UDC 004.93:004.5:364.4
DOI https://doi.org/10.32782/2663-5941/2025.6.2/06

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CONTEXT-AWARE, ADAPTIVE HMI TECHNOLOGY FOR ENHANCING THE AUTONOMY OF USERS WITH DISABILITIES

The paper presents an integrated information technology for human–machine interaction that supports the autonomy of users with disabilities across four domains: navigation (indoor/outdoor), information access and authentication, activities of daily living (smart-home control), and inclusive education. The technology fuses wearable and stationary sensors, multimodal input/output channels (gaze, gestures, voice; audio, visual, and haptic feedback), and actuators within a single adaptive loop of "event → interpretation → decision → action → learning." At its core is a context-aware module that, in real time, accounts for environmental conditions, the user's physiological capabilities, and interaction history, together with a personalized ergonomic profile that is automatically updated based on scenario performance. The work introduces principles for dynamic modality selection and redundancy of safety-critical alerts across multiple channels, offline-robust mechanisms for essential functions, and architectural interfaces for integration with smart-home platforms and educational services.

The approach demonstrably reduces cognitive and motor load via context-appropriate interaction choices, enhances safety through multimodal warnings, and sustains accessibility by aligning with WCAG/EN 301 549 requirements and software quality characteristics. Practical significance is achieved through the systematic integration of object/obstacle recognition for navigation, passwordless (or near-passwordless) authentication using gaze/gestures/voice, adaptive voice- and gaze-based commands for household tasks, and automatic tailoring of instructional content (font size, contrast, information density, pacing). The proposed principles, architecture, and methods establish a reproducible foundation for building inclusive services that support the independence of people with visual, hearing, mobility, and cognitive impairments in everyday scenarios.

Key words: *human-machine interaction, assistive technologies, inclusivity, context-aware systems, adaptive interface, ergonomic profile, multimodal interaction, people with disabilities.*

Formulation of the problem. The World Health Organization estimates that 1.3 billion people live with significant health impairments, while access to medical and rehabilitation services remains unequal. The need for assistive technologies already exceeds 2.5 billion people and will rise to 3.5 billion by 2050. This directly demands scalable, interoperable digital accessibility solutions. [1-2].

The pathway map shown in Figure 1 illustrates how services and infrastructure that are familiar to many create a series of critical barriers for a person with a disability on a daily basis. The map demonstrates not just individual problems but their accumulation and interconnection, which leads to:

– systemic exclusion from education, work, healthcare, and social life;

– constant stress and high cognitive load due to the need to overcome these barriers;

– deepening isolation, where every area of life requires heroic effort for basic participation.

The proposed journey map visualizes a typical day of a person with a disability through the lens of three key aspects:

– areas of activity;

– barriers;

– assistive technologies.

The timeline sequentially marks the phases of the day: morning (daily routines and mobility), daytime (professional activity and education), and evening (social interaction and rest). For each phase, critical barriers are identified: from physical obstacles in the environment to communication and information limitations in the digital space. At the same time, the map shows how these barriers are systematically compensated by technological solutions: from screen readers and assistive devices to inclusive applications and platforms.

The presented set of barriers and solutions is the main motivation for developing the scientific and methodological foundations for creating an information technology to support people with disabilities based on the analysis of multimodal data. A systematic scientific approach to creating information technology for supporting people with disabilities is necessary because assistive technologies are not isolated

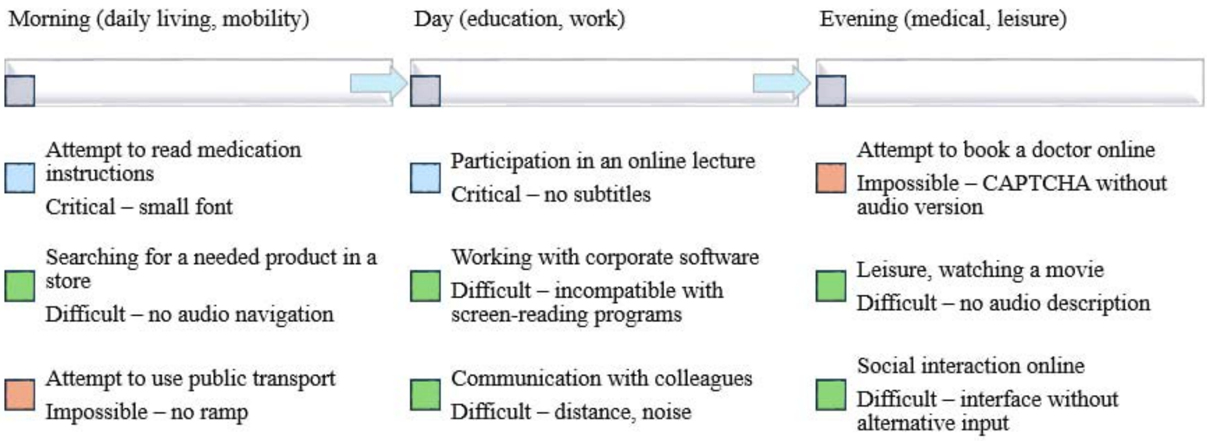

Fig. 1. User journey map with barriers (an illustration of a typical day of a person with a disability)

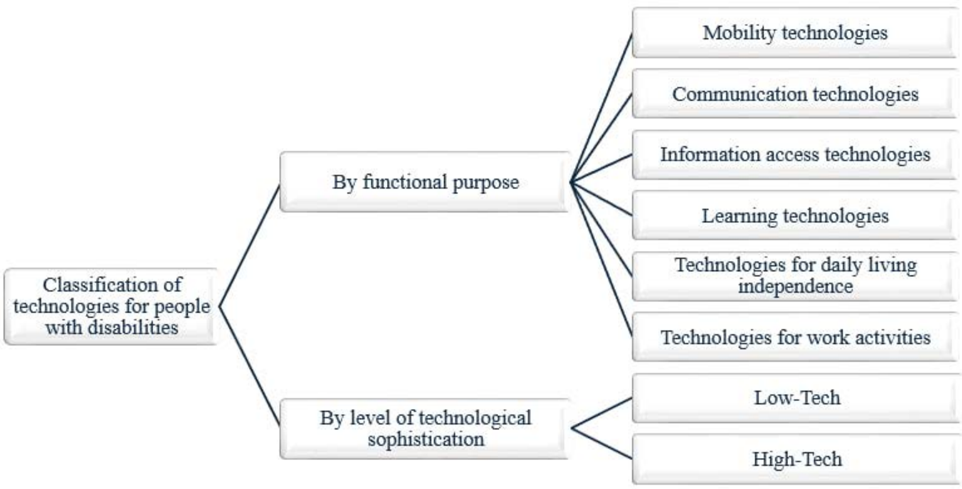

Fig. 2. Classification of support and assistance technologies for people with disabilities and special needs

tools but a unified ecosystem solution that ensures continuity and quality of life, transforming passive existence with constant limitations into active living with all its possibilities.

Analysis of the latest research and publications. Given the scale of needs, inclusive IT solutions must be based on four interrelated principles: first, multimodality is a fundamental requirement, as different impairment profiles (vision, hearing, motor, cognitive features) require combining human-centered user data (speech, gestures, gaze) with scene data (video, depth, audio context) and context-adaptive system operation; second, accessibility must be a standard – this includes interoperable formats, open APIs, and compliance with accessibility principles (in particular WCAG and universal design), ensuring solution scalability; third, rehabilitation and reintegration of veterans is a priority, which dictates a focus on wearable devices with on-device processing, low latency, and energy efficiency for daily navigation and communication; fourth, fair access is necessary, meaning accessibility policies and deployment models in public spaces, transport, shopping and entertainment centers, educational and medical services, so that technologies genuinely remove barriers rather than reproduce them.

To systematically analyze the social significance of assistive technologies, it is appropriate to consider their impact through the lens of key areas of human activity [3]. This multifaceted impact can be visualized and structured, clearly demonstrating how technologies transform the lives of people with disabilities from passive existence to active participation. To do this, we first present a summary classification diagram of the main types of technologies according to their functional purpose.

Technologies for people with disabilities (Assistive Technologies, AT) can be classified by functional purpose and level of technological advancement (Figure 2).

By level of technological advancement, the following types can be distinguished:

Table 1

Analysis of barriers and risks in technology implementation

Barrier category	Examples	Consequences
Economic	High cost of high-tech solutions, lack of funding from national or local budgets.	Widening inequality: technologies are available only to affluent groups.
Informational	Lack of awareness among people with disabilities and their families about existing solutions, absence of training. Interfaces without alternative channels (gestures, voice, text).	Ineffective use or complete rejection of technologies.
Organizational	Difficulty obtaining technologies due to bureaucratic procedures, lack of service centers.	Delays in obtaining the necessary
Psychological / cognitive	Fear of new technologies, reluctance to stand out, internal stigmatization. Overloaded UIs, complex navigation scenarios.	Refusal to use useful tools, reinforcing a state of dependency.
Physical / technical	Lack of internet in remote areas, incompatibility of different systems, rapid obsolescence of technology.	Restricted access for certain groups

– low-tech solutions – simple and low-cost tools such as trackball mice for people with tremor, special writing grips, tactile paving;

– high-tech solutions – advanced computer-based and software-driven tools such as eye-tracking for web navigation, bionic prostheses with neural interfaces.

As follows from the presented diagram (Figure 2), the range of assistive technologies is extremely broad. To assess their true social significance, we analyze the direct impact of these solutions on various areas of life and identify the main barriers to their widespread implementation. This analysis is presented in Table 1. Economic and organizational barriers create a “digital divide” between different social groups and countries, while informational and psychological obstacles limit the effective use of even existing technologies.

Thus, overcoming these barriers requires a comprehensive approach that includes both government regulation and funding, as well as the development of the innovation market and public awareness. Today, assistive technologies are not only a tool for support but also a powerful investment resource in social capital and the sustainable development of society.

Task statement. The aim of this work is the development and formal justification of an information technology for context-adaptive human–machine interaction, which ensures the selection of optimal modalities in real time, taking into account safety requirements, the ergonomic profile of the user, context, and the user’s current state.

To achieve the stated goal, the following tasks must be addressed:

– determine the objective function of ergonomic efficiency and the criteria for selecting modalities for different impairment profiles and contexts;

– develop procedures for sensor fusion and semantic interpretation of environmental and user-state data, taking into account uncertainty and reliability of sources;

– design a coordinated multimodal interface for auditory, visual, haptic, and actuator output with rules for duplicating critical events.

Outline of the main material of the study. Taking into account the above-mentioned barriers and risks in the implementation of assistive technologies, this work proposes a human–machine interaction (HMI) information technology for people with disabilities using various input and output sensors (multisensory), which adheres to the following basic functional principles:

is subordinated to

– the principle of adaptability and flexibility;

– the principle of multimodality;

– the principle of interface intuitiveness.

The proposed technology adheres to the basic functional principles and includes the following key components: a data collection component, a user ergonomic profile, a context-aware core, and an adaptive query analysis model based on personalized templates. The technology integrates an information access/authentication subsystem, a daily independence subsystem (smart home control), a navigation subsystem (indoor/outdoor), and an education subsystem (adaptive learning content) (Figure 3), representing a fundamentally new approach to ensuring the inclusion of people with disabilities through the creation of a unified adaptive interaction space. A distinctive feature is the integration of the four key subsystems into a single architecture with a context-aware decision-making core and a dynamic ergonomic profile.

The practical significance is that the proposed technology eliminates barriers for people with visual, hearing, motor, and cognitive impairments in four critical areas: daily independence, navigation, education, and access to information.

The proposed information technology is an adaptive multimodal system S, whose operation is aimed at maximizing the ergonomic efficiency and functional independence of a user with disabilities. The system can be formally represented as a tuple:

$$S = \langle C, U, P_E, K, I.A \rangle$$

here:
C – set of external environment sensors (Context sensors);
U – set of user-state sensors (User state sensors);
P_E – dynamic ergonomic user profile (Ergonomic Profile);
K – context-aware decision-making core (Core);
I – multimodal input–output interface (Interface);
A – set of application subsystems (Applications) that implement target functions (independent living, navigation, education, information access).

The main task of the system at time t is to select the optimal set of interaction modalities $(m_{in}, m_{out}) \in M$ (where M is the total set of available modalities), that maximizes the ergonomic efficiency objective function. F_{eff} :

$$\left(m_{in}^{*}, m_{out}^{*}\right) = \arg\max_{(m_{in}, m_{out}) \in M} F_{eff}(m_{in}, m_{out} \mid C_t, U_t, P_E)$$

where C_t and U_t – are the vectors of the environment and user states at time (t).

The data collection module (sensors C and U) is designed to perform the initial collection of raw data about the external context and the user's current physical and cognitive state. This module generates two data vectors:

– environment data vector C_t :

$$C_t = \{l, n, loc, o, \ldots\},$$

where l – illumination level, n – acoustic noise level, loc – geolocation data (GPS/GLONASS, BLE-beacons), o – presence and distance to obstacles (data from LIDAR/cameras);

– user-state data vector U_t :

$$U_t = \{g, h, v, b, \ldots\},$$

where g – gaze vector, h – head/hand pose and gesture parameters, v – digitized voice signal, b – biometric indicators (pulse, blink rate).

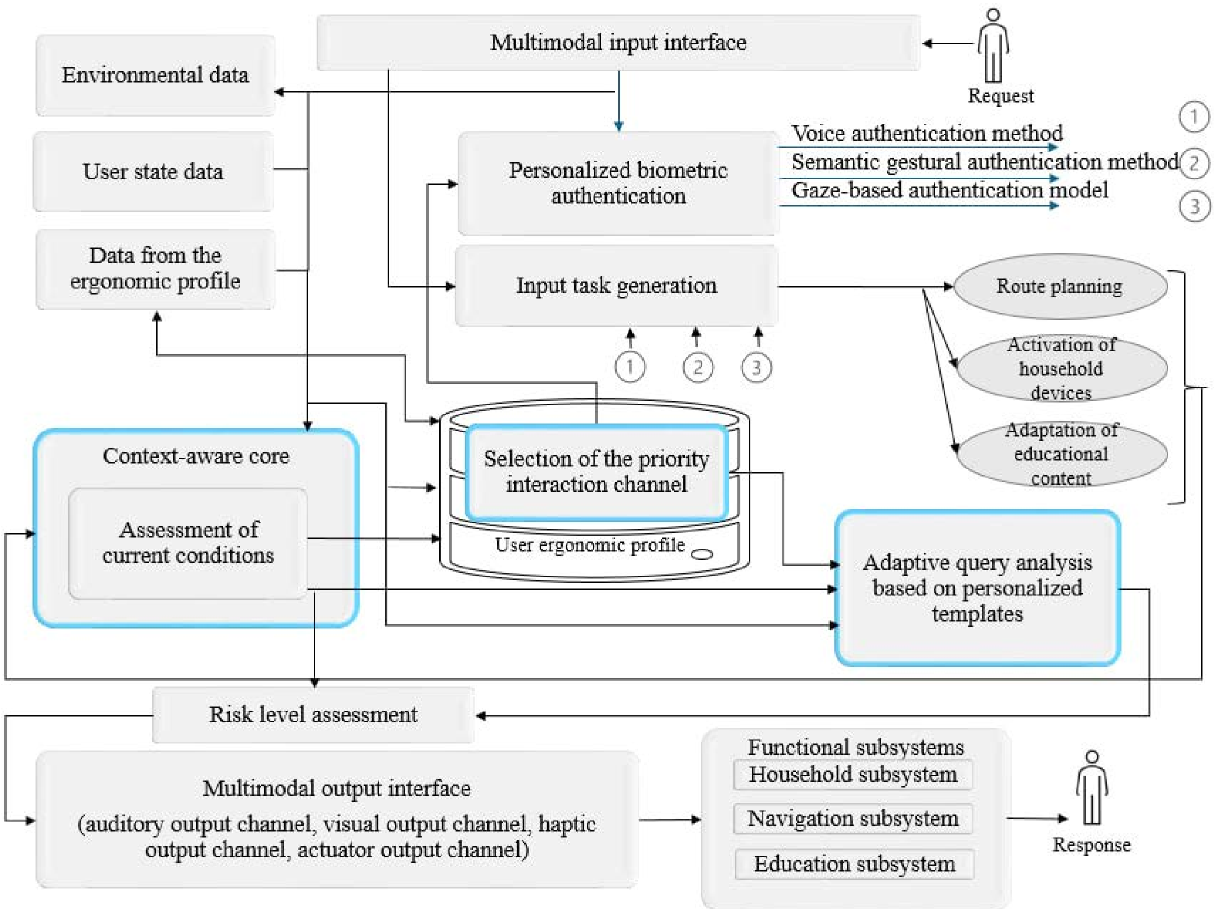

Fig. 3. Human–machine interaction information technology for people with disabilities

For initial signal processing, the following are applied:

– image preprocessing methods – computer vision algorithms (OpenCV, MediaPipe) for detecting key points on the face and hands, and determining gaze direction;

– audio preprocessing methods – noise filtering (Kalman filters, spectral subtraction) and speech-to-text conversion (Speech-to-Text, STT);

– sensor signal processing – triangulation and filtering algorithms to refine geolocation.

The user ergonomic profile (P_E) is designed for accumulating and long-term storage of individualized data about the user, including their preferences, limitations, and interaction history. The module serves as a knowledge base for personalization and adaptation, which the adaptive analysis model consults to make informed decisions. The ergonomic profile P_E is a structure that includes:

– static data (such as type of impairment, anthropometric data);

– dynamic parameters.

Dynamic parameters refer to the modality priority matrix $W_{m\times c}$, where w_{ij} represents the weighted effectiveness (priority) of the *(i)* modality in the *(j)* typical context (for example, the "voice" modality in a "noisy room" context would have a low priority); personalized templates based on biometric patterns (gaze patterns, voiceprints, gesture signatures); and the interaction history *H* – a sequence of pairs {(action, context, result}.

The profile is updated using machine learning methods, in particular reinforcement learning, where:

– state – the current context (C_t , U_t);

– action – the system's choice of interaction modality (m_{in}, m_{out});

– reward – a function based on proxy metrics (high speed and success yield positive reward). The system updates the weights *W*, aiming to maximize cumulative reward.

The central computational module is the context-aware core (K), which functions as an aggregator and interpreter of context. Its task is to transform disparate, low-level sensor data into a single, structured, semantically meaningful model of the current environment and user state.

The context-aware core addresses the question:

"What is happening around the user and with the user right now?".

The block receives raw data vectors from environment sensors $\mathrm{C_t} = \{\mathrm{l}, \mathrm{n}, \mathrm{loc}, \mathrm{o}, \ldots\}$, and user-state sensors $\mathrm{U_t} = \{\mathrm{g}, \mathrm{h}, \mathrm{v}, \mathrm{b}, \ldots\}$.

The output is a unified context vector $\mathrm{Ctx_t}$, which is sent to the adaptive analysis model. This vector contains already interpreted data, for example:

Ctx$_t$={location_type: 'store', noise_level: 'high',

user_state : fatigue ,new_obstacle : true }

The operation of this module is based on sensor fusion methods to form a comprehensive picture of the context, such as Bayesian trust networks. This method allows integration of data from various sources (e.g., GPS, Wi-Fi access points, BLE beacons for location determination), assigning a weighted trust coefficient to each source. This ensures system robustness in case of failure or inaccuracy of individual sensors. Classification and pattern recognition, necessary for converting quantitative data into semantic descriptors, are performed using machine learning methods. For example, the acoustic fingerprint of a room (microphone signal) can be classified by a model to determine the type of location ("street," "kitchen," "store").

The adaptive query analysis model based on personalized templates (MDA) is the central decision-making component in the proposed technology. Its function is to determine the optimal interaction strategy for the user at a given moment based on the contextual vector $\mathrm{Ctx_t}$ received from the context-aware decision-making core K and the knowledge from the user's ergonomic profile (P_E).

The adaptive query analysis model based on personalized templates addresses the question:

"Given the current situation and the individual characteristics of the user, which interaction method will be the most effective?"

The output is a control vector Cmd_t . for the multimodal interface. The control vector is defined as $Cmd_t = \{m^*_{in}, m^*_{out}, P_{adapt}\}$ and contains the selected modalities and adaptation parameters.

Decision-making is based on utility-based decision making. For each available interaction modality m_i a utility function $U(m_i)$, is calculated as a weighted sum: $U(m_i) = \sum_j w_{ij} \times f\left(Ctx_t^j\right)$, where w_{ij} – is the priority of the (*i*) modality for the (*j*) context parameter (taken from the priority matrix in the profile (P_E), and $f\left(Ctx_t^j\right)$ – is a function that evaluates the current value of the *(j)* context parameter. The system selects the modality m^* , that maximizes this function: $m^* = \arg max_{m_i} U\left(m_i\right)$.

In parallel with the utility-based model, a hard-constraints rule engine operates, imposing vetoes on certain decisions to ensure safety and functionality. For example, the rule:

**"IF location_type is 'магазин' AND new_obstacle is 'true' THEN force_duplicate('audio', 'haptic')"`*

has higher priority than any decision from the utility-based model. This ensures guaranteed duplication of critical notifications.

The personalized biometric authentication module (AuthService) is designed as a specialized service responsible for secure, passwordless user identity verification. Its key task is to provide protected access to the functions of system S and external services, dynamically adapting authentication methods to the current context and the user's individual capabilities. The module acts as an "access gateway," ensuring data integrity and confidentiality.

The input data for the module is an authentication request $Auth_{req}$, which contains the required security level (risk level), the context vector Ctx_t from the context-aware core (K), containing information about environmental conditions (noise, illumination), and access to biometric templates (references) stored in the user's ergonomic profile (P_E).

The output data in case of successful verification is an access session token $Auth_{Token}$, which contains information about the access rights granted to the application subsystems A.

In case of failure – a denial signal is generated.

The module implements a multimodal approach, using several parallel biometric channels for verification. The selection and combination of channels are determined by the MFA policy:

– gaze-based authentication, in which the user reproduces a personalized gaze password pattern (Gaze-password) by following a specific trajectory with their gaze. The input time series of gaze coordinates $g(t)$ is compared with the reference template from the PE profile. To compare time series invariant to reproduction speed, the dynamic time warping (DTW) algorithm is used. For more complex pattern analysis, a transformer-encoder–based architecture is applied, capable of capturing intricate dependencies in the trajectory;

– voice biometrics (speaker verification) provides a higher level of reliability through a hybrid two-factor approach that simultaneously analyzes both the physiological characteristics of the voice (who is speaking) and the semantic content of what is said. The verification process requires the user to speak a specific keyword or phrase. The system performs two tasks in parallel: first, using a speech recognition model (Speech-to-Text), it checks the correctness of the spoken word against the reference; second, the voice signal $v(t)$, after passing through a noise-robust frontend, is converted into a voice embedding (x-vector or ECAPA-TDNN embedding). This vector is compared with the reference speaker biometric template from the PE profile using PLDA or cosine similarity methods. Authentication is considered successful only if both checks are positive – correct keyword recognition and user identity verification;

– gestural identification analyzes a unique static or dynamic gesture. The 3D coordinates of key points of the hand, obtained from the vector $h(t)$, are fed into a Siamese neural network. The network is trained to determine the similarity between the input gesture and the reference template stored in the P_E profile.

Liveness and anti-spoofing mechanisms ensure that the biometric data comes from a live person rather than a recording or forgery. Depending on the active modality, a different set of techniques is applied:

− for gaze, normalization is performed based on blink analysis and the Eye-Aspect-Ratio (EAR) to confirm presence;

− for voice, spectral and phase characteristics of the signal are analyzed to counter replay attacks (ASVspoof detection);

− in general, a challenge-response system is implemented, where the user is asked to perform an unexpected action (e.g., look in a specific direction, speak a random phrase), preventing the use of pre-recorded inputs.

Conclusions. The work describes a developed integrated human–machine interaction information technology aimed at enhancing autonomy and supporting the independence of users with disabilities. The technology covers four key areas of daily life: navigation (indoor and outdoor), access to information and authentication, daily independence, and inclusive education. The core of the proposed technology is the synergistic interaction of two key components: a context-aware module that analyzes environmental conditions, the user's physiological state, and interaction history in real time, and a personalized ergonomic profile containing the user's individual needs and limitations, which can automatically update based on the success of scenario execution.

The main principles of the adaptive system's operation have been formulated, including the dynamic selection of optimal input/output channels (gaze, gestures, voice; audio, visual, haptic), mandatory duplication of critically important notifications across multiple modalities to enhance safety, and the provision of offline-resilient mechanisms for basic functions.

It has been shown that the proposed approach reduces cognitive and motor load on the user through proactive context-based selection of the most appropriate interaction method. It also enhances safety (through multimodal alerts) and maintains a high level of accessibility by complying with WCAG and EN 301 549 standards.

The practical significance of the work lies in the systematic integration of previously separate functions, such as obstacle recognition for navigation, passwordless authentication, adaptive commands for smart home control, and automatic adjustment of educational content. The principles, architecture, and methods developed in this work create a reproducible scientific and technical foundation for the development of future inclusive services.

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Барковська О.Ю. ІНФОРМАЦІЙНА ТЕХНОЛОГІЯ ЛЮДИНО-МАШИННОЇ ВЗАЄМОДІЇ З КОНТЕКСТНОЮ АДАПТАЦІЄЮ ДЛЯ ПІДТРИМКИ АВТОНОМНОСТІ КОРИСТУВАЧІВ З ОБМЕЖЕНИМИ МОЖЛИВОСТЯМИ

В роботі описано цілісну інформаційну технологію людино-машинної взаємодії для підтримки автономності користувачів з обмеженими можливостями у чотирьох сферах: навігація (внутрішня/зовнішня), доступ до інформації та автентифікація, побутова незалежність (керування «розумним домом»), інклюзивна освіта. Технологія поєднує носимі та стаціонарні сенсори, мультимодальні канали вводу/виводу (погляд, жести, голос; аудіо, візуальний та гаптичний вивід) і виконавчі пристрої в єдиному адаптивному циклі «подія → інтерпретація → рішення → дія → навчання». Ядром є контекстно-обізнаний блок, що в реальному часі враховує умови середовища, фізіологічні можливості користувача та історію взаємодій, а також персоналізований ергономічний профіль, який автоматично оновлюється за підсумками успішності сценаріїв. Запропоновано принципи динамічного вибору каналів та дублювання критичних сповіщень у кількох модальностях, офлайн-стійкі механізми для базових функцій, а також архітектурні інтерфейси для інтеграції з платформами розумного дому та освітніми сервісами.

Показано, що підхід зменшує когнітивне та моторне навантаження за рахунок контекстного підбору способу взаємодії, підвищує безпеку через мультимодальні попередження і підтримує доступність завдяки узгодженню з вимогами WCAG/EN 301 549 та характеристиками якості програмних систем. Практична значущість полягає в системному об'єднанні розпізнавання об'єктів і перешкод для навігації, безпарольної (або майже безпарольної) автентифікації на основі погляду/жестів/голосу, адаптивних голосових і поглядових команд для побутових дій та автоматичного підлаштування навчального контенту (шрифт, контраст, щільність, темп). Розроблені принципи, архітектура та методи створюють відтворювану основу для побудови інклюзивних сервісів, що підтримують самостійність людей з порушеннями зору, слуху, опорно-рухового апарату та когнітивними особливостями у повсякденних сценаріях.

Ключові слова: *людино-машинна взаємодія, асистивні технології, інклюзивність, контекстно-обізнані системи, адаптивний інтерфейс, ергономічний профіль, мультимодальна взаємодія, люди з обмеженими можливостями.*

Дата надходження статті: 29.11.2025
Дата прийняття статті: 18.12.2025
Опубліковано: 30.12.2025