10.1088/1757-899X/776/1/012076
[11] Wieczorek B and Warguła Ł 2019 Problems of dynamometer construction for wheelchairs and simulation of push motion MATEC Web of Conferences 254 01006
[12] Kuśla M Wieczorek B Warguła Ł and Gorecki J 2019 The determination of the parameters of wheelchair driving with the use of a test bench Autobusy: technika, eksplatacja, systemy transportowe 20
[13] Wieczorek B and Kuśla M 2020 Biomechanical Relationships Between Manual Wheelchair Steering and the Position of the Human Body's Center of Gravity Journal of Biomechanical Engineering 142(8)
[14] Wieczorek B and Kuśla M 2019 Effects of the performance parameters of a wheelchair on the changes in the position of the centre of gravity of the human body in dynamic condition PloS one 14(12) e0226013
[15] Wieczorek B Kuśla M and Warguła Ł 2020 Methods for measuring the position of the center of gravity of an anthropotechnic human-wheelchair system in dynamic conditions Materials Science and Engineering Conference Series 776(1) 012062
[16] Wieczorek B Gorecki J Kuśla M and Wojtokowiak D 2017 The analytical method of determining the center of gravity of a person propelling a manual wheelchair Procedia Engineering 177 405-10
[17] Wieczorek B Warguła Ł and Rybarczyk D 2020 Impact of a hybrid assisted wheelchair propulsion system on motion kinematics during climbing up a slope Applied Sciences 10(3) 1025
[18] Rybarczyk D and Milecki A 2020 Electrohydraulic Drive with a Flow Valve Controlled by a Permanent Magnet Synchronous Motor Transactions of FAMENA 44(2) 0-0
[19] Waluś K J Warguła Ł Krawiec P and Adamięc J M 2017 The impact of the modernization of the injection-ignition on the parameters of motion of the motorcycle Procedia Engineering 177 393-8
[20] Krawiec P Róžański Ł Czarnecka-Komorowska D and Warguła Ł 2020 Evaluation of the Thermal Stability and Surface Characteristics of Thermoplastic Polyurethane V-Belt Materials 13 1502
[21] Krawiec P Pajtášová M Meler F and Warguła Ł 2020 Testing functional features of V-belt transmissions IOP Conf. Series: Materials Science and Engineering 776 012008 https://doi.org/10.1088/1757-899X/776/1/012008

Acknowledgments
The research was made as part of the Lider VII project “Study of the biomechanics of manually propelled wheelchair for innovative manual and hybrid drives” (LIDER/7/0025/L/-7/15/2016) financed by the National Centre for Research and Development.