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**INNOVATIVE TECHNOLOGIEN, INFORMATIK, SICHERHEIT, PHYSIK UND
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KAPITEL 3 / CHAPTER 3⁶

METHODS AND ALGORITHMS FOR MULTILEVEL CONTROL OF MOBILE REHABILITATION PLATFORMS

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Introduction

Today, nearly 10% of people with disabilities, or approximately 2% of the world's population, require wheelchairs for mobility. Among them, about 45% are not provided with specialized mobility devices for various reasons, and many existing wheelchairs are insufficiently suited to the specific needs of individual users. For example, modern powered wheelchairs typically require direct manual control of movement, usually via a joystick, and many individuals with impaired motor functions are unable to use them. This determines the importance and relevance of developing a multifunctional wheelchair for people with disabilities that accounts for all aspects of functional impairments [1].

There are two main approaches to interaction between people with physical disabilities and technical devices:

- the first approach involves the creation of new types of interfaces;
- the second approach focuses on simplifying the interaction process through the intellectualization of technical devices and the expansion of their functionality.

The development of algorithms enables the creation of comprehensive interaction systems for robotic wheelchairs for people with disabilities. The combination of new types of human-machine interfaces and an intelligent control system can significantly improve control quality [2].

Ultimately, a wheelchair for people with disabilities should implement the concept of delegated autonomy, solving a set of both local and global control tasks. At the same time, an advanced interface should enable the user to control the wheelchair at both the operational and task/behavioral scenario levels. In other words, user commands should be reduced to high-level task sequences, while the autonomous control system handles the interpretation and execution of each task [3].

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Author's sheets: 1,43



It is assumed that the use of such a high-level interface will simplify the control process, making the wheelchair practically useful for a wide range of people with disabilities, while also improving accuracy and speed performance. It should also be noted that the use of an autonomous control system with high-level commands enables expanding the range of applicable human–machine interfaces, including slow neurointerfaces based on electroencephalography (EEG) and functional near-infrared spectroscopy (FNIRS), which cannot be used for direct low-level control. At present, such interfaces are unable to provide an acceptable command input rate for direct motion control. However, certain low-level commands must still be available to the user, such as an emergency stop command [4].

As a base architectural model for the control system of a robotic wheelchair, a service-oriented transport system with autonomous operation capabilities is proposed. A multimodal human–machine interface is used to define control commands at the upper level of the control hierarchy. Direct control is also possible, depending on user preference. The most important aspect of robotic wheelchair development is the method of user interaction. Interfaces of many complex systems already allow people with disabilities to operate them successfully; however, in this case, users are highly diverse in their requirements [5].

Virtually every known method is unsuitable for certain user groups. The robotization of the wheelchair is further complicated by the need to control it in real time under highly diverse conditions, where the cost of error can be extremely high.

3.1 Analysis of Electromechanical Wheelchairs from Foreign Manufacturers

An electromechanical wheelchair is designed for independent mobility both indoors and outdoors for individuals with impairments of the upper and lower limbs. It is powered by an electric drive. Electromechanical wheelchairs may be equipped with various functions, such as:

- tilt of the entire seat;



- backrest recline;
- seat elevation;
- and other features beneficial or necessary for the user's health.

Powered wheelchairs are classified according to the drive wheel configuration:

- rear-wheel drive;
- front-wheel drive;
- mid-wheel drive;
- or all-wheel drive.

Each type has its own motion characteristics. Electromechanical wheelchairs also differ in seat type:

- some resemble standard wheelchair seats;
- others are similar to automotive seats.

The design of electromechanical wheelchairs encompasses a wide range of models, from small, portable units that can be folded or disassembled to large, heavy devices with a full set of functions (often referred to as rehabilitation chairs). The user typically controls speed and direction using a joystick mounted on one of the armrests, connected to a controller, and operated with whichever hand is more convenient. When hand control is not possible, alternative input devices, such as chin-controlled interfaces, may be used. Initially, wheelchairs were designed without consideration for transportation, making them difficult to disassemble. Today, many electromechanical wheelchairs are transportable, and some are easy to disassemble. With increasing user demands, wheelchairs have emerged that are equally suitable for both indoor and outdoor use. The largest foreign manufacturers of electromechanical wheelchairs include:

1. Invacare Corp.;
2. Sunrise Medical;
3. Permobil AB;
4. Pride Mobility Products Corp.



1. Invacare Corporation.

Invacare Corporation is one of the global leaders in the development and manufacturing of medical equipment for home care and rehabilitation. The company name originates from the combination of three English words:

- innovation;
- value;
- care.

Founded in 1885 (as Worthington Company), its modern history began in 1979 when a group of investors led by Malachi Mixon acquired a division from Johnson & Johnson. The headquarters is located in Elyria, Ohio, USA. The company specializes in equipment for people with disabilities and patients requiring long-term care.

Invacare focuses on three main segments integrated into modern digital healthcare platforms:

- mobility: production of manual and powered wheelchairs (TDX, Storm series), as well as sports wheelchairs for Paralympic athletes under the Top End brand;
- lifestyle / Post-acute care: electric homecare beds, pressure-relief mattresses, and patient positioning systems;
- respiratory therapy: stationary and portable oxygen concentrators.

Invacare's activities demonstrate digital transformation through the implementation of monitoring systems. Modern Invacare wheelchairs are equipped with LiNX modules, enabling Bluetooth configuration of motion parameters. The company also implements remote equipment monitoring services. Spare parts supply management at Invacare requires the use of CRM/ERP systems with API support, which is critical for the modern technical equipment market. An interesting case is Invacare's adaptation to regulatory changes. The company operates in more than 80 countries, requiring complex logistics coordination similar to humanitarian logistics challenges. Strict FDA (USA) requirements and European standards compel the company to continuously improve quality control processes. In modern commercial enterprises (for example, in air conditioner sales), the choice of accounting method directly affects the volume of data that must be processed during peak seasons (table



1).

Table 1 – Comparative Analysis of Accounting Methods and Load Forecasting for Information Systems

Accounting Method	Key Characteristics	Level of Automation	Risks (in accordance with ERM)
Automated.	Use of specialized software (Poster, TorgSoft).	Medium.	Limited functionality for service planning.
Integrated.	Integration of CRM, ERP, and accounting systems via APIs.	High.	Complexity of initial data synchronization.
Omnichannel.	A unified mechanism for offline, online, and social media channels.	Maximum.	High load on communication channels and databases.

Author's development.

The quality of the products and their compliance with the specific needs of people with disabilities have enabled the company to achieve leading positions in many markets. Invacare offers a wide range of manual and powered wheelchairs. Its products are characterized by functionality, quality, reliability, and safety. Invacare has repeatedly received awards for its research and innovation activities (figure 1).



Figure 1 – Electromechanical Wheelchair Invacare Karman Healthcare XO-202 Stand-Up Power Wheelchair

Reference: [6].



Invacare powered wheelchairs use rechargeable batteries and can cover distances of 23 to 42 km, depending on the model and additional options. The batteries are charged from a standard power outlet. Battery consumption can be monitored using an LED charge indicator. The obstacle height that an Invacare powered wheelchair can overcome ranges from 10 to 60 mm (for a high-mobility wheelchair).

The travel speed ranges from 6 to 10 km/h; however, it is important to note that the wheelchair's braking distance is approximately 1 meter, which is especially relevant for indoor use. The battery charge should be carefully monitored using a dedicated LED indicator near the power button. When the battery is depleted, the wheelchair can be used in transit (manual) mode. A small turning radius provides the wheelchair with high maneuverability and mobility.

2.Sunrise Medical.

This company is Invacare's main competitor, and its experience is particularly noteworthy in implementing innovative materials and control systems. Sunrise Medical is one of the world's leading manufacturers of high-tech mobility solutions and positioning systems. Mission: "Improving People's Lives" through the combination of advanced engineering and ergonomics. Global presence: The company's products are distributed in more than 130 countries, with manufacturing facilities located in the United States, Mexico, Germany, the United Kingdom, and China. Business model: The company focuses on the premium and high-end segment, offering products with a high degree of individual customization. Figure 2 shows the Sunrise Medical Magic Mobility electromechanical wheelchair.

Unlike many competitors, Sunrise Medical develops a portfolio of specialized brands, each occupying its own niche:

1.Quickie: A legendary brand of active wheelchairs, known for the use of aerospace-grade aluminum and carbon fiber to minimize weight.

2.JAY: Systems of pressure-relief cushions and backrests, which are critical for the reliability of long-term care systems, as mentioned in the context of humanitarian logistics.

3.Zippie: Specialized pediatric equipment featuring mechanisms that "grow" with



the child.

4.SOPUR: A German division specializing in professional sports equipment for Paralympic athletes.



Figure 2 – Electromechanical Wheelchair Sunrise Medical Magic Mobility

Reference: [7].

The company utilizes complex online configuration algorithms. Each wheelchair can have thousands of possible parameter combinations, which requires robust databases and decision support systems (DSS). Innovative control systems (joysticks, sensors, eye-tracking control) are also implemented. This is a real example of a human–machine interface (HMI), where software reliability is critical to user safety. Sunrise Medical processes large volumes of service-related data through integrated CRM platforms.

3.Permobil AB.

Permobil AB is a Swedish company and one of the most technologically advanced players in the industry, often referred to as the “Tesla of the wheelchair world.” The company was founded in 1967 by Swedish physician and inventor Per Udden. His vision was that access to mobility technology is a fundamental human right. The headquarters is located in Timra, Sweden. A key innovation of Permobil was being the



first company in the world to develop a front-wheel-drive wheelchair, which significantly improved maneuverability and mobility. Since 2013, the company has been owned by the investment group Investor AB (controlled by the Wallenberg family), ensuring stable funding for research and development (R&D).

Permobil is of particular interest due to its “Connected Wheelchair” concept:

1. MyPermobil: A cloud-based platform that collects data via a mobile application on battery status, distance traveled, and seating activity.

2. Remote diagnostics: Service centers can receive system error data via APIs. This is an example of integrated systems similar to those discussed in the context of sales accounting.

3. Smart Drive: An assistive propulsion system for manual wheelchairs, controlled via gestures using a smartwatch (gesture recognition technology).

Unlike Sunrise Medical, Permobil emphasizes maximum integration of electronics:

1. M-Series (mid-wheel drive): Compact indoor wheelchairs with an exceptionally small turning radius.

2. F-Series (front-wheel drive): Powerful models designed for off-road use.

3. TiLite: A brand of ultra-lightweight manual wheelchairs made of titanium, customized according to individual user anthropometric data (analogous to personalized system design).

4. ROHO: A world-leading air flotation technology for skin protection, used in advanced positioning systems.

For more than 45 years, Permobil has held a leading position in the electromechanical wheelchair industry. The company is characterized by a high level of innovation and a strong influence on the development of mobility solutions for people with disabilities. The company's powered wheelchairs are divided into two main categories: outdoor and indoor use. Their outdoor models differ significantly from conventional electric wheelchairs (figure 3).

These powerful electromechanical wheelchairs can safely transport the user far beyond paved roads. They are equipped with high-performance electric motors,



energy-absorbing suspension systems, and high-capacity batteries, providing a smooth, extended ride at up to 15 km/h. The Enhanced Steering Performance system makes Permobil's outdoor wheelchair models among the best for both on-road and off-road mobility. Such models can support users weighing up to 136 kg and travel 30-45 km on a single charge, with a maximum speed of 15 km/h.



Figure 3 – Electromechanical Wheelchair Permobil M Corpus VS

Reference: [8].

They can also overcome obstacles up to 110 mm in height and have a turning radius of 1680 mm. For user comfort, the wheelchair is equipped with a tilt system that allows adjustment of the entire seat and separate adjustment of the seat and backrest. Indoor-use models are more maneuverable.

The combination of ease of use, modern design, and comfort makes these models suitable not only for indoor use but also for outdoor use on flat surfaces. They are easy to operate in confined spaces, while powerful motors, combined with an advanced base, deliver strong performance outdoors. Such models represent a universal solution for most use cases.



4. Pride Mobility Products.

Pride Mobility Products is a private American company and one of the largest manufacturers of mobility solutions for people with disabilities in the world. Founded in 1986, its headquarters is located in Exeter, Pennsylvania, USA.

The company focuses on combining functionality, attractive design, and affordability, targeting a broad consumer market (B2C). Its products are carefully designed and tested, incorporating technologically innovative features to enhance user convenience.

Pride Mobility's product portfolio covers all major segments of rehabilitation equipment:

1. Jazzy: The world's most well-known brand of powered wheelchairs. Pride Mobility popularized the Mid-Wheel 6 technology (six wheels with a central drive), which provides maximum stability and maneuverability indoors.

2. Go-Go Travel Mobility: A series of compact scooters that can be easily disassembled for transportation in a vehicle. This is an example of modularity, which requires precise spare parts accounting in ERP systems.

4. Pride Power Lift Recliners: Chairs equipped with a lifting mechanism to assist users in standing up.

5. Quantum Rehab: A separate division established to compete with Permobil in the high-tech segment (advanced positioning systems and customized electronics).

Although Pride Mobility is oriented toward the mass market, it actively implements digital solutions:

1. Integration with mobile devices: Modern Quantum models are equipped with Bluetooth modules that allow users to control wheelchair functions via a smartphone. This is an example of "mobile technologies in digital environments and everyday life."

2. Service management optimization: Pride Mobility's extensive dealer network requires automated platforms for tracking orders and warranty cases.

The company's powered wheelchairs are lightweight and highly maneuverable, making them suitable for everyday use both indoors and outdoors on flat surfaces (figure 4).



Figure 4 – Electromechanical Wheelchair Jazzy Carbon

Reference: [9].

Jazzy Carbon provides maximum stability combined with the advantages of front-wheel drive. The Active-Trac suspension and 6-inch front and rear wheels ensure strong performance both indoors and outdoors.

A wide range of standard convenience features makes this wheelchair easy to use.

3.2 Analysis of Electromechanical Wheelchairs from Domestic Manufacturers

Among domestic Ukrainian manufacturers, there is a relatively limited selection of powered wheelchairs. The largest domestic producer of such devices is the company “Forward-Orto” (figure 5). Their wheelchairs offer higher load capacity and a longer operating range on a single charge; however, their maximum speed is 5 km/h, which is lower than that of most other manufacturers' models. They can overcome obstacles up to 5 cm high and are equipped with safety belts, making them well-suited for outdoor



use. “Forward-Orto” is a leading Ukrainian enterprise specializing in the production of both standard and customized rehabilitation devices, prosthetics, and orthopedic footwear. The company’s headquarters is located in Ternopil, with a network of service centers throughout Ukraine. It operates a full production cycle, from design and engineering to maintenance and service. The company actively cooperates with the Ministry of Social Policy of Ukraine, providing free rehabilitation equipment to citizens in the categories eligible under government programs.



Figure 5 – Netti 4U CE Electromechanical Wheelchair by “Forward-Orto”

Reference: [10].

Unlike global corporations such as Sunrise Medical and Permobil, “Forward-Orto” focuses on adapting global technologies to Ukrainian operating conditions:

1. Wheelchairs: production of a wide range of models, from basic indoor units to active wheelchairs and powered models (e.g., the “Forward” series).

2. Prosthetics: use of components from global leaders (Ottobock, Össur) combined with the company’s own developments of sockets and fixation systems.



3. Orthopedic footwear: manufactured based on individual casts, requiring precise digital foot scanning.

The activities of “Forward-Orto” illustrate several challenges:

1. Integration with state registries: The company operates within the Centralized Data Bank on Disability Issues. This is an example of an information platform where data fragmentation can lead to delays.

2. Accounting automation: With large volumes of government orders, “Forward-Orto” requires the implementation of ERP systems to track the product lifecycle.

3. APIs and interoperability: The need for transparent interaction among manufacturers, social protection authorities, and end users requires modular solutions, as proposed in your research.

3.3 Human-Machine Interfaces for Controlling an Electromechanical Wheelchair

Human-Machine Interface (HMI) for controlling electromechanical wheelchairs is a key element in research on automation and the reliability of complex technical systems. In modern rehabilitation engineering, the interface is not merely a joystick, but a sophisticated signal-processing system that enables interaction between the user’s biological commands and the wheelchair’s actuating mechanisms.

I. Classification of Control Interfaces.

Modern HMIs are classified according to the method of acquiring the control signal and the user’s level of physical capability.

A. Standard (Contact) Interfaces.

These are the most common types used by companies such as Pride Mobility and Invacare.

1. Proportional joysticks: The speed and direction of movement depend on the angle of joystick deflection. They require preserved hand motor function.

2. Large-button switches: Designed for users with low movement precision. They



operate on a binary (“on/off”) principle.

B.Specialized Adaptive Interfaces.

These are intended for patients with severe spinal cord injuries (for example, users of Quantum Rehab or Sunrise Medical systems):

1.Sip-and-Puff: Control is achieved through changes in air pressure within a tube (a short inhalation corresponds to turning, while a long exhalation initiates forward movement).

2.Chin control: Used when mobility is limited to head movements.

3.Head array: Sensors integrated into the headrest; movement is controlled by head tilting.

C.Intelligent and Contactless (High-End) Interfaces.

This segment is actively developed by Permobil AB:

1.Eye-tracking: Cameras monitor pupil movement to select a direction on a display.

2.Brain-computer interfaces (BCI): Acquisition of brain EEG signals (currently mostly at the clinical trial stage).

3.Gesture control: Control via gestures using smartwatches (as implemented in the SmartDrive system).

II.Algorithmic Architecture of the Human-Machine Interface. The control process can be represented as a cycle consisting of three stages:

1.Input Filtering: The algorithm must filter out random tremors or spasms of the user in order to prevent sudden and unintended movements.

2.Mapping: Transformation of the physical signal (for example, voltage from a Hall sensor in a joystick) into velocity vectors (v) and angular velocity (ω).

3.Safety Override: Interruption of the control algorithm if proximity sensors detect an obstacle (safety automation mechanism).

Since wheelchairs became self-propelled, a wide variety of control methods have been proposed. These methods can be classified by the type of signals used, recognizing that signals of different types are often combined.

If a person retains motor functions of the limbs, vision, and higher cognitive



functions, the simplest approach is to implement direct wheelchair control using conventional means:

- buttons;
- joystick;
- steering controls or pedals.

However, if at least one of these functions is impaired or weakened, direct control becomes difficult, impossible, or unsafe.

In this situation, there are two possible approaches:

- to attempt to restore the impaired function using other preserved functions to a level sufficient for direct control;
- to implement an indirect control scheme in which real-time motion control is performed entirely automatically, while the user provides only high-level commands, such as destination points or additional actions.

The first strategy has a long history of development. For example, conventional eyeglasses can correct certain visual impairments. The use of myographic signals from preserved muscles enables the restoration of some motor functions. The application of eye-tracking systems enables direct motion control even in cases of significant impairment of muscular regulation. However, in some cases, achieving the required speed or accuracy is not possible. For instance, existing brain–computer interfaces have a temporal resolution measured in seconds, even under optimal conditions. To restore certain aspects of visual functionality, devices have been developed that verbally describe objects located in front of the user.

As for higher cognitive functions, means to facilitate them are still at the research stage. The second strategy enables overcoming the limitations associated with the low speed and reliability of natural or restored functions. For example, in an automated control system, a low rate of high-level command input, on the order of several minutes, is acceptable and achievable with all existing brain-computer interfaces. Such a control scheme is robust against errors, since all commands are valid and real-time control is performed automatically. It can be applied even in cases of certain impairments of higher cognitive functions, which is not possible with direct control



systems.

In some cases, a combination of these strategies is used:

- direct control via a joystick;
- facilitation of motor functions for direct control using eye-tracking and electromyography;
- implementation of indirect control with high-level commands, where commands can be provided through various available user modalities, such as speech, limb movements (buttons, joystick), eye movements (eye-tracking), muscle activity (electromyography), brain bio-potentials, changes in cerebral blood flow, or other signals.

Duplication of input methods for indirect commands can also be used to increase system reliability. Let us consider potential human–machine interfaces suitable for both direct and high-level control.

Voice control of wheelchairs has been studied for a long time. In early developments, speech recognition systems typically identified individual command words from a limited vocabulary. Subsequently, methods were developed to generate commands in a language close to natural speech, achieving recognition accuracy of up to 97%. With a sufficiently rich recognition language, it becomes possible to define high-level tasks in a form that is convenient and intuitive for the user.

Caregivers of wheelchair-bound patients are well aware of how difficult it is to provide assistance without making the patient feel dependent or inadequate. To address this issue, researchers have developed voice control systems for wheelchairs. This motivated a scientist at the Georgia Institute of Technology to design a specialized mechanism that incorporates voice control, enabling wheelchair users to operate it via verbal commands. Voice control relies on understanding the connections between the brain and the movement of body parts, such as the arms, legs, and tongue.

The arms and legs, as is well known, are connected to the brain via the spinal cord, while speech is connected through the cranial nerves. This knowledge enabled researchers to develop voice-controlled wheelchair operation, allowing operation through speech while requiring minimal physical effort.



Among the disadvantages of such a system are its sensitivity to external noise and the need to articulate commands clearly for accurate recognition. Control can also be achieved using signals generated in muscles during contraction. In this approach, a set of simple movement commands (such as moving in a specific direction or stopping) corresponds to signals captured by sensors that detect electrical activity in muscles. Muscles of the face, torso, neck, and arms can be used for control.

As a rule, a limited number of signals generate commands that define the direction of movement, similar to joystick control. A significant problem for such systems is false triggering caused by involuntary muscle contractions, including those resulting from fatigue (for example, in some studies, the false activation rate for certain muscles reached up to 50%).

Vision is a sensory system that provides up to 70% of all information about the surrounding environment. In everyday life, a person continuously observes and analyzes space, identifying relevant information. The object of perception changes approximately twice per second, and the direction of gaze changes accordingly. The study of eye movement and gaze direction has a long history spanning several centuries. This problem has been investigated by prominent scientists from a mechanical perspective (J. Kepler, I. Newton, I. M. Sechenov), as well as within various psychological frameworks, including physiological psychology, cognitive psychology, activity theory, and others. The relationship between eye movement and cognitive processes, as well as the perception of works of art, was also noted by Leonardo da Vinci and Auguste Rodin.

One of the first researchers to systematize knowledge about eye movements was A. L. Yarbus (1965). He identified the existence of specific scan paths when viewing images of faces. According to his eye-tracking records (representations of changes in gaze direction), eye movements exhibit a cyclical pattern: the gaze moves across the same image in the same sequence repeatedly. The pattern of eye movement reflects the dynamics of attention, thinking, imagination, and perception, while its direction indicates a person's interest, intention, and attitude.

Therefore, systems that utilize information about changes in gaze direction can be



highly diverse:

1. Human state diagnostics systems:

- determination of psycho-emotional (stress) states to identify potentially antisocial behavior;
- monitoring the condition of operators working under challenging conditions;

2. Control systems:

- control of robotic devices (including manipulators such as a “mouse”-type interface);

3. Marketing research systems:

- assessment of interest in billboards;
- evaluation of the effectiveness of online advertising.

4. Training simulators (for example, flight control simulation).

When developing a system to evaluate gaze direction, it is first necessary to define requirements for the characteristics of eye movement. Oculomotor activity refers to the motor activity of the eyes, which is characterized by a wide variety of movement types and transitions. The human eye moves due to six extraocular muscles attached to the eye socket. The center of rotation of the eyeball is located inside the eye along the visual axis. The distance between the apex of the cornea and the center of rotation is approximately 13.5 mm.

All eye movements can be classified according to amplitude, speed, trajectory, and functional purpose, including tremor, drift, micro- and macro-saccades, smooth pursuit movements, vergence movements, torsional movements, and nystagmus. At the same time, all movements are generally divided into micro- and macro-movements. Micro-movements are primarily associated with maintaining gaze fixation, while macro-movements are related to changes in gaze direction. The development of systems that use gaze direction information requires identifying eye movements associated with human cognitive activity. Such movements are macro-movements, specifically smooth pursuit movements.

They are characterized by $\pm 60^\circ$ horizontal and $\pm 40^\circ$ vertical amplitudes, with velocities ranging from $5^\circ/s$ to $12^\circ/s$. The duration of these movements depends on the



time spent tracking an object. At the same time, during object observation, fixations occur along with macro-saccades, whose amplitude under normal conditions is about 20°, and duration is approximately 70 ms. Currently, various methods exist for measuring and evaluating the characteristics of human eye movements. The most commonly used are video-oculography and electro-oculography. When developing a system for automated gaze direction estimation, we will use the simplest method from a technological standpoint, video capture, which allows recording macro-movements reflecting a person's attitude toward the observed object or space, without using contact-based devices that may cause discomfort or introduce distortions.

After determining the characteristics of the recorded movements, it is necessary to define the camera requirements, specifically resolution and frame rate. There are two main approaches to determining gaze direction from video data: using reference points and using facial texture features. Reference points can be obtained through calibration, calculated based on facial geometry, or derived from reflections produced by infrared sensors. In the development of the automated gaze direction estimation system, an algorithm was created to determine gaze direction using reference points at the corners of the eyes. Libraries such as OpenCV and EMGU were used for detecting these reference points.

Gaze direction was determined in two coordinate Systems-Cartesian and polar-in order to identify the most optimal approach. In the Cartesian coordinate system, gaze direction is calculated relative to the corner points of the eyes. Accordingly, three possible gaze directions are defined:

- straight ahead;
- to the left;
- to the right.

The probability of correctly determining gaze direction from the image of the first subject is 95.1%, while for the second subject it is 60.1%. The decrease in recognition accuracy is explained by individual facial anatomical features and the low precision of eye corner point detection. The use of a polar coordinate system is justified by the anatomy of the eye, as the eyeball has a spherical shape. The center of the polar



coordinate system is defined as the intersection of the lines through points 1 and 7 and points 3 and 8.

There are existing systems that use gaze control to operate wheelchairs. According to Christopher McMurrough, a professor of computer science and engineering at the University of Texas at Arlington, calibration of conventional eye-tracking control systems requires the assistance of qualified experts. In addition, delays in processing tracked eye movement data are often observed.

In other words, this does not provide real-time interaction. In the new 3D headset called “Gaze Point,” invented by McMurrough, these problems are eliminated. The device was initially developed as a student thesis project when McMurrough was still a student. The upper part of the prototype is equipped with a dedicated 3D camera oriented toward the direction of movement, as well as two eye-tracking devices aimed at the user’s eyes. Software running on a computer connected to the prototype generates a 3D map of the environment in front of the user based on the camera’s input data. By combining this information with data obtained from the eye-tracking system, it becomes possible to determine the user’s gaze direction. As a result, the system can identify exactly what object the user is looking at within the 3D map. This approach is highly promising, as it may enable independent mobility even for users who cannot rely on voice control or muscle activity. The types of input signals used in such systems are highly diverse. In some cases, gaze movement functions similarly to joystick control. In other cases, the user is required to fix their gaze on a specific area of space to which they wish to move, while the control system independently computes the trajectory to reach the desired target. This method allows for a higher level of control abstraction. Tracking gaze movement introduces several important challenges. It is necessary to define mechanisms for entering and exiting the motion control mode using specific gaze patterns that do not occur during normal visual observation. It is also necessary to distinguish intentional, controlled gaze shifts from accidental ones caused by involuntary eye movements or fatigue (the “Midas touch” problem), as well as from monitoring the execution of a previously issued command. Because of this, the complexity of signals that a user can consistently produce and that the control system



can reliably recognize is limited.

Among the proposed methods for reducing false activations is gaze fixation on a specific object for a predefined duration (approximately 0.5 seconds), as suggested in studies based on previously obtained estimates of fixation time in communication processes. Methods based on measuring the electrical activity of neural networks in the brain during cognitive processes are also being developed. Their advantage is that brain activity can be recorded even in completely paralyzed patients, making this approach applicable to the widest possible range of users.

However, this approach has significant drawbacks: the operator requires assistance to prepare for data acquisition, high-quality equipment is expensive, and the rate of false readings can reach up to 50%. For example, due to difficulties in accurately acquiring signals, the average time to register a stop command was about 5 seconds, which is unacceptable for practical applications. Nevertheless, it has been noted that when using higher-level control, such as specifying a destination point, and with increased system intelligence, both reliability and response speed improve. In recent years, research on brain–computer interfaces has intensified. According to developers, thought-controlled wheelchairs are primarily designed for individuals who are paralyzed from the neck down and retain full cognitive function.

It is noted that the computer system converts brain signals into a set of commands such as “stop,” “forward/backward,” “left/right,” “turn lights on/off,” and “tilt the seat forward/backward.” Neural impulses generated in the brain are transmitted via electrodes of a “neuro-cap” to a computer for processing, which in turn activates the wheelchair’s movement. “Tests have demonstrated that a wheelchair can be controlled using brain impulses.”

Developers must also address another critical problem: the emergency shutdown of the wheelchair by a physically immobilized user in the event of loss of control. Since this technology is based on changes in cerebral blood flow (which correlates with the electrical activity of brain neural networks), its response time is measured in tens of seconds per command. The use of hybrid systems enables reducing response time to a few seconds and increasing command classification accuracy to 98%. Such speed and



accuracy are sufficient for issuing high-level commands to robotic systems, but are insufficient for direct control.

Many of the presented control methods have significant advantages; however, it is not possible to select a single method that is equally suitable for all patient groups. Since errors produced by different signal recognition methods are often independent, system performance can be improved by combining multiple data acquisition methods within a single system that captures different physiological indicators of the same cognitive process. Numerous approaches have been proposed that combine eye-tracking with systems monitoring the operator's field of view. Such systems attempt to recognize the objects the user is looking at and determine whether the gaze represents an intentional control command. In general, the brain–computer interface (BCI) represents the pinnacle of modern convergence between information technology, neurophysiology, and robotics. Brain–computer interfaces are the most complex type of human–machine interface, in which the source of data is the brain's bioelectrical activity. A brain–computer interface is a system that enables a person to interact with the external environment (computers, prosthetics, wheelchairs) without the involvement of muscles or peripheral nerves, using only the digital interpretation of brain signals. According to approaches to the design of complex systems, BCIs are classified by the degree of invasiveness (intervention in the human body):

A. Non-invasive interfaces.

These are the safest and most widely used in civilian rehabilitation (for example, in projects by Permobil or NeuroSky):

-eeg (Electroencephalography). Electrodes are placed on the scalp to measure the aggregate electrical activity of neurons.

Advantages:

- low cost;
- no need for surgical intervention.

Disadvantages:

- low spatial resolution;
- significant noise interference caused by blinking or muscle movements.



B. Semi-invasive interfaces (ECoG)

Electrodes are placed beneath the skull on the surface of the dura mater. They provide higher signal quality than EEG, but require surgical intervention.

C. Invasive interfaces

Electrodes are implanted directly into the cerebral cortex (e.g., Elon Musk's Neuralink project or Blackrock Neurotech).

Advantages:

- highest accuracy;
- enables control of complex prosthetic devices with multiple degrees of freedom.

Risks:

- biological rejection;
- risk of infections;
- loss of reliability over time.

The proposed architectural solution must support a wide range of interface devices. However, all the above-mentioned methods of user interaction have significant drawbacks that make real-time, low-level wheelchair control unreliable and potentially unsafe. The accuracy of command recognition is relatively low, and attempts to improve it are constrained by fundamental physiological limitations. At the same time, interface response delays are too long for convenient, precise real-time control.

These limitations can be overcome by delegating control to a higher level. Instead of issuing low-level motion commands, the user can initiate high-level actions composed of multiple commands generated and managed by an intelligent wheelchair control system. Such an approach reduces the requirements for interface response time and limits the impact of incorrectly recognized commands. A high-level control system also enables the combination of interfaces best suited to a specific user. Some interface devices are suitable for both high-level and low-level commands (e.g., joystick, myoelectric sensors, eye trackers), while others are primarily intended for high-level control. To operate with devices of different classes, the system must simultaneously



analyze commands at different levels; therefore, it must incorporate powerful mechanisms for describing complex behaviors in terms of simpler ones.

When implementing high-level control, necessary to address latency issues in real-time (low-level) control, a key challenge arises in determining user commands. Since high-level commands exhibit a wide variety of forms and may be associated with observed objects, unlike low-level motion commands, it is necessary to apply models and methods capable of operating with such concepts. One such approach is an architecture based on semiotic networks (hereinafter, the semiotic control approach). Ontology-based methods (e.g., RoboBrain and SO-MRS for multi-agent systems) can also handle objects and concepts; however, they primarily focus on knowledge transfer between robots and on the association of objects with concepts. In these approaches, the conceptual system serves as an external knowledge source.

In contrast, in the proposed approach, the semiotic structure acts as an integrating mechanism:

- the semiotic network unifies action activation mechanisms into a single system;
- provides a representation of the world model;
- defines the agent's goals and establishes connections with operator commands expressed in natural language.

Since commands (and even simple statements) expressed by a human are conveniently represented within a conceptual description framework, it is natural to transfer them to a control system that plans actions based on a network containing such concepts.

The tasks of automating wheelchair control at the low level are defined and solved separately. The following mechanisms must be implemented:

- 1) low-level reflexes. These are responsible for emergency braking of the wheelchair in abnormal situations, such as collisions with obstacles or the risk of falling from a height;
- 2) computer vision system. Since the interface involves interaction with a human, some high-level commands will be expressed in terms understandable to humans. For example, a command such as “move to the table” is natural. To



execute this, the system must detect a table in the environment and construct a path to it;

- 3) navigation and localization system. Recognition of characteristic environmental objects and the ability to build a map are essential for effective orientation.
- 4) path planning and execution system. This system must guide the wheelchair from its starting position to the user-defined destination while avoiding collisions and hazardous areas.

The core element of the control system is a semiotic network composed of signs and the relationships between them defined by rules. The system description formalism is a grammar based on first-order logic. An intelligent wheelchair features a multi-level control architecture, including its own sensors, effectors, reflex system, and other low-level components. All these components are interconnected through a sign-based system that describes elements of perception (sensory data) and actions using signs. The names of the signs make it possible to link semantic networks generated by the text command analysis system with the semiotic network that serves as the agent's world model.

At the same time, individual elements are combined into signs, which can then be further connected into more abstract, high-level constructs (for example, the sign "living room," which is a subclass of the sign "room"). Since the system operates with a limited set of concepts determined by sensory capabilities and embedded low-level action algorithms, a fixed vocabulary of sign names (object types), attributes, and actions is used as the interface description between the language analysis system and the control system based on the semiotic network.

The signs that describe the world model consist of statements (closed atomic formulas of first-order logic) and STRIPS operators, which are represented as triples (or productions) R :

$$R = \langle C, A, D \rangle, \tag{1}$$

where C - is the applicability condition of the operator represented as a set of statements;



A - is the set of statements added by the operator;

D - is the set of statements to be removed.

Everything significant that is perceived by the agents in the semiotic world model is represented by signs (figure 6). Formally, each sign is described by an ordered set of four components:

$$S = \langle n, p, m, a \rangle, \tag{2}$$

where n – name – links the elements of the semantic network of the command obtained from language analysis with the corresponding sign in the control system;

p – image – consists of observable (or sensor-detectable) statements about the defined entity;

m – a set of STRIPS operators (see formula 2) that allow, through logical inference, the enrichment of world knowledge that is not directly observable;

a – a set of actions associated with the sign, each corresponding to a STRIPS operator.

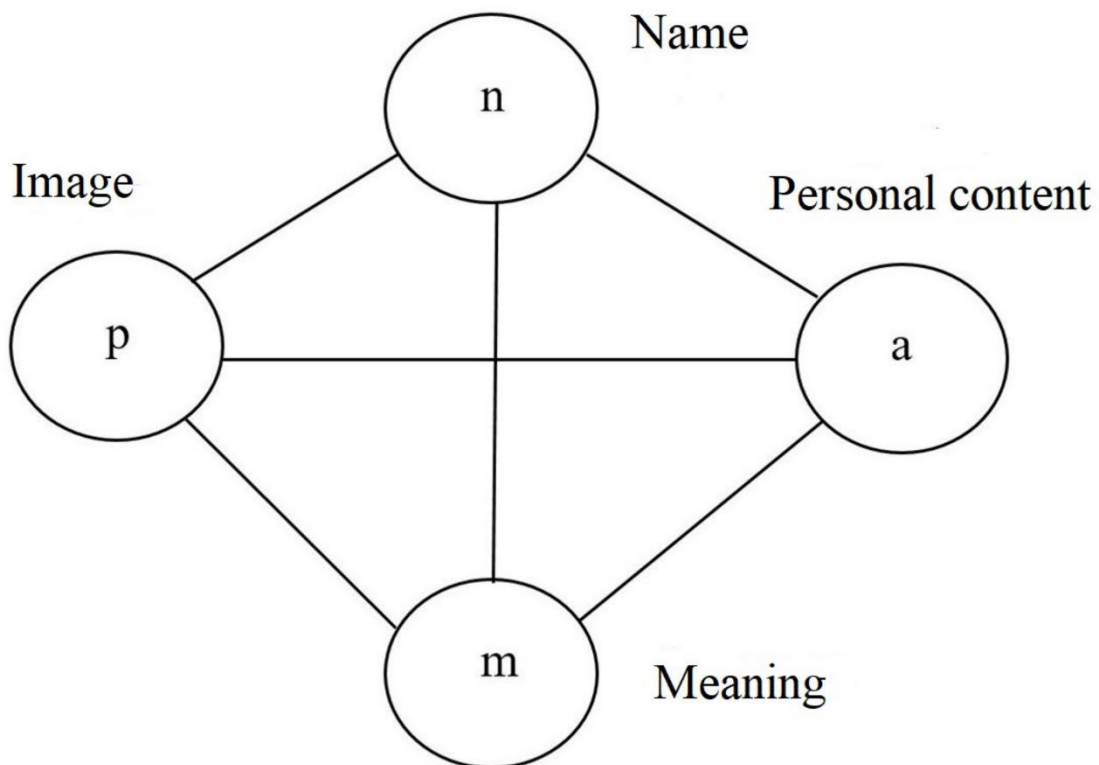


Figure 6 – Robot World Model Based on Signs

Author's development.



Figure 7 presents the robot's semiotic network, which includes both signs and semantic networks built on homogeneous sign components. The semantics of a specific action is a low-level algorithm (described outside the sign system) implemented using standard control methods, for example, a finite-state machine. The semantics of the image p of a given sign consists of recognition algorithms of the perception system that directly determine the presence of a particular property in the observed object (or in the scene as a whole). The description of signs and the relationships between them is carried out using the language of first-order logic. Triples of conditions, additions, and deletions are STRIPS operators, which are applied once in a specific order during logical inference and, during planning, allow the use of an algorithm similar to the STRIPS method but based on a sign-based representation of the task.

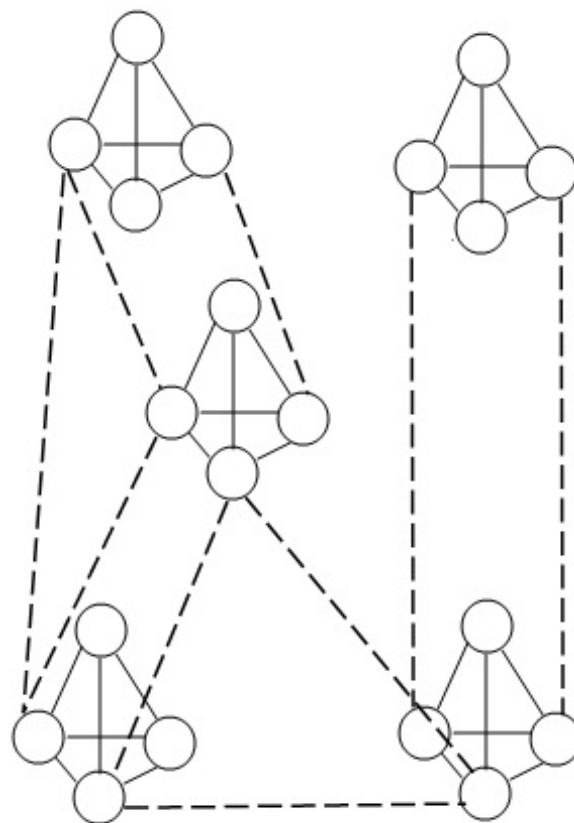


Figure 7 – The robot's semiotic network includes both signs and semantic networks based on homogeneous sign components

Author's development.



It should be noted that STRIPS planning has already been applied to control systems based on a semiotic network in previous work, although in a somewhat different manner. Nevertheless, this method is suitable for models of this type. The STRIPS planning algorithm uses a dynamic state represented as a list of true facts and performs a search in the state space using operators. In the proposed method, these operators update the robot's world model by adding facts about the environment's new state, rather than being used solely for planning. Moreover, the state of the world is preserved between consecutive robot actions. This means that the order of operator application is important, and the constructed logical system may be non-monotonic. Despite these issues, this approach allows for faster updating of world facts at each step by preserving previously inferred facts, provided they do not contradict new data.

This also makes it possible to implement memory within the sign system, as facts that are not directly derived from current observations remain in the agent's knowledge base. At the lower level, various implementations of actions can be used (e.g., finite-state machines or hierarchical strategies). Both approaches rely on state transitions as a natural way to decompose control tasks into stages. Such transitions may occur, for example, upon completion of a basic action within the hierarchy.

Between these actions, the control system completes the remaining cycle: sensor data are used to update the semiotic network, which serves as the agent's knowledge base. Then, the following processes are executed sequentially: logical inference, planning, and processing of user commands. The intelligent agent's activity is ensured by an intentional mechanism, i.e., a set of algorithms and data structures that initiate actions to achieve specific goals. For safety purposes, one of the reflex levels is implemented outside the sign system (which is responsible for "cognitive" processes) at a lower level and can override control to avoid collisions. In addition to user commands, the system must also consider the surrounding environment and ensure the operator's safety. Executing a command may require a sequence of actions, interrupted by reflexes, under changing environmental conditions, and necessitating replanning. All of this necessitates treating the user's command as a goal that should be considered during execution, rather than as the sole purpose governing all processes within the



system. Instead, the system itself should be designed based on its own activity and a set of internal mechanisms that regulate behavior. An example of an architecture that supports the concept of autonomous goal formation is the emotion-driven (need-based) architecture; however, without modification, it is difficult to incorporate external control, such as user commands, into such a system. Instead, it is possible to partially represent needs within the sign-based framework as rules in the value component (i.e., as part of the sign component m).

The selection of the need to be satisfied is complemented by an algorithm external to the semiotic model. To decide on its next action, the agent must also determine which action conditions in its internal representations are satisfied. These conditions may include both predicate checks within the image components of signs and facts added by operators from the value component (elements of m). The system provides multimodal input and output, designed to support similar interfaces wherever possible in order to accommodate a wide range of users with different disabilities and to improve interaction efficiency with the wheelchair. The input subsystem includes a microphone, mechanical manipulators (joystick and buttons), an eye-tracking-based gaze-control system, and neurointerfaces based on electromyography.

The standard operating mode assumes the use of high-level commands, i.e., setting goals for the intelligent wheelchair; however, the system also supports activating a lower-level (operational) mode for direct motion control. As feedback, the user receives voice messages (e.g., notifications of command execution failure or requests for clarification), on-screen messages, and various LED indicators and haptic feedback. These two groups of devices are connected to the computer either through a controller or directly. The lower level of the robot control system, which directly interacts with the hardware components, includes a camera, a set of sensors (rangefinders and encoders), actuators (motors), and a control unit that coordinates their interaction with the computer.

The main robot controller uses essentially “raw” sensor data to implement simple low-level behavioral patterns, such as forward movement with collision avoidance, wall-following, obstacle bypassing, and similar actions. It also incorporates a reflex-



based system using rangefinders that can block a potentially dangerous low-level action at any moment to prevent collisions. The video stream is transmitted directly to the image processing system. Other sensor data are also processed before being used by the control system on the computer side. At the higher level, the control system is based on a semiotic world model. It receives processed data in the form of objects, their relationships, and the relative positions of obstacles. This information is further enriched through logical inference using knowledge stored within the system of signs. Based on a sign-based representation of the world, planning either selects an action for immediate execution or generates a plan consisting of a sequence of high-level actions (behaviors). Planning systems, goal-setting mechanisms, and the world model are integrated by a continuous control module that, at each step of operation, initiates the necessary processes to update the world model, perform planning, monitor user commands, and issue high-level execution commands. This module also includes an additional reflex system that enables the interruption of dangerous wheelchair behavior based on sensor analysis available only at the high-level system and not accessible at the main controller level.

Conclusions

This paper investigates modern approaches to the intelligent design of control systems for robotic mobility devices in the context of digital transformation and the increasing complexity of human–machine interaction algorithms. The main results of the study allow the following conclusions to be drawn.

The use of semiotic models of the environment is proposed as a high-precision simulation environment. Similar to the concept of digital twins in corporate systems, a semiotic representation enables the safe evaluation of planned trajectories and actions before their execution. This significantly reduces operational risks of collisions and minimizes the user’s “cognitive load” during interaction with the device.



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