A Reference Architecture for Pro-adaptive Cognitive Assistive Technology

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***Abstract*—Cognitive Assistive Technology (CAT) provides support for individuals in specific activities and in everyday life. It is used to monitor parameters and activities, act as a reminder, or to inform users of threatening scenarios. The development of CAT for people with cognitive impairments poses a particular challenge due to requirements regarding data protection, acceptance, mobility, and consideration of disease-specific limitations. In neurodegenerative diseases, such as Parkinson's disease or dementia, the limitations and thus motor- as well as non-motor-symptoms increase, resulting in assistive systems that are only able to adapt to specific needs at a given moment and therefore may no longer remain suitable over time. Instead, systems with higher levels of adaptability are required, eventually culminating in Pro-adaptive Cognitive Assistive Technology (Pro-CAT). To better enable the design of highly adaptive assistive systems, this paper presents a reference architecture for Pro-CAT, which serves as a foundation for systems that predict the progression of the user's condition and can adapt the assistance to the needs and limitations accordingly. If the assistance is provided proactively, Pro-CAT falls into the category of adaptive agents.**

Keywords-pro-adaptive cognitive assistive technology; reference architecture; privacy-by-design; levels of adaptability of assistive technology; adaptive systems.

I. INTRODUCTION

Population aging is accelerating worldwide along with a rising prevalence of disability, creating substantial challenges for individuals and societies alike. According to projections from the United Nations, there were approximately 727 million people aged 65 years or older in 2020, representing 9.3% of the global population. This number is expected to more than double to over 1.5 billion by 2050, corresponding to 16% of the global population [1]. In addition, the World Health Organization estimates that approximately 15% of the global population lives with some form of disability, of whom 2%–4% experience significant difficulties in functioning, and that prevalence rises sharply with age [2]. By closing the gap between intrinsic capacity and environmental barriers, an Assistive Technology (AT) can play an important role in promoting functional ability in such individuals [3] with neurodegenerative disorders like dementia or Parkinson's disease, entailing cognitive symptoms [4].

ATs encompass a broad range of technical interventions that aim to support daily functioning across various contexts, such as home care [5][6][7], workplace support [8][9][10] and rehabilitation [11][12]. Within this landscape, ATs that anticipate changes in user capabilities and adapt themselves accordingly, known as Pro-adaptive Cognitive Assistive Technology (Pro-CAT) [13], have the potential to align assistance with individual requirements. This highlights the need for structured design approaches to integrate predictive adaptation into ATs.

Reference architectures have been found to reduce reduplicated effort, lower risk through implementing proven solutions and encourage compatibility between systems [14][15][16]. In this paper, we present a reference architecture for a Pro-CAT and introduce the essential components to meet both functional and non-functional requirements. Most importantly, we contribute to the field of the reference architectures for ATs by providing an architecture that can not only support models at run-time but also focuses and provides a framework for introducing and maintaining pro-adaptive components. Moreover, we also provide privacy components that can serve as a guideline for meeting privacy regulations that might be required from the system. The aim of this work is to provide a basis for future Pro-CAT to identify potential risks and corresponding mitigation measures. In addition, the reference architecture enables the comparison of ATs and supports modular changes and easy adaptation of software and hardware components.

The paper is organized as follows: Section II reviews related work and summarizes recent reference architectures for ATs. Section III introduces the concept of Pro-CAT and discusses different levels of adaptability. Section IV presents the results of this work, including the identified requirements and the proposed reference architecture. Section V discusses

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and evaluates the proposed architecture, including limitations. Finally, Section VI concludes the paper and outlines directions for future work.

II. RELATED WORK

In [17], the authors propose a software reference architecture for ATs. Their contribution is an architecture that supports models at run-time for providing assistance and is achieved through (i) investigating multiple literature sources of functional requirements for the ATs, (ii) defining a set of components and inter-component connections building a reference architecture and (iii) validating the proposed architecture in two scenarios. The scenarios include assistance for elderly people where the system acquires knowledge about the user's behavior and helps by making suggestions once any daily activity is found problematic. The additional scenario is a CAT for operators in manufacturing, where a digital twin supports operators in the production processes.

A reference architecture targeted towards Active and Healthy Aging (AHA) has been proposed in [18]. Here, the aim is to improve the quality of life for elderly living at their homes through an Internet of Things (IoT) system, thus it is an advancement in the field of Ambient Assisted Living (AAL) [19]. As opposed to a very generic reference architecture proposed in [17], this is domain specific; however, it supports integration of different platforms, technologies, and standards for deploying a large-scale system for AHA. Here, the evaluation process is rather focused on testing and assuring interoperability of the modules and components that are part of the deployed example architecture rather than a theoretical analysis of the applicability of the suggested reference architecture to different scenarios (as in [17]).

ATs can also include robots, such as socially assistive robots [20], which can provide support in education or healthcare, and an approach for a reference architecture helping in designing those is proposed in [21]. The authors present a template for the organization of the software components so that the development of the features enabling robot's personalizable social interaction is facilitated. Unlike the aforementioned reference architectures, this one can be only applied while developing robots and was instantiated and evaluated on a social robot supporting people with dementia. Finally, [22] presented a software reference architecture for IoT-based healthcare applications focused on monitoring patients and the surrounding environment. It is designed for broader scenarios than [18] and is more specific than [17]. Moreover, unlike [17], the reference architecture in [22] has been designed based not only on functional but also nonfunctional requirements, such as security or availability. The evaluation is conducted by instantiating the reference architecture in the form of the platform integrating patients and caregivers to facilitate fast reactions in case of critical situations.

The reference architectures discussed in [17][18][20] and [22] do not accommodate the design principles of Pro-CAT [13]. Moreover, some architectures [17][20] overlook critical security aspects, raising ethical concerns especially when developing CAT for vulnerable groups.

III. PRO-ADAPTIVE COGNITIVE ASSISTIVE TECHNOLOGY (PRO-CAT)

ATs have increasingly incorporated adaptive and personalized mechanisms to better accommodate individual user needs. Over time, this has led to a broad spectrum of capabilities and configuration options [23]. However, most existing systems remain primarily reactive, adapting only to the current context or explicitly configured parameters. Such systems are inflexible to adapt automatically to changing user requirements.

Pro-CAT extends this paradigm by explicitly considering temporal dynamics and longitudinal trends. Instead of responding only to the present situation, pro-adaptive systems anticipate future changes in user abilities and proactively adjust assistance strategies to maintain effectiveness, usability, independence, and user acceptance over time.

A. Levels of Adaptability of Assistive Technology

Analogous to the concept of technology-readiness levels [24] and levels of driving autonomy (level 0: no automation to level 5: full driving automation, [25]), we define different *levels of adaptability* of Assistive Technology (AT):

1) Static AT: Assistance is available to the degree defined by the manufacturer of the AT.
2) Adaptive AT: The extent of assistance is adapted based on current sensor data readings.
3) Personalizable AT: Users can manually adapt the AT to their specific needs and requirements.
4) Auto-individualizing AT: The AT adapts to the user automatically based on past observed behavior and sensor data.
5) Pro-adaptive AT: The functionalities of items 2 to 4 are combined. Moreover, the AT adapts to meet the user's (future) needs based on anticipated conditions that are derived from past and current sensor data (e.g., aging or disease related changes in the user's capabilities).

Personalizable AT (level 3) is well established and can be found in consumer products like cars. For example, users can adjust the steering control sensitivity, engine response curves ('sport mode') or cabin air conditioning (for a review, see [26]). Systems with a level 4 adaptability were conceptualized in the context of Advanced Driver Assistance (ADAS), suggesting a modular decomposition for the next generation of personalized ADAS and human machine interaction, which can be expected to continuously adapt in interaction with the driver [27]. For example, researchers from Toyota and the Georgia Institute of Technology developed a data-driven approach to personalized autonomous driving [28]. This approach automatically adapts the driving style of autonomous vehicles based on observed driving data of an individual user. Another example of a level 4 adaptive AT, in which assistance is adjusted based on past sensor data, was proposed in [29]. Here, the authors present a behavior model that enables a socially assistive robot to adapt to the user based on the past interaction. The model is implemented as a deep neural network that is trained on multiple input modalities and outputs actions to be performed by the robot.

B. Concept and Definition of Pro-Adaptive Cognitive Assistive Technology

While existing AT aims to address a user's immediate needs, the concept of Pro-CAT, as introduced in [13], is intended to have a broader scope. Various aspects are to be taken into account in order to offer users the most effective support feasible: Pro-CAT aims to continuously evaluate its users' situational data, e.g., concerning health or learning progress, the context in which the users are situated, and their abilities, thereby learning over a longer period of use how the user's state, aging process, and condition develop and change. On this basis, a prediction of how the user's condition may develop in a given amount of time can be calculated and the CAT may provide the user with the best possible support at the current stage as well as simultaneously prepare them for the expected course. Due to the predictive functionality, in the event of deteriorating abilities, compensation options can be practiced with the user at an early stage to well prepare them before their condition worsens. In certain cases, these measures may help maintain abilities and increase acceptance over time. The system operates in such a way that tasks which users are still able to master independently are not performed for them or assisted strongly. Likewise, as skills are acquired and the condition improves, the level of support is reduced accordingly. Providing more support than needed at a given time may lead to negative effects, such as dependence on the AT or a deterioration in the user's abilities, as skills may be unlearned. In Pro-CAT, the concept of a 'human digital twin' [13] may be applied, which aims to display, model and continuously adjust all parameters and data relating to a person on the basis of regular measurements, and to predict the further course of development.

Following our concept paper [13], the interplay of three core components can enable pro-adaptive systems (see Figure 1): 1. a prognostics module that predicts changes in relevant abilities based on competence- and progression models, 2. a cognitive state estimation module that assesses the user's current state, and 3. a context module inferring user intentions. On top, continuous learning may be applied to update the models over time to deliver highly individualized assistance.

The key advantages of Pro-CAT include sustained personalization, improved long-term usability, and the ability to proactively adjust assistance strategies in response to predictable changes in user capabilities.

IV. PRO-CAT ARCHITECTURE

This section briefly presents functional and non-functional requirements of a Pro-CAT. Furthermore, the proposed reference architecture for a Pro-CAT is described in detail, including the components and functionality.

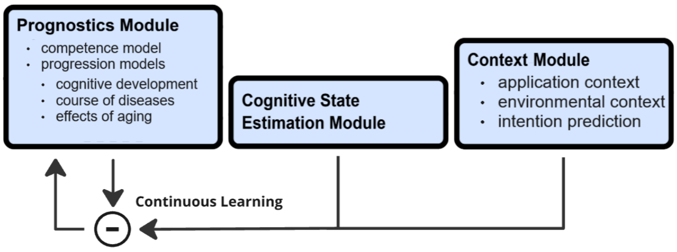

Figure 1. Components enabling Pro-CAT: User data and environmental information is processed by three modules: 1. a prognostics module predicting changes in relevant abilities, 2. a cognitive state estimator assessing the user's current state, and 3. a context module inferring user intentions. Continuous learning updates the models over time to deliver individualized assistance.

A. Identified Requirements of Assistive Technologies

For the development of AT, several functional and non-functional requirements must be met. The detection of disease-related symptoms, in addition to the monitoring of parameters, such as pulse, activity, and noise, is a significant requirement, especially for people with cognitive impairment or neurodegenerative disorders, such as Parkinson's disease or dementia, since disease progression worsens over time and there is no cure. An example of this is the detection of tremor or freezing of gait in people with Parkinson's disease, or the measurement of activities as well as focusing time for a specific task in patients with Attention Deficit Hyperactivity Disorder (ADHD). The local storage of detected symptoms can support long-term tracking of, e.g., a neurodegenerative disease like Parkinson, and, in addition, be used to train an AI-based digital twin of the patient in order to model the disease course. This can help and support physicians as well as patients in medication therapy. In addition to the detection of disease-related symptoms, the detection of falls and reminder functions for appointments, medication, or fluid intake are also essential components of cognitive AT especially for elderly people. The preliminary detection of these events can reduce falls and thus the risk of further injuries. In this case, real-time capability and optimized sensor data processing are also important requirements. To actively support the motor or non-motor functions of the patient, the AT should provide assistance based on the capabilities of the patient, which are reduced over time in neurodegenerative disorders. In this case, the AT adapts and provides assistance according to the specific user's needs to avoid over-assistance [30].

As symptom-related constraints may limit interaction, usability must be given. These constraints include motor impairments (e.g., tremor or bradykinesia), cognitive limitations (e.g., reduced attention, memory, or executive functioning) or sensory limitations (e.g., impaired sense of vision or hearing). Consequently, user interfaces and output components should be adaptive and configurable, presenting only the information necessary for the current situation, while respecting individual preferences and disease-related requirements (e.g., larger targets, reduced interaction steps, reminder timing, modality selection) [30][31]. Moreover, the reference architecture must support transparency and explainability of AI-driven behavior, enabling users to understand why recommendations, prompts, or adaptations occur, thereby fostering trust, perceived control, and safe use. The architecture should enable local computing to ensure low latency, robust operation during connectivity disruptions and privacy-preserving processing of sensitive data (e.g., on-device inference and local data minimization). While local autonomy is critical, the system must retain cloud integration capability to support external resources and services, specifically including interoperability with cloud-based services. Significant offerings are updates, model life-cycle management, cross-device synchronization, or optional analytics, without making core functionality dependent on continuous cloud access. Finally, the architecture must be expandable, supporting incremental integration of additional components and ecosystems (especially smart home systems) through modular design and standards-based interoperability. To prevent the collection of data from third parties in AT that use environmental sensors, additional security measures are required alongside local data storage, anonymization, and data encryption. These measures may include rules for specific scenarios, such as visits from family members, caregivers, or physicians, during which data acquisition from certain sensors is disabled or completely stopped. To this end, these rules can be configured and activated using a physical switch called privacy switch in our reference architecture.

B. *Components*

For the selection of suitable components, various reference architectures for ATs were analyzed, and frequently occurring components were adopted. In addition, we identified and specified components required to enable **Pro-Adaptivity** of CAT. The result is shown in Table I, which lists all components together with their respective functionality.

C. *Proposed Reference Architecture*

The reference architecture (shown in Figure 2) developed in this paper follows a modular, privacy-by-design approach for Pro-CATs. It is designed to support secure data acquisition, adaptive AI-based processing, and context-aware actuation while maintaining a clear separation of concerns between data handling, decision-making, and system control. Privacy enforcement, Pro-Adaptivity, and AI management are treated as first-class architectural elements, enabling both local and externally supported intelligence under configurable privacy constraints.

Interaction with the system occurs through three primary channels:

(i) the `Privacy Switch`, which defines which data may be processed, stored, or forwarded,

(ii) the `User Interface`, through which services are selected and information is displayed,

(iii) the `Acquisition Devices` (e.g., wearables or environmental sensors), which are responsible for data acquisition.

TABLE I. COMPONENTS AND THEIR TASKS

ID	Component	Task
C1	Anonymization (Security)	Removes or masks sensitive data to protect privacy.
C2	Encryption / Decryption	Encrypts data for secure transmission and decrypts incoming data.
C3	Privacy Switch	Physical switch to interrupt data acquisition or transmission.
C4	Privacy Mode Handler	Controls privacy modes, stops data flows if necessary, or restricts system access.
C5	Storage Manager	Manages stored data and its organization.
C6	Physical Storage	Physical storage of data (e.g., database, file system).
C7	Data Management	Organizes, manages, and provides data within the system.
C8	Actuators	Execute physical actions as defined by the system.
C9	Actuator Control Unit	Translates system decisions into control commands for actuators.
C10	Acquisition Devices	Devices for data acquisition, e.g., sensors or cameras.
C11	AI Management	Manages AI models, including loading, configuring, or switching.
C12	Pro-Adaptivity	Adapts the system to changing environments or user needs.
C13	System Administration / System Log	Monitors and logs system activities, supports maintenance and error analysis.
C14	External Communication	Interface for communication with external systems or services.
C15	User Interface	Visual/interactive interface for user interaction and result presentation.

The `Privacy Mode Handler` receives signals from the `Privacy Switch` and enforces the corresponding privacy and operational policies throughout the system. Depending on its configuration, it regulates the processing and transmission of data, particularly with respect to `Data Management` and `External Communication`.

In Figure 2, the process of allowing or denying external communication is visualized using a diamond-shaped decision element. This explicitly highlights that external communication is not implicit but subject to a configuration-dependent decision by the `Privacy Mode Handler`, ensuring privacy-by-design and a clear separation of concerns.

Sensor data collected by the `Acquisition Devices` are first anonymized within `Anonymization (Security)` before being forwarded to `Data Management`.

`Data Management` acts as the central integration component of the architecture. It ingests data from multiple sources, performs preprocessing and structuring, and routes information to downstream components, such as `AI Management`, the `Storage Manager`, `Pro-Adaptivity`, or `External Communication`. Relevant information may also be fed back to the `User Interface`.

The `AI Management` component comprises two main functional areas. The first functional area (i), the *AI Component*, is responsible for executing the deployed AI models (inference). In this process, AI models are loaded from the `Storage`

`Manager` and applied to the incoming data in order to generate predictions or classifications.

The second functional area is the *Model Optimizer*. This component is responsible for the training or optimization of AI models based on feedback from `Pro-Adaptivity`. In this context, optimization may include updating model parameters (weights) or adjusting model configurations to improve system performance.

The resulting updated model versions or parameters are then stored again in the `Storage Manager`. Depending on the application scenario, the updated models can subsequently be loaded and executed by the *AI Component*.

`Pro-Adaptivity` processes inputs from `AI Management` and `Data Management`, requests additional external data when required via `Data Management` and transmits its results to the `User Interface` and the `Actuator Control Unit` to trigger actions if necessary. Its key capability is self-adaptation: it analyzes variations in inputs or system states, adjusts internal parameters or model weights accordingly, and returns optimized values to `AI Management`, allowing the system to dynamically adapt to new conditions and evolving user needs.

Beyond technical adaptation, `Pro-Adaptivity` explicitly addresses cognitive aspects of assistance. By anticipating changes in user capabilities, the system can gradually adjust assistance intensity, avoid abrupt behavioral changes, and prevent negative psychological effects, such as over-reliance or loss of agency. This cognitive perspective is essential for long-term acceptance and distinguishes Pro-CAT from purely reactive adaptive systems.

The `User Interface` visualizes system and status information received from `Pro-Adaptivity`, the `Actuator Control Unit`, `System Administration/System Log`, and `Data Management`. In addition, it forwards user inputs to `Data Management`.

The `Actuator Control Unit` translates high-level decisions into device-specific commands for the `Actuators`, which execute actions in the physical environment.

The `Storage Manager` coordinates data flows to persistent storage, performs encryption and decryption of sensitive information via `Encryption/Decryption`, and interacts bidirectionally with `Physical Storage` as well as with `AI Management` for storing models and weights.

`External Communication` encapsulates interaction with external systems, such as cloud-based AI services. Access is governed by the `Privacy Mode Handler`, while data and results are exchanged bidirectionally with `Data Management`. It also connects to external AI services that provide additional models or analytical capabilities.

Finally, `System Administration/System Log` monitors operational states, collects event logs, and supports traceability and auditing of security- and privacy-relevant processes.

V. DISCUSSION | EVALUATION

This paper proposes a modular, privacy-by-design reference architecture for Pro-CAT [13], which is evaluated in this section from an architectural and quality-attribute–driven perspective. The architecture deliberately separates concerns between (i) privacy control and enforcement, (ii) data acquisition and management, (iii) AI model operation and optimization, and (iv) pro-adaptive decision-making and actuation. This separation constitutes a key architectural design decision and directly supports maintainability, extensibility, and reuse: individual components can be replaced or specialized (e.g., different AI models, storage backends, or communication mechanisms) without requiring structural changes to the overall system.

A. Privacy-by-Design

A key architectural decision is to treat privacy enforcement as a first-class concern. The combination of the `Privacy Switch` and the `Privacy Mode Handler` enables explicit user control and systematic policy enforcement across internal processing and external communication. This is particularly relevant for sensitive domains, such as healthcare and education, where data minimization and controllable data flows are critical for acceptance and compliance. In addition, the explicit integration of `Anonymization (Security)` and `Encryption/Decryption` provides a clear architectural pathway to implement privacy-by-design in a consistent and reusable manner, rather than relying on ad-hoc measures.

B. Pro-Adaptivity

The architecture emphasizes Pro-Adaptivity as a distinct capability, implemented through the interaction between `AI Management` and `Data Management`. In contrast to purely reactive adaptation based only on the current context, pro-adaptive behavior requires longitudinal signals, temporal modeling, and feedback loops for continuously adjusting parameters, models, or assistance strategies. The architecture supports this by (i) enabling data integration from diverse sources, (ii) allowing model updates and persistence over time, and (iii) supporting closed-loop feedback from observed outcomes to model optimization. As a result, Pro-Adaptivity is treated as an explicit architectural capability rather than an implicit consequence of AI-based processing.

C. Limitations

- **Conceptual validation:** The reference architecture is derived from literature and design reasoning and has not yet been validated through a longitudinal deployment or controlled user study.
- **Operationalization of Pro-Adaptivity:** The paper outlines pro-adaptive mechanisms at an architectural level; the concrete selection of prognostic models, update strategies, and calibration procedures depends on the application domain and remains to be specified.

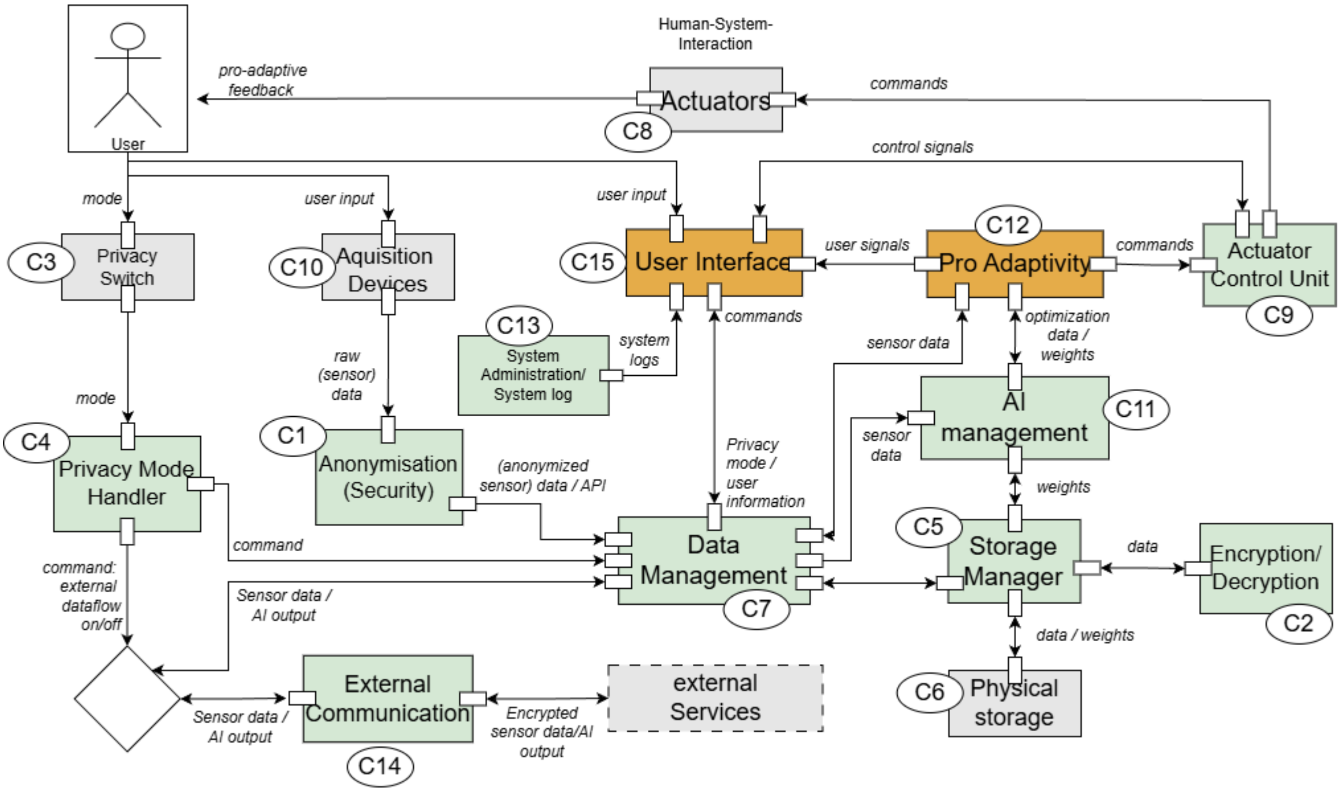

Figure 2. Overview of the reference architecture for Pro-CAT, which depicts the interaction between privacy control, data management, adaptive AI management, and actuation.

VI. CONCLUSION AND FUTURE WORK

The proposed architecture addresses a key limitation of existing ATs by explicitly supporting longitudinal adaptation to predictable changes in user capabilities, such as those resulting from aging, progressive disease, recovery, learning, or skill acquisition. In contrast to purely reactive or manually configurable systems, the architecture enables pro-adaptive behavior by integrating continuous data acquisition, AI-based analysis, and feedback-driven model refinement within a clearly structured architectural framework.

A central contribution of this work is the explicit treatment of privacy and Pro-Adaptivity as first-class architectural concerns. The architecture supports transparent data governance, user control, and compliance with privacy regulations while maintaining adaptability and system autonomy. The clear separation of concerns between data management, AI management, decision-making, and actuation enhances modularity, reusability, and maintainability, allowing individual components to be replaced or extended without affecting the overall system structure.

Furthermore, the reference architecture provides a common conceptual basis for comparing, designing, and evolving pro-adaptive ATs across different application domains. It supports both local, privacy-preserving operation and optional cloud-based services, thereby balancing robustness, low latency, and extensibility.

We also provide a concept of levels of adaptability of assistive technologies analogous to technology-readiness levels. As such, the architecture contributes not only a technical blueprint but also a structured guideline for future Pro-CAT.

Future work should focus on making the architecture actionable and empirically grounded:

1) **Monitoring, evaluation, and user studies:** Evaluate the architecture through implementation, e.g., in scenarios outlined in this paper (Parkinson support, dementia support, ADHD support, cognitive training), using measurable criteria, such as usability and acceptance, perceived control, adaptation quality, and system robustness. Longitudinal studies are particularly important to evaluate the benefits of Pro-Adaptivity over purely reactive adaptation.
2) **Prognostic module and temporal modeling:** Specify how prognostics and longitudinal user modeling are realized within `Pro-Adaptivity` (or as an explicit submodule), including update triggers, uncertainty management, and personalization strategies.

Overall, the proposed reference architecture provides a structured foundation for engineering pro-adaptive cognitive ATs. By making privacy and Pro-Adaptivity explicit architectural concerns, it supports both trustworthy data handling and continuous personalization.

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