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Simulation of Fuzzy-Logic-Based Intelligent Wheelchair Control System

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Abstract. Fuzzy logic control system for an intelligent wheelchair aimed for assistance by the severely handicapped persons is presented in the paper. It is based on a computer simulation of wheelchair navigation, in which fuzzy logic enables control priority to smoothly alternate between manual and automatic control of the wheelchair in the vicinity of obstacles. The main purpose of designing and simulating this control approach is to improve the safety of a wheelchair in the presence of obstacles. To analyze the success of the wheelchair control, a dynamic model of the wheelchair, together with the models of distance sensors, has been developed using Lagrange analysis.

Key words: wheelchair control, intelligent control system, fuzzy logic, computer simulation.

1. Introduction

Increasingly more handicapped persons, as well as the elderly, are compelled to make use of rehabilitation technology for their mobility. *Sensor-integrated wheelchairs* have begun to be developed, sometimes termed "intelligent" wheelchairs. Their purpose is to enable disabled persons that are incapable of quickly reacting to nearby obstacles to convey themselves from one end of a space to the other. In doing so, such a robotic wheelchair must be capable of recognizing its position in space at any given moment, determining relative distances to obstacles, and avoiding them.

The majority of such wheelchairs are based on standard commercial electric wheelchairs, equipped with various sensor systems [7]: ultrasonic sensors, infrared sensors, microswitches on their bumpers, active (camera and laser diode) and passive vision, and GPS. The user can steer the wheelchair with manual controls – joysticks (like an ordinary wheelchair) or through other systems: eye movements, head movements, voice recognition. Because the system being tested transports handicapped or elderly persons that are dependent on the system's behavior in an environment surrounded by other persons and objects, safety is a very important factor. In contrast to other service robots, an autonomous wheelchair is guided in two ways: either by the user with manual controls or automatically [4, 6]. If the user steers the wheelchair in a way that will cause it to collide with an obstacle, the navigation system then takes over and controls the wheelchair so that it avoids collision with the obstacle.

The purpose of this article is to present the operation of a PC-based experiment system for persons with special needs, by simulating the operation of an intelligent wheelchair with added safety systems. We conceived the improvement of electric wheelchair safety through the use of fuzzy logic, which offers the possibility of blending information and establishing principles with regard to expert experience. The literature [1, 5, 7] presents models that, based on the state of sensors and using advanced algorithms (a vector field histogram, switching between basic behaviours), calculate the optimum angle and speed of a wheelchair based on the distance of each sensor from an obstacle. In our case, we directly control the drive motors of the wheelchair with fuzzy logic.

Because all of the results presented are the outcome of computer simulations, in Section 2 the dynamic model of a wheelchair is presented using Lagrange analysis. In the model of the wheelchair we have added the characteristics of the drive motors, and in the simulation scheme a joystic control is included. Because all the principles of controlling *safe* wheelchairs are based on the recognition of the distance of the wheelchair from obstacles, we have developed a method for calculating the distance from a sensor to an obstacle through homogenous transformations.

Wheelchair navigation with fuzzy logic, which is divided in to two modules, is presented in Section 3. The first module defines the control priority in a space (manual/automatic), and the second calculates the voltage of the drive motors in automatic control mode.

2. Modeling

The structures of wheelchairs differ depending on their intended use. The typical structure of an electrical wheelchair that enables a high degree of maneuverability is that with two front drive wheels. The difference in angular velocity defines the direction of the wheelchair movement. The rear wheels are free-moving castors and therefore follow the movements of the wheelchair. Such a system is very maneuverable at low speeds and suited for indoor use.

We are dealing with a coupled electro-mechanical system in which two independent electrical motors produce torques influencing the rotation angle (φ_1 and φ_2) of the two front drive wheels [9]. Figure 1 shows the structure of the wheelchair with defined coordinate systems. The wheelchair is composed of a rigid platform and non-deforming wheels, and it moves in a horizontal plane ($z = 0$). The position and orientation of the wheelchair is described by the vector:

$$\boldsymbol{\xi} = \begin{bmatrix} x \\ y \\ \alpha \end{bmatrix}. \tag{2.1}$$

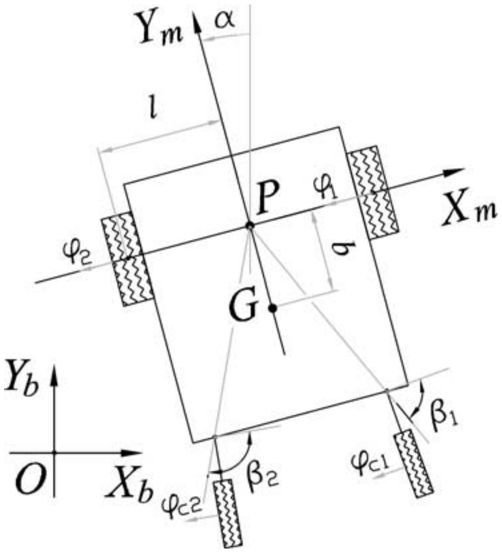

Figure 1. Presentation of wheelchair in a coordinate system.

The rotational matrix $\mathbf{R}(\alpha)$ expresses the orientation of the base coordinate system (X_b, Y_b) with regard to the moving coordinate system (X_m, Y_m), which is attached to the wheelchair at point P:

$$\mathbf{R}(\alpha) = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{2.2}$$

The plane of rotation of the drive wheel is constant in relation to the wheelchair. The time variable describing the angle of rotation is $\varphi(t)$. The plane of rotation of the castor wheel changes with respect to the platform of the wheelchair. The wheel turning axis is vertical and does not intersect with the wheel axis of rotation. The two time variables are the angle of rotation $\varphi(t)$ and the turning angle of the wheel plane of rotation $\beta(t)$.

Translational and angular velocity of the wheelchair are indicated with the vector $\boldsymbol{\eta}$:

$$\boldsymbol{\eta} = \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} = \begin{bmatrix} \dot{Y}_\mathrm{m} \\ \dot{\alpha} \end{bmatrix}. \tag{2.3}$$

The further derivation of the dynamic model relies on Lagrange analysis. Here, we must know the difference between the kinetic and potential energy of the system. Because of the assumption that the wheelchair is moving only horizontally, its potential energy is constant. The kinetic energy of the entire wheelchair is a combination of the kinetic energy derived from individual parts of the wheelchair: platform and the person, drive wheels and the castor wheels. The rear wheels are smaller than the drive wheels, and their contribution to the dynamics is therefore

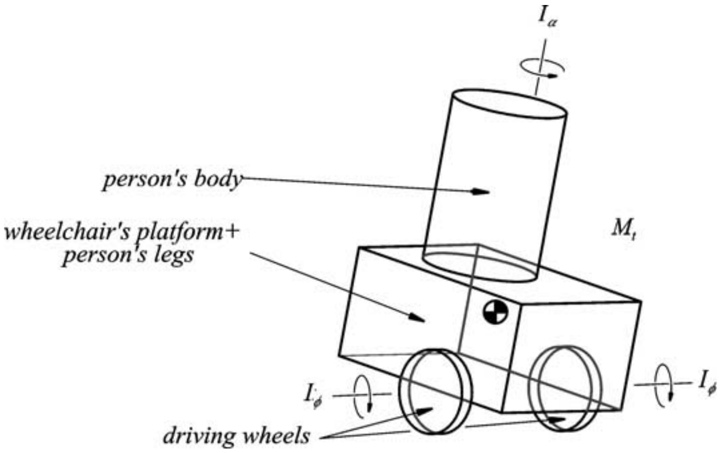

Figure 2. 3D model of the wheelchair.

negligible. We consequently lose four variables (two angles of rotation φ and two turning angles β) which are completely insignificant for our needs in the model.

The entire kinetic energy of the system, as shown in Figure 2, is thus

$$T = \frac{1}{2}M_t v_{gt}^2 + \frac{1}{2}I_\alpha\dot{\alpha}^2 + \frac{1}{2}I_{\varphi 1}\dot{\varphi}_1^2 + \frac{1}{2}I_{\varphi 2}\dot{\varphi}_2^2; \tag{2.4}$$

v_{gt} is the relative velocity of the center of gravity of the entire system, M_t is the mass of the entire system, I_α is the inertial moment of the entire system around the vertical axis through its center of gravity, and I_{φ_1} and I_{φ_2} are the inertial moments of the drive wheels around the horizontal axes through their center of gravity.

We must define the velocity of the movement of the wheelchair center of gravity v_{gt}. O is the center of the base coordinate system, G is the center of gravity of the entire wheelchair (platform with motors and batteries, drive wheels and the disabled person), and b is the distance from the center of gravity of the system to the coordinate system of the wheelchair.

With respect to Figure 1, vector $\overline{OG}$ is defined as

$$\overline{OG} = (x + b\sin\alpha,\, y - b\cos\alpha)\,. \tag{2.5}$$

The kinetic energy described in quadratic form is as follows:

$$T = \frac{1}{2}\dot{\boldsymbol{\xi}}^T\mathbf{M}(\alpha)\dot{\boldsymbol{\xi}} + \frac{1}{2}\dot{\varphi}^T\mathbf{I}_\varphi\dot{\varphi}, \tag{2.6}$$

in which the individual matrices are defined

$$\mathbf{M} = \begin{bmatrix} M_t & 0 & 0 \\ 0 & M_t & 0 \\ 2M_t b\cos\alpha & 2M_t b\sin\alpha & I_\alpha + b^2 M_t \end{bmatrix}, \qquad \boldsymbol{\xi} = \begin{bmatrix} x \\ y \\ \alpha \end{bmatrix},$$
$$\mathbf{I}_\varphi = \begin{bmatrix} I_{\varphi_1} & 0 \\ 0 & I_{\varphi_2} \end{bmatrix}, \qquad \varphi = \begin{bmatrix} \varphi_1 \\ \varphi_2 \end{bmatrix}. \tag{2.7}$$

With the use of Lagrange analysis [10], we arrive to a final form of the equation of the wheelchair's dynamics:

$$\begin{bmatrix} M_t + \frac{1}{r^2}(I_{\varphi_1} + I_{\varphi_2}) & 0 \\ 0 & I_\alpha + b^2 M_t + \frac{l^2}{r^2}(I_{\varphi_1} + I_{\varphi_2}) \end{bmatrix} \begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -M_t b\dot{\alpha} & 0 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} = \left(\frac{1}{r}\right) \begin{bmatrix} 1 & 1 \\ l & -l \end{bmatrix} \begin{bmatrix} \tau_{\varphi_1} \\ \tau_{\varphi_2} \end{bmatrix}. \tag{2.8}$$

Two additional equations, which represent the kinematic part, complete the dynamic model:

$$\dot{\boldsymbol{\xi}} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} = \begin{bmatrix} -\sin\alpha & 0 \\ \cos\alpha & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix}, \tag{2.9}$$

$$\dot{\varphi} = \frac{-1}{r} \begin{bmatrix} 0 & 1 & l \\ 0 & -1 & l \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} = \frac{1}{r} \begin{bmatrix} 1 & l \\ 1 & -l \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix}. \tag{2.10}$$

Here r is the radius of the drive wheel and $2l$ is the distance between the drive wheels.

The above derivation of the dynamic equations of the movement of the wheelchair is valid only for conservative systems and does not take any losses into account. Therefore, we must supplement the system with the effects of friction. A simplified equation for calculating the necessary torque to cover the loss through the friction of the rubber wheels on the floor is

$$M_{\text{loss}} = M_t g e, \tag{2.11}$$

in which e is the equivalent lever arm of the rolling friction, and g is gravitational acceleration.

For the authentical simulation of a real system, the system parameters (mass, inertial moment, lever arms) of the model must be assessed as precisely as possible. The inertial moment I_α was derived from a three-dimensional model of the wheelchair (Figure 2). We have assumed that the person is in a rigid position in the wheelchair, and his or her inertial moment is therefore added to the inertial moment of the wheelchair. Because the axes of the centers of gravity of the individual parts do not coincide with the axis through the center of gravity of the entire system, for which we calculate the inertial moment, we have used the Steiner's theorem.

Table I gives the parameters that were used in simulating the movement of the wheelchair and they are estimated from the dimensions of an ordinary electric wheelchair.

For wheelchair drive, we chose two 150 W DC motors, which were installed using gear boxes in each drive wheel (right and left). The characteristic of the motor and gear ratios (1 : 20) was calculated so that the final velocity of the wheelchair would be 5 km/h, and the acceleration and deceleration times satisfactory (ca. 1 s).

Table I. Description of parameters and their values

Parameter	Meaning	Value	Unit
r	Drive wheel radius	0.15	m
l	Distance of the wheel center from the wheelchair axis	0.28	m
M_t	Mass of the entire system	120	kg
I_α	Inertial moment around the vertical axis through the center of gravity	7.6	$\mathrm{kg\,m^2}$
I_φ	Inertial moment of the wheels around the horizontal axis	0.028	$\mathrm{kg\,m^2}$
e	Equivalent lever arm of rolling friction	0.002	m
b	Distance of the system center of gravity from the center of the wheelchair coordinate system	0.1	m

Motors are also capable of braking if the wheelchair inertia causes the motor to rotate faster than desired according to the rotation selected for the motor (depending on the position of the joystick). In this case we are speaking of motor four-quadrant operation, because the operating point is found in all four quadrants of motor speed/torque characteristic.

The majority of control systems of DC motors operate on the principle of pulse width modulation (PWM). For a clearer presentation, the desired number of revolutions of the motor is designated j and is within the range between -1 (100% PWM, reverse) and 1 (100% PWM, forward) for both directions of rotation.

2.1. SENSORS USED IN THE MODEL

For the safe navigation of a smart wheelchair, sensors installed on the wheelchair measuring the distance to obstacles in the space are of primary importance. The best-known contactless sensor systems are based on the *time of flight measuring principle* [2]. Usually ultrasonic sensors are used, although laser and optical sensors are also possibilities. Ultrasonic sensors emit short, pulsating ultrasonic waves that hit against obstacles and travel back to a receiver, which measures the time of flight and calculates the distance

$$D = \frac{t v_\mathrm{s}}{2}. \tag{2.12}$$

D is the distance between the sensor and the obstacle, t is the time interval between the emission of the wave pulse and receiving its reflection, and v_s is the speed of sound (340 m/s in air at room temperature).

We "*mounted*" eight ultrasonic sensors on the wheelchair to measure the distance to obstacles in directions at 45° relative to the wheelchair coordinate system

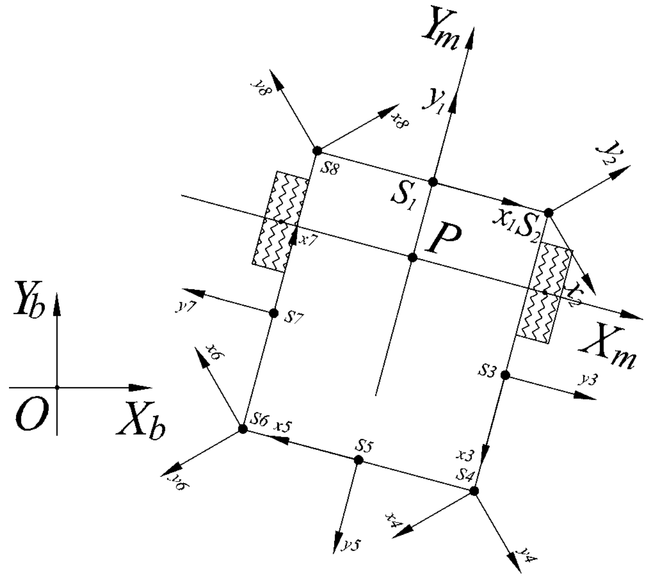

Figure 3. Mounting of distance sensors on the wheelchair.

(X_m, Y_m). The positions and their coordinate system is shown in Figure 3. Each sensor is represented with its own coordinate system (x, y), in which the direction of the y-axis defines the direction of the emitted waves.

During navigation the values of the sensor signals change with regard to the position and orientation of the wheelchair. By using homogeneous transformations, the position and orientation of a particular sensor at any moment are defined. The transformation matrix that defines the pose (position and orientation) of the coordinate system of the wheelchair with respect to the base coordinate system has variable elements with regard to the position ad orienation of the wheelchair (coordinates x and y, and angle α). On the other hand, the transformation matrices that define the position of the coordinate system for a particular sensor with regard to the coordinate system of the wheelchair are matrices with constant elements.

By multiplying the individual matrix $\mathbf{T}_i$ by the basic matrix $\mathbf{T}_0$, we obtain the position of the sensor coordinate system with respect to the base coordinate system $\mathbf{T}_{0i}$ for all eight sensors mounted on the wheelchair:

$$\mathbf{T}_{0i} = \mathbf{T}_0 \cdot \mathbf{T}_i, \quad i = 1, \dots, 8. \tag{2.13}$$

It is thus possible to define a straight line that shows the direction the sensor waves are emitted and the position of the sensor. If we assume that the obstacles (e.g., walls) are fixed, then we can describe them with series of short straight lines if we know their beginning and the end point. Geometric procedures allow us to calculate the distance that the sensor measures.

A certain amount of time is needed for the waves to reach the wall and be reflected from it, and for the sensor to recognize the reflection. In our simulation scheme, therefore, a variable delay for each sensor must be added. The noise with maximal amplitude, which corresponds to the accuracy of the real ultrasonic sensor, is also added to the sensor model.

3. The assistance of fuzzy logic in controlling the wheelchair

The goal was to develop a navigation system based on fuzzy logic for controlling an intelligent wheelchair. Controlling the wheelchair with fuzzy logic works in such a way that we control the wheelchair with the joystick while tracking its movements on a monitor, and the fuzzy algorithm ensures that we do not strike a wall or other potential obstacle. The configuration of rooms (hallway, wall, corner, etc.) for the navigation system can be chosen before the simulation.

The fuzzy algorithm is divided into two parts:

- Defining the control priority (manual-automatic).
- A fuzzy switching between different navigation modes in the vicinity of obstacles.

The input signals to the fuzzy regulators are the sensors outputs; that is, distance x in meters. Because of the limits on sensor range, the highest value is 10 m.

Fuzzy sets are the basis of the theory of fuzzy logic. Characteristic for the Mamdani principle [3, 8] are fuzzy control rules written as:

$$\textbf{if } x_1 \text{ is } A_1 \text{ and } \dots \text{ and } x_n \text{ is } A_n \textbf{ then}$$

$$y_1 \text{ is } B_1, \dots, y_n \text{ is } B_n.$$

In all blocks, for fuzzy operators we used *max* operation for the OR function, and *min* for the AND function. The *truncate* principle was used for *implications*, and *aggregation* used the *max* method. For computing the defuzzified value of the control output the following methods were used: *center of area* (COA), *mean of maximum* (MOM), and *bisector of area* (BOA) [3].

3.1. FUZZY DEFINING OF CONTROL PRIORITY

A sensor-integrated wheelchair represents a shared control system, in which the user and the computer-sensor system share control of the wheelchair depending on presence of obstacles. The switching between manual and automatic control of intelligent wheelchairs is described as abrupt in the literature [4–6]. The user unexpectedly loses control over the wheelchair without being prepared for this. It is also very awkward for the user when the ability to control the wheelchair is returned. If this is not gradual, the position of the joystick can be incorrect at this moment, which can lead to the wheelchair incorrect movement. It is more efficient if the switching is smooth and the user can feel the change. During the transition time, the user can continue to exert some influence on the wheelchair movement,

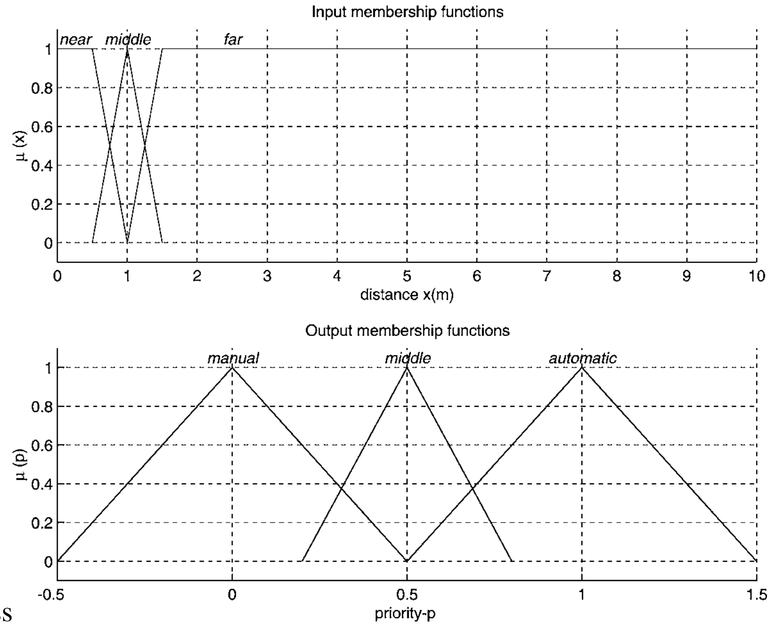

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Figure 4. Input and output membership functions (priority).

because control by the user and the automatic control are weighted differently. The tool that offers this possibility in theory is fuzzy logic.

All eight input signals are fuzzified through three membership functions (*near*, *middle*, and *far*). Output is a priority value, which also has three membership functions (*manual*, *middle*, and *automatic*), so that the transition between the individual methods of control is smoother. The value 0 indicates full manual control and 1 full automatic control, and all values between 0 and 1 are weigh of automatic control. Triangular and trapezoidal configurations of membership functions were used for simplicity and the finite areas (Figure 4).

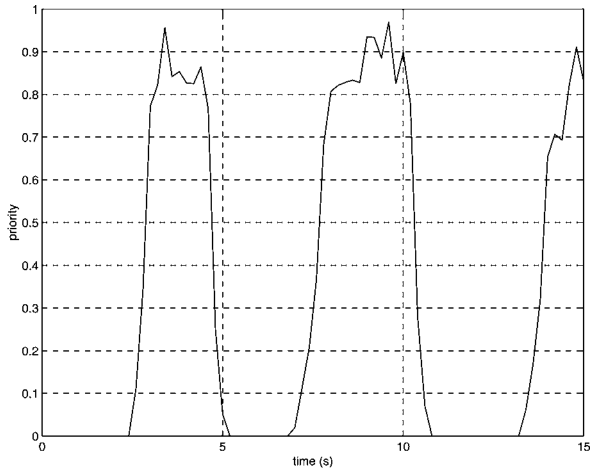
Rules form the basis of the fuzzy controller. It is necessary to ensure that there is at least one rule for each combination of states of the eight sensors representing input into the fuzzy system. We have used three rules, all weighted equally at 1.

As an example of the operation of the *priority* fuzzy system, we used navigation into a corner, where the wheelchair was manually navigated with the joystick. Figure 5(b) shows the path of free navigation of the wheelchair (distances in m), and Figure 5(a) shows the output of the *priority* system.

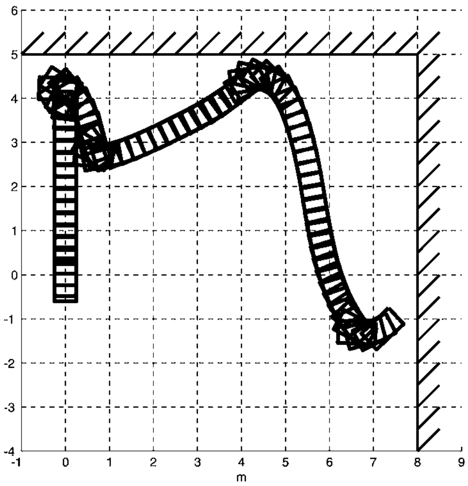
In Figure 5(a) we can see the smooth switching between the manual and automatic control methods. Priority signifies weighting the automatic control method.

3.2. FUZZY CONTROL OF THE WHEELCHAIR'S MOTORS

If the wheelchair approaches an obstacle, priority must switch over to the automatic control method, which takes care that the wheelchair is safely driven past the



(a)



(b)

Figure 5. Priority fuzzy system results while navigating a corner: (a) priority block output; (b) wheelchair path.

obstacle. In this section the operation of the *motor* fuzzy system, which calculates the voltage (PWM) of the left and right motor when the wheelchair is in the vicinity of obstacles is presented. This switching smoothly between the predefined modes of the wheelchair movement (*left, right, forward, reverse, stop*). The output is the voltage to the wheelchair left and right motors, which is given at relative levels between −1 (100% PWM, reverse) and 1 (100% PWM, forward).

Just as with *priority*, input has eight signals, which are the outputs of the sensors. Each has only two membership functions, because such a precise recognition

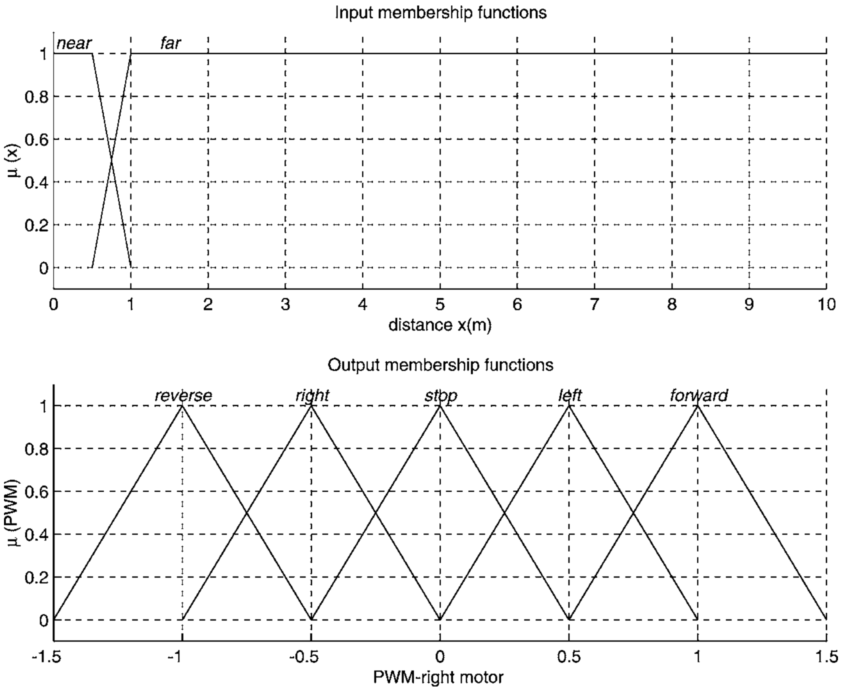


Figure 6. Input and output membership functions (motor).

of the distance of the sensor to the obstacle is not necessary to define the voltage to the motors. The output consists of two voltages with five membership functions. The core consists of a Mamdani controller with 17 rules.

The membership functions are selected triangular and trapezoidal configurations. The membership input functions are identical in all eight input signals, and two membership functions with a trapezoidal configuration are used: *near* and *far* (Figure 6). The range of the membership input functions is between 0 and 10 m.

There are five membership output functions for each motor. All have a triangular shape and are differentiated by the position of the membership functions for the directions *right* and *left*, if we compare both outputs (voltage in the left and right motors).

We selected the rules used in the fuzzy system to most closely follow how humans react when an obstacle appears in their vicinity. These differ somewhat with respect to whether the wheelchair is approaching an obstacle head-on or in reverse. We attempted to satisfy the demand for the *completeness of the rules*, which means that for every state of the sensor output signals there exists at least one rule. Otherwise it happens that the output from the fuzzy controller (voltage to both motors) is the middle value in the range of output magnitude between -1 and 1. This means that PWM equals 0 and the wheelchair would come to a stop. Two of 17 rules (with its weights at the end) are presented bellow:

If (sensor1 is near) and (sensor3 is far)
then (motor-r is right)(motor-l is right). (1).
If (sensor2 is near) and (sensor4 is far)
then (motor-r is left)(motor-l is left). (0.5).

Because of the wheelchair inertia, it is very important what the output voltage signal powering the wheelchair motors is like, and how fast the change in the voltage reference in the motors is in a conflicting situation. We have ascertained that the very choice of the method of crisping in fuzzy blocks has a great influence on the course of the trajectory. The most applicable methods proved to be *mean of maximum* (MOM) and *bisector of area* (BOA).

3.3. SIMULATION SCHEME

Because of the simplicity of the block presentation of the simulation scheme and the accessibility of software tools, for the simulation we used the Matlab 6.5 software package, which includes Simulink for dynamic systems simulation. Several integration methods have been tested, but the most convenient is single step explicit Runge–Kutta (4,5) integration method with adaptive integration step. Results obtained with explicite Runge–Kutta (2,3) and implicite Runge–Kutta integration methods not differ a lot. Mutistep solver (Adams–Bashforth–Moulton) gives different results and is not convenient.

We described the entire dynamic model of the wheelchair with the software tool Simulink with its standard blocks. In addition to these, we used the *S*-function for more complex calculations. For animation we entered the *S*-function *wheelanim, joystick* for joystick output calculation, and *RT SINH* was used for synchronization the computing time with real time.

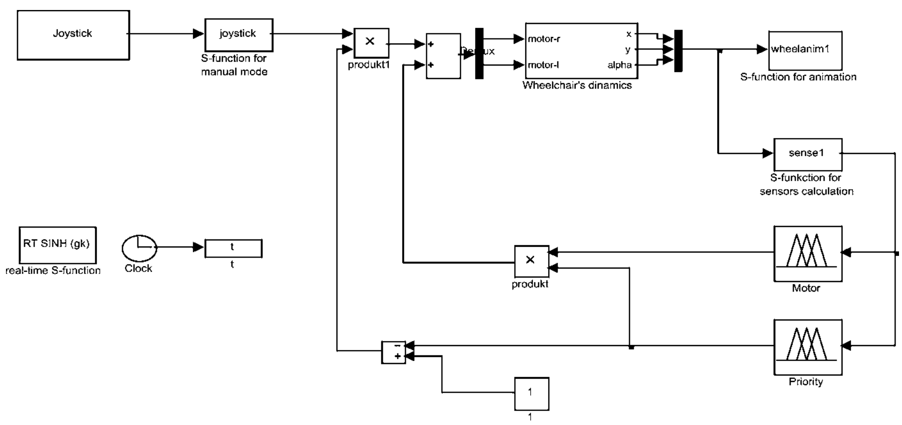
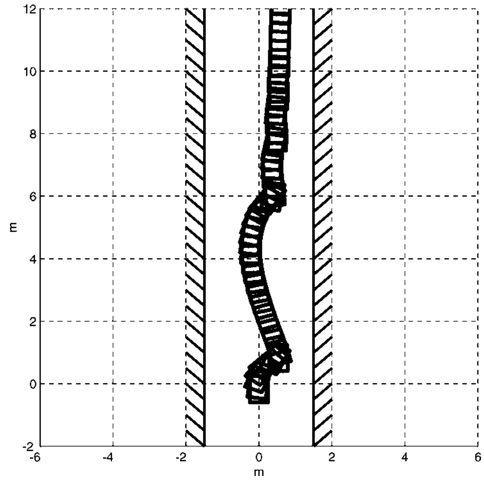
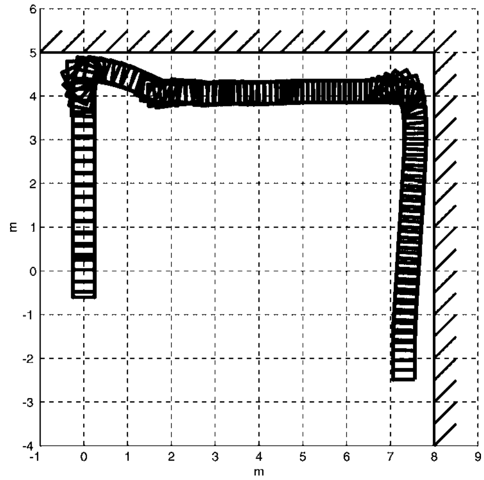


Figure 7. Simulation scheme of wheelchair fuzzy logic control.



(a)



(b)

Figure 8. Simulation results: (a) long corridor, (b) corner.

In the wheelchair simulation of the movement through space, for the purposes of studying the effectiveness of automatic control in comparison to manual, a joystick is included. During a simulation in real time we can use it to influence the torque of the electric motor and represent the function of the manual control installed on the wheelchair.

The simulation scheme of wheelchair fuzzy logic control, which contains the *Priority* and *Motor* fuzzy systems, is shown in Figure 7.

We wished to present the results of the simulation (Figure 8) as navigation through some typically configured spaces that appear in real life: a long corridor and a corner. In both cases we deliberately held the manual control in such a position as to steer the wheelchair into the wall. The idea underlying this decision was to show the effectiveness of the control in the most critical cases.

Noise, which was added to the sensor outputs, influences on the wheelchair trajectory. However, if the maximal amplitude of the added noise is lower than 0.5 m (which corresponds to 5% accuracy of the total sensor range – 10 m), the collision with an obstacle is always avoided. This confirms the robustness of the presented control method.

4. Conclusion

The article has described an experimental system for an intelligent wheelchair control. The goal is to improve the safety of the electric wheelchair, which has become an indispensable means of transport both for the handicapped and for the elderly.

We based the control of the wheelchair on fuzzy logic, which is becoming an increasingly used tool for controlling nonlinear processes, and which is superior in designing of a controller on the basis of human experience.

For the needs of analyzing the success of controlling the wheelchair through simulation, we developed a dynamic model of the wheelchair with Lagrange analysis taking into account the characteristics of DC motors and including a manual joystick control in the simulation scheme. Our evaluation of the model demonstrated that its operation is sufficient and that it approximates the operation of an actual wheelchair.

The experimental system operates sufficiently well to be learned by handicapped persons that have reduced reaction capabilities and by the visually impaired and those that have decided to use a sensor-integrated wheelchair, although they still do not have sufficient experience to be able to use an actual sensor-integrated wheelchair. For approach a learning system to the real situation, it is necessary to add a hydraulic platform to simulate the forces that act upon the wheelchair during its navigation.

Acknowledgements

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References

1. Bell, D., Borenstein, J., Levine, S., Koren, Y., and Jaros, A.: The NavChair: An assistive navigation system for wheelchairs, based on mobile robot obstacle avoidance, in: *IEEE Internat. Conf. on Robotics and Automation*, San Diego, CA, 8–13 May 1994, pp. 2012–2017.

2. Borenstein, J., Everett, B., and Feng, L.: Where am I? Sensors and methods for mobile robot positioning, Technical Report, University of Michigan, 1996.
3. *Fuzzy Logic Toolbox User's Guide*, Version 2, The Math Works, Natick, MA, 2000.
4. Lankenau, A. and Röfer, T.: The role of shared control in service robots – The Bremen autonomous wheelchair as an example, in: T. Röfer, A. Lankenau and R. Moratz (eds), *Service Robotics – Applications and Safety Issues in an Emerging Market, European Conf. on Artificial Intelligence 2000 (ECAI 2000)*, pp. 27–31.
5. Lankenau, A. and Röfer, T.: A versatile and safe mobility assistant, in: *Reinventing the Wheelchair, IEEE Robotics Automat. Mag.* **7**(1) (2001), 29–37.
6. Levine, S. P., Bell, D. A., Jaros, L. A., Simpson, R. C., Koren, Y., and Borenstein, J.: The NavChair assistive wheelchair navigation system, *IEEE Trans. Rehabilitation Engrg.* **7**(4) (1999), 443–451.
7. Mazo, M.: An integral system for assisted mobility, in: *Reinventing the Wheelchair, IEEE Robotics Automat. Mag.* **7**(1) (2001), 46–56.
8. Reznik, L.: *Fuzzy Controllers*, Newnes, Oxford, 1997.
9. Vries, T. J. A., Hetern, C., and Huttenhuis, L.: Modeling and control of a fast moving, highly maneuverable wheelchair, in: *Proc. of the Internat. Biomechatronics Workshop*, Enschede, Netherlands, 1999, pp. 110–115.
10. Wit, C. C., Siciliano B., and Bastin, G.: *Theory of Robot Control*, Springer, London, 1996.