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FORMAL DESCRIPTION OF INTERACTION AND DATA FLOWS IN MULTIMODAL ASSISTIVE SYSTEMS FOR USER AUTONOMY SUPPORT

The growing number of people with disabilities, particularly among war veterans, generates a pressing demand for technological solutions capable of providing support in everyday activities, mobility, education, and information access. This paper presents a formalized description of multimodal data flows within context-aware assistive interaction systems designed for users with special needs.

A complete data processing cycle is described – from the initial input (including voice commands, visual cues, spatial parameters, and physiological indicators) to the generation of an adaptive system response, tailored to the current context such as environment, user condition, and interaction history. Special attention is given to the synchronization of input channels and prioritization strategies in cases of incomplete or noisy data.

Representative use-case contexts are explored (e.g., spatial navigation, information requests, task execution), in which the system must adapt its output in the form of voice prompts, visual guidance, or haptic feedback. A functional model is proposed, outlining the key stages of processing: identification of the user's state, dynamic update of their ergonomic profile, and selection of the most relevant interaction scenario.

The paper also addresses technological constraints, including sensor data quality, influence of external conditions (lighting, noise, spatial obstacles), computational demands, and the need for user-specific personalization.

The proposed description provides a foundation for further development and implementation in multimodal systems for indoor navigation, independent living support, educational platforms, and information access services for individuals with disabilities.

Key words: multimodal systems, assistive technologies, context-aware interaction, people with disabilities, personalized interfaces.

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ФОРМАЛЬНИЙ ОПИС ВЗАЄМОДІЇ ТА ПОТОКІВ ДАНИХ У МУЛЬТИМОДАЛЬНИХ АСИСТИВНИХ СИСТЕМАХ ДЛЯ ПІДТРИМКИ АВТОНОМНОСТІ КОРИСТУВАЧІВ

Зростаюча кількість людей з інвалідністю, особливо серед ветеранів війни, формує запит на технологічні рішення, здатні забезпечити підтримку у побутовій діяльності, мобільності, навчанні та доступі до інформації. У статті формалізовано потік мультимодальних даних у контекстно-залежних системах асистивної взаємодії для користувачів з особливими потребами.

Описано повний цикл обробки даних – від моменту отримання вхідної інформації (включаючи голосові команди, візуальні сигнали, просторові параметри, фізіологічні індикатори) до формування адаптивної відповіді, що враховує поточний контекст: середовище, стан користувача, історію взаємодії. Основну увагу приділено синхронізації каналів та визначенню пріоритетів у випадку неповних або зашумлених даних.

Розглянуто приклади контекстів (рух у просторі, запит на інформацію, виконання завдань), у яких система має адаптувати свій вихід – голосовий супровід, візуальні підказки, тактильний фідбек. Запропоновано функціональну модель, що описує етапи обробки: ідентифікація стану користувача, динамічне оновлення його ергономічного профілю, вибір найбільш релевантного сценарію взаємодії.

Особливу увагу приділено технологічним обмеженням: залежності від якості сенсорних сигналів, впливу зовнішніх факторів (освітлення, шум, просторові бар'єри), обчислювальним вимогам та необхідності персоналізації під конкретного користувача.

Запропонований опис може бути основою для подальшої розробки та впровадження в мультимодальні системи навігації, підтримки побутової незалежності, навчальних платформ та сервісів доступу до інформації для людей з інвалідністю.

Ключові слова: мультимодальні системи, асистивні технології, контекстно-залежна взаємодія, люди з інвалідністю, персоналізовані інтерфейси.

Introduction

Before the full-scale invasion, approximately 2.7 million people with disabilities were officially registered in Ukraine (2021). As of 2024–2025, the Ministry of Social Policy and humanitarian agencies report over 3.0–3.4 million registered; estimates of the actual number exceed 6 million (taking into account new injuries, trauma, age, and unregistered cases). Separately, the Ministry of Veterans reports over 130,000 veterans with disabilities, increasing the need for rehabilitation, employment, and technological support. This situation exacerbates an already difficult labor market, where the employment rate of people with disabilities before the war did not exceed 2–3%, making assistive technologies not just tools of support but a key factor in socio-economic recovery and inclusion under martial law and subsequent reconstruction.

Inclusion is the creation of conditions under which people with different abilities have equal access to resources, services, and participation in social life. In the technical (IT) context, inclusion means designing and implementing information technologies that reduce barriers in interaction with the environment, information, and other people.

The key idea of this work is the use of two types of multimodal data to build a context-adaptive support system for people with disabilities:

- human-centered data
- environmental data.

The relevance of assistive technology for people with disabilities in the modern world is driven by a number of powerful factors that affect all areas of social life.

Analysis of the latest research and publications

Analyzing the scenarios, barriers, characteristics of technical solutions, technical requirements, and user features typical for ensuring a comfortable and safe life and activity for people with disabilities and special needs [1], this work formulates the main scenarios that require the development and implementation of scientific and methodological foundations for creating an assistive information technology based on multimodal data analysis (Figure 1).

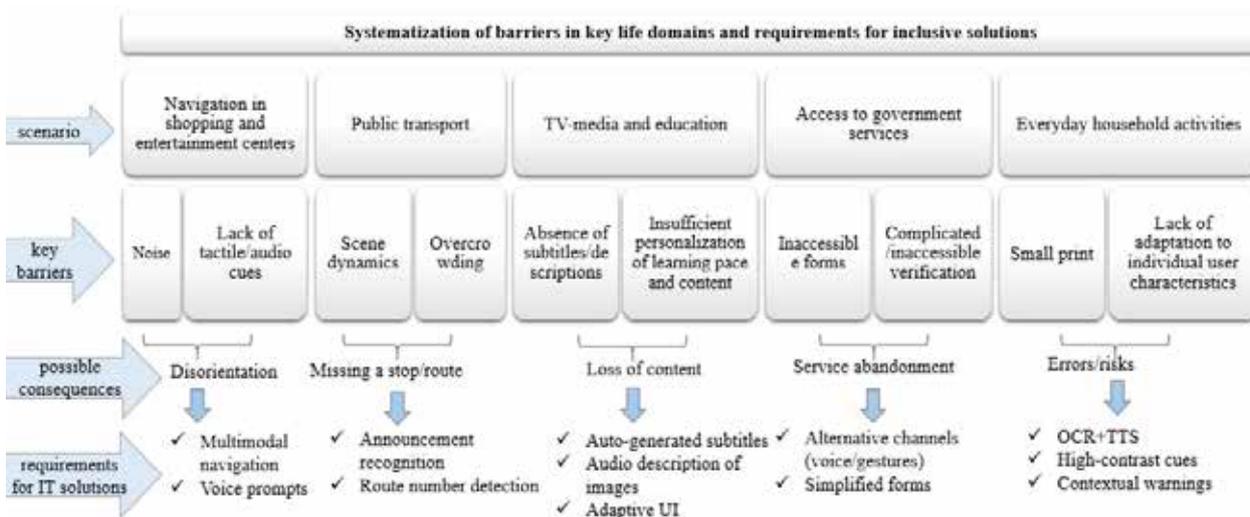


Fig. 1. Ontological map of problems and requirements for assistive and support technologies for people with disabilities

Navigation in shopping and entertainment centers, hospitals, and universities is complicated by the user moving through a complex multi-zone space while searching for stores, exits, and elevators [2,3]. Critical barriers include noise and the absence of clear tactile or audio cues, which lead to disorientation. This can be mitigated by multimodal navigation with an audio guide and/or tactile feedback, complemented by indoor localization for stable positioning within the building.

When using public transport, a person needs to reliably identify the route, avoid missing their stop, and make connections amid noise and crowds; the dynamics of the scene and overcrowding can easily cause confusion, creating the risk of boarding the wrong vehicle or missing a stop. This can be addressed by combining automatic recognition of

announcements and visual route cues (displays, numbers, directions) with geolocation, as well as short audio and vibration prompts with low latency that guide the user during movement and work even offline. However, solving this task is accompanied by challenges due to variable environmental conditions [4].

In telemedicine and education, during online lectures and instructional videos, it is crucial not to lose content due to the absence of subtitles and text descriptions of images; when these formats are missing, part of the material simply “drops out” [5]. Accessibility is restored through real-time auto-generated subtitles, captioning for graphics and slides, as well as an adaptive interface with adjustable fonts, contrast, and keyboard navigation.

In access to digital services, complex or inaccessible verification procedures stop the user midway and often result in abandoning the service. The problem is addressed by alternative interaction channels (voice, gestures, simplified text mode), simplified forms with clear step-by-step guidance, and accessible methods of identity verification without barrier-based CAPTCHAs [6].

In daily household activities, reading small labels or instructions causes errors and risks, especially under low lighting. Assistance is provided by instant text-to-speech via OCR+TTS, high-contrast on-screen cues, and contextual warnings about dangerous actions or incorrect choices.

Formulation of the purpose of the research

The aim of this work is to formalize the architecture and information flow in multimodal assistive systems for context-dependent interaction, supporting autonomy and access to information for people with disabilities, particularly war veterans, under variable environmental conditions and individual user limitations.

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

- analyze the key types of input data (audio, video, spatial, physiological) and usage scenarios for multimodal systems supporting users with special needs;
- describe the functional stages of input data processing in context-dependent interaction systems, from collection to adaptive response;
- identify the main technological constraints and requirements for implementing assistive systems in the areas of daily living, mobility, education, and access to digital services.

Materials and methods

The operation of the developed information technology is aimed at maximizing ergonomic efficiency and functional independence for users with disabilities through the sequential implementation of four logical stages: data collection, preprocessing, analytical processing, and direct user interaction. The diagram below (Figure 2) provides a detailed illustration of the architecture and the sequence of information flow between the key components of the technology, revealing the logic of data transformation from event to action.

Each block in the diagram performs a specific data transformation function. A key advantage is the integration of the context-aware core with a dynamic ergonomic profile, which provides personalized system adaptation to the individual needs of the user and to changing environmental conditions.

At the sensor stage, the technology converts physical phenomena from the environment and the user’s state into digital representations. Hardware sensors (cameras, microphones, LiDAR/ultrasound, light and noise sensors, GPS/BLE, physiological sensors) digitize light waves, sound vibrations, radio signals, and physiological changes. This creates two state sources at time t : the environment C_t and the user U_t . Raw data streams are heterogeneous, redundant, and noisy; they are unsuitable for direct semantic analysis, so the next step is unification and quality enhancement.

At the multisensor preprocessing stage, data are transformed from low-level signal representations into high-level feature representations. The operator $\varphi(\cdot)$ performs noise suppression, exposure normalization, time-series synchronization, channel reliability assessment, and feature extraction (key points, spectral descriptors, depth maps, etc.). The result is a structured feature vector

$$Z_t = \varphi(C_t, U_t),$$

which radically reduces the entropy of the input streams, unifies heterogeneous sensors, and prepares the data for semantic interpretation. Importantly, Z_t preserves the temporal synchronization of different modalities-this is critical for subsequent fusion.

Next, the transition from data to information occurs. The context-aware core $C(\cdot)$ performs high-level fusion and semantic interpretation of features, forming the context vector

$$Ctx_t = C(Z_t),$$

which contains situation descriptors (indoor/outdoor, room zone, illumination level L_{lux} , background noise N_{dB} , estimated distance to screens/objects \bar{d}_t [7], presence of obstacles, scene density, channel trustworthiness, etc.). At this stage, the interaction risk/criticality level is also calculated:

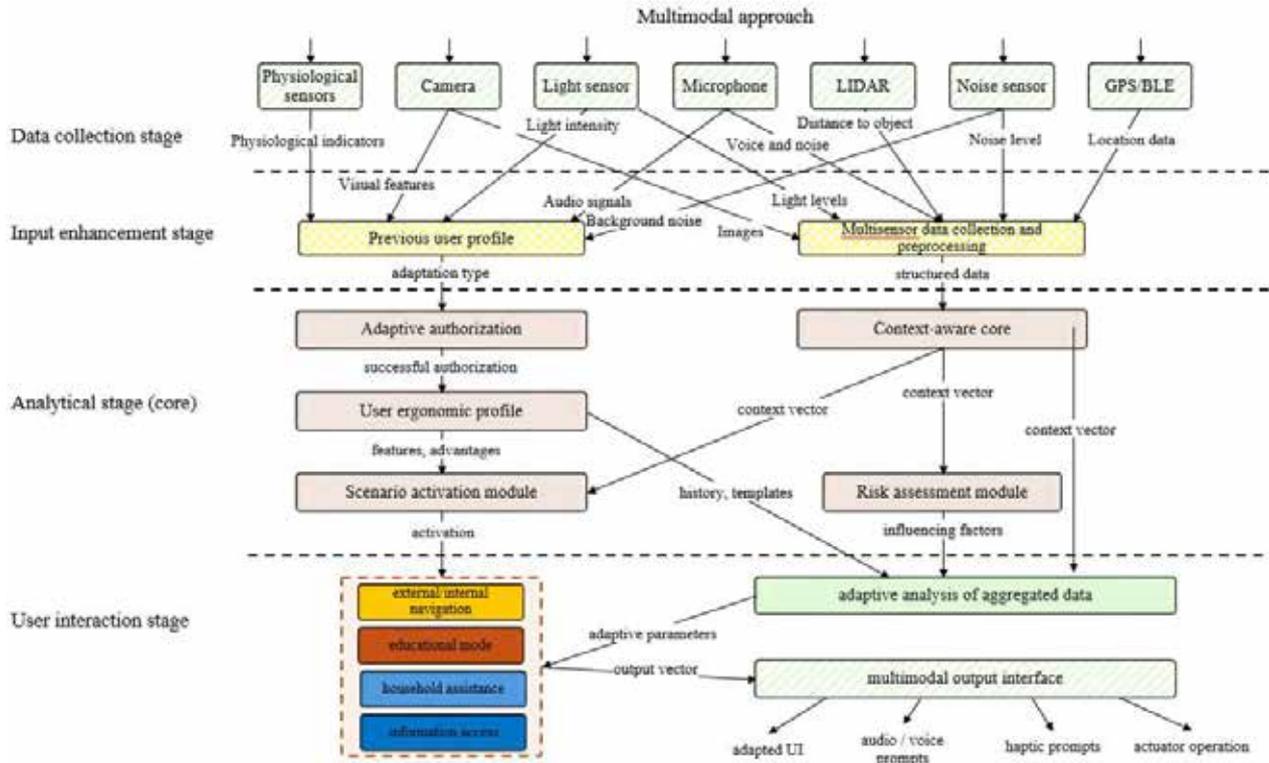


Fig. 2. Activity diagram of data flows in the human-machine interaction technology for people with disabilities.

$$\rho_i = R(Ctx_i),$$

which subsequently affects the output duplication policy (audio + haptics, etc.) to ensure guaranteed user perception.

With the context established, the system proceeds to personalized interaction planning. For each available modality $m \in M$, the utility is calculated:

$$J_m(Ctx_i, E_i) = \alpha q_m(Ctx_i) + \beta Pref_m(E_i) - \gamma Effort_m(Ctx_i, E_i),$$

where E_i – is the user’s ergonomic profile (history H_i , priority matrix W_i , biometric templates). The component $q_m(Ctx_i)$ reflects the channel quality in the given context (SNR for voice; illumination/glare for vision; availability of vibrofeedback for haptics), $Pref_m(E_i)$ – represents the individual familiarity/success of the channel based on history $Effort_m$ – denotes the costs (fine motor demands, cognitive complexity, etc.). The selection of the priority modality:

$$m_i^* = \arg \max_{m \in M} J_m(Ctx_i, E_i).$$

This formalizes the principle: “select the interaction method that is simultaneously reliable under current conditions and least demanding for this particular user”.

Once the optimal channel is determined, the policy π_i generates the control (command) vector Cmd_i with parameters for display/audio/haptic output and commands for the “smart home” actuators:

$$Cmd_i = \pi_i(Ctx_i, E_i) = \begin{cases} \{m_i^*, parameters\}, \rho_i < \tau_p, \\ \{m_i^*, m_i', parameters\}, \rho_i \geq \tau_p \text{ (duplication } y \geq 2 \text{ channels)} \end{cases}$$

where τ_p – is the criticality threshold, m_i' – is the backup channel (for example, haptics in addition to audio). For the visual modality a distance-aware UI is applied: to ensure angular legibility $\theta \in [24, 30] \text{ arcmin}$ (recommended for x-height), the size of elements is scaled according to distance \bar{d}_i :

$$size_{px} = \frac{2\bar{d}_i \tan(\theta/2)}{mm/px},$$

and is also adjusted by the contrast-sensitivity factor $k(L_{max}, glare)$. For interactive targets that are pressed or fixed by gaze, the parameters are additionally aligned with Fitts' law (a compromise between target size and distance).

At the output stage, the multimodal interface decodes the command into physically perceivable signals:

$$y_t = O(Cmd_t),$$

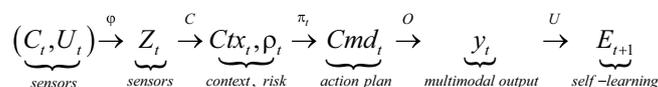
which materialize as voice/spatial prompts (TTS), visual changes (adaptive rendering, ROI highlighting), haptic patterns, as well as commands to actuators (lighting, locks, navigation beacons). If $\rho_t \geq \tau_p$, the message is mandatorily duplicated in at least two channels, which increases reliability of perception under noise/glare/stress.

After executing an action, the system collects operational metrics (time, number of repetitions, errors, need for confirmation) and self-learns by updating the profile:

$$E_{t+1} = U(E_t, Ctx_t, y_t, metrics(y_t)).$$

The update $U(\cdot)$ can be implemented through exponential smoothing of the priorities W_t , context-dependent multi-armed bandits (for selecting channels based on reward), as well as incremental learning of biometric templates (voice/gaze/gestures) with drift control. As a result, with each session the cognitive and motor load decreases, and the decisions π_t become increasingly accurate for the specific person in specific contexts.

In summary, the system implements a reproducible cycle:



Each module has a clear function and defined parameters, with transparent dependencies between levels: context and risk depend on the quality of sensor data and preprocessing; policy depends on context and the personal profile; output depends on policy and the criticality threshold; the profile depends on the history of successes under various conditions. This multilayered structure ensures context-aware, personalized, and reliable interaction for people with disabilities.

Conclusions

The article systematizes the operating principles of multimodal context-aware systems for assistive support of people with disabilities. It formalizes the data flow from sensor input to the generation of adaptive responses that take into account the environment, user state, and task. It is noted that successful functioning of such systems requires synchronization of different channels, flexible updating of the user profile, and robustness to partially lost or noisy data.

The practical significance of the study lies in creating a unified approach to designing multimodal assistive solutions in the areas of rehabilitation, daily navigation, education, and social integration. In the future, the proposed approaches can be applied to the design of interfaces and services supporting voice, visual, and tactile interaction scenarios, adapted to the specific limitations of the user.

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