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Adaptive Visualization Framework for Human-Centric Data Interaction in Time-Critical Environments

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ABSTRACT

In today's data-driven era, handling information overload in time-sensitive scenarios poses a significant challenge. Visualization is a valuable tool for comprehending vast amounts of data. However, it's crucial to have self-adapting visualizations that are tailored to the user's cognitive level and grow with their expertise. Existing solutions often fall short in this regard. This paper introduces a framework integrating Artificial Intelligence (AI) techniques for context awareness and emotion sensing, offering visualizations that adjust to user requirements. The framework makes use of cross-modal sensors and Machine Learning (ML) algorithms to analyse behavioural signals, usage statistics, and user feedback. This data guides real-time data ingestion techniques and ML-driven mechanisms, ensuring that visualizations adapt while safeguarding data privacy and confidentiality.

Keywords: Visualization, Human interaction, AI-based adaptive systems

INTRODUCTION

In today's data-driven era, the task of making objective decisions through complex information visualization systems is increasingly daunting (Shakeel et al., 2022). This is especially true in time-sensitive contexts such as Security Operation Centers (Adams & Snider, 2018) and health monitoring dashboards (Kim, 2022), where humans must navigate information overload, understand data clearly, and interact efficiently with machines. This task is very challenging for the non-expert human operator since thinking in purely numerical and mathematical abstractions is unnatural, especially in critical situations. Therefore, it is becoming crucial to have self-adapting visualizations tailored to the user's cognitive level, which evolve alongside their increasing expertise and learn from past experiences.

Achieving this requires adopting AI agents that are capable of enhancing context awareness and human-centric attributes of the presented data (Wu et al., 2022). Despite the success of some recent computational models in predicting expert performance on various tasks, there is still a gap in modeling how other types of users (for example, non-experts) acquire new skills over time and how visualizations may be intelligently adapted to their needs.

This paper presents a framework proposed by the SYMBIOTIK project[1] that aim to integrate biological principles, collaborative and social-like properties, and tailor-made agents guided by AI techniques for context awareness, emotion sensing, and expressing capabilities. Prior psychological theories have identified the selected properties as highly relevant to the development of human consciousness. The proposed framework incorporates a mechanism to deliver self-adapting visualizations tailored to the user's cognitive level, evolving in response to their growing expertise and learning from previous experiences. Specifically, the system enables continuous learning and integration capabilities through knowledge exchange and analysis loops formulated via data communication pipelines across the operational environment, the processing components, and the visualization interface. The Paper is organized as follows: first, we detail the different components of the framework and the interactions between them. Then, we describe the evaluation strategy of the proposed solution. Finally, we present the conclusion of the work.

PROPOSED FRAMEWORK

The proposed framework composes of four main layers as depicted in Figure 1. In the following we will discuss each of these layers in details.

- ***Layer 1 - Data Gathering and Annotating***: This layer is responsible for gathering data from users, annotating it, and then passing it on to the subsequent layers. Data collection is achieved through different cross-modal sensors, which collect multimodal behavioural signals. These signals are later analysed using various techniques. The sensors capture information related to the users' physiological conditions, as well as behavioural data generated through user interactions with the *Dashboard*. All this information is stored in the *Compact Data Representation* module, which enables fast and efficient data storage. Simultaneously, the module utilizes various compression and encoding techniques to further reduce data size while preserving data integrity.
- ***Layer 2 - Reinforcement Learning Loop***: This layer is responsible for receiving and processing the annotated data from layer 1. The first module to receive this information is the *Neural-mechanistic Understanding* module, which processes it using various AI techniques to gain a deeper understanding of the patterns in the transformed data. The output of this module is shared with the *Reinforcement Learning Module (RLM)*, which designs a Multi-Objective Deep Reinforcement Learning (MODRL) algorithm to identify optimal adaptation actions. These recommended actions are shared with the *Awareness Inside module*, which manages all RL aspects and shares the adaptation strategies that could be selected and later applied with the *SYMBIOTIK Adaptation Module*. Additionally, it receives user feedback from the *SYMBIOTIK Adaptation Module*, which is used for the reward function of the RL algorithm.

[1] https://symbiotik-infovis.eu/

- ***Layer 3 - Continuous Adaptation Loop:*** This layer is responsible for providing an adaptation plan for the user dashboard and continuously monitoring the adaptation of such a plan. To achieve this, the *SYMBIOTIK Adaptation Module* computes an adaptation for the Dashboard by performing one or several cycles of the adaptation process. While performing this task, the SYMBIOTIK Adaptation Module interacts with other modules to gather required inputs. Specifically, it uses the biosignals captured by the *Behavioral Sensing module* and requests the end user profile, which consists of demographic data, preferences, and settings for conducting an adaptation life cycle, from the Adaptation Panel. Furthermore, it considers the current configuration file of the Dashboard that can be requested from the *InfoVis Gateway*. The output of the *SYMBIOTIK Adaptation Module* is an adaptation request, which is shared with the *Adaptation Panel*. The Adaptation Panel, in turn, shares the configuration file with the *InfoVis Gateway*, which is integrated within the *Dashboard*. This integration enables the realization of dashboard adaptations in real-time. The sensors will capture the user behaviour resulting from the new dashboard configuration and share this with layer 3 and 2.

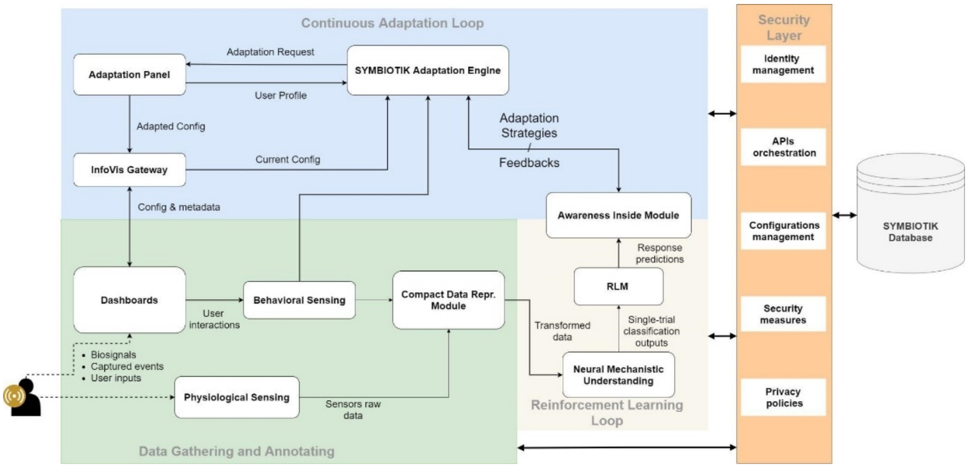

Figure 1: High-level system architecture of the proposed framework.

- ***Layer 4 - Security Layer:*** The security layer is responsible for defining, inspecting, and monitoring privacy and technical measures that ensure the security of assets across different layers. It also ensures the protection and compliance of the data used and exchanged by the system. This is achieved through several subcomponents, including *Identity Management, Security Measures, APIs Orchestration, Privacy Policies, and Configuration Management*. This layer will implement the following security features. Firstly, it ensures data pseudonymization; a process that replaces personally identifiable information (PII) fields within data records collected by the sensors with one or more artificial identifiers. This significantly reduces the risk of linking a dataset to a user's original identity. Additionally, the layer employs robust encryption schemes for data encryption, selected for their strength to ensure high-level security. Finally, strict access control mechanisms are implemented to restrict data access, preventing unauthorized entry, and ensuring that only authorized personnel can interact with the data.

EVALUATION STRATEGIES

To implement, test, and validate the framework, we will employ two distinct real-world use cases that align with the criticality of time-sensitive decision-making and the acceleration of the end-user transition from novice to expert. In particular, the *Crime Investigation* use case will primarily target the achievement of the novice-to-expert transition, while the *Security Operation Center* use case will facilitate time-sensitive decision-making.

The ***Crime Investigation*** use case aims to utilize the adaptive visualization mechanism to enhance the operational environment of Law Enforcement Agencies (LEA). Specifically, it will involve scenarios where criminals or suspicious individuals are identified through the investigation of phone-extracted data. The analyzed data will encompass a combination of diverse formats (auditory, visual, or textual) and types (e.g., Call Detailed Records, audio files, documents, images, etc.). Visualizing and exploring such datasets result in high-complexity representations (network graphs, timeline analysis, multi-modal charts, and more). Through the adaptation mechanism, our goal is to reveal missing or hidden interactions, identify uncovered patterns, and significantly improve overall usability and situation awareness.

The ***Security Operation Center*** use case aims to improve the decision-making process (detect, prevent, and respond) of security operators responsible for efficiently managing various tools and technologies to monitor the threat landscape of their organization. The primary investigation scenarios involve exploring vast amounts of data and identifying and mitigating potential malicious incidents detected from various processes (e.g., abnormal, or high-severity events/alerts, malware analysis, data breaches, Denial of Service (DoS) and Distributed DoS attacks, and more). Through AI-powered adaptations, our objective is to optimize runtime monitoring and user-driven threat detection and response capabilities by providing visual adaptations to highlight critical information, reduce visual noise, and ultimately assist in responding rapidly in time-critical contexts.

DEPLOYMENT TECHNOLOGY OVERVIEW

To guarantee a modular architecture and provide a secure, scalable, and interoperable solution with other dashboards, we've designed the deployment topology shown in Figure 2. Concentrating on the components and modules within the Adaptive Visualization Mechanism, we have developed components and services to establish communication pipelines, facilitate front-end to back-end data transfer, manage authentication and authorization, offer advanced storage, enable agile orchestration, and more. In more detailed, we use AEGIS AVT[2], which is a web application utilized in an Angular-based framework, has been dockerized in a way to support the necessary set

[2]https://aegisresearch.eu/solutions/advanced-visualization-toolkit/

of environment variables and network parameterization options. A Nginx[3] dockerized version is being used as the environment's webserver. In addition, distinct implementations in a NodeJS[4] programming environment that involve JavaScript services and associated libraries and frameworks (e.g., RxJS[5], ExpressJS[6], etc.) have been developed to support a set of initial functionalities for the *InfoVis Gateway* and the *Behavioral Sensing* components. Similarly, these implementations are being offered as a docker image with the essential environment variables exposed. In order to integrate these docker images and create a communication network between them, a YAML Docker Compose file was used. By using the Docker Compose[7] tool, we were able to interconnect and run multi-container applications at once, both in local or production hosts, while laying the foundation for a scalable and robust docker setup through a Kubernetes[8] orchestration plan. Additionally, the Docker Volume[9] mechanism is employed to persist user-imported data or data generated by and used by the containers. Thus, the necessary config files for the sub-modules and the adapted configuration files from the Adaptation Engine mechanisms were handled by the Docker Volume file system.

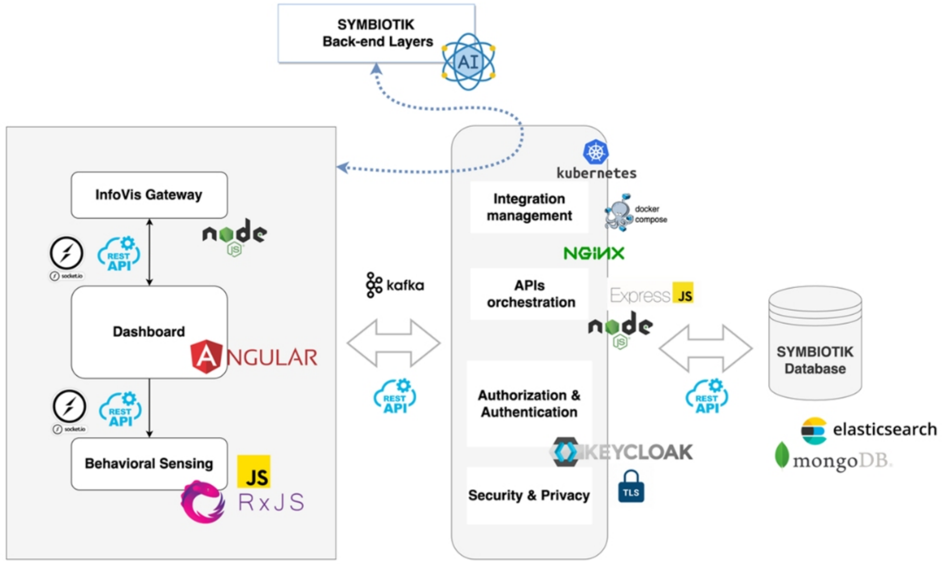

Figure 2: Technologies involved in the deployment of the proposed framework.

[3] https://www.nginx.com/
[4] https://nodejs.org/
[5] https://rxjs.dev/
[6] https://expressjs.com/
[7] https://docs.docker.com/compose/
[8] https://kubernetes.io/
[9] https://docs.docker.com/storage/volumes/

CONCLUSION

This paper introduces a novel framework that utilizes Artificial Intelligence techniques to deliver adaptive visualizations tailored to the user's cognitive level and expertise. By employing cross-modal sensors and Machine Learning algorithms, the framework analyzes behavioral signals, usage statistics, and user feedback to guide real-time data ingestion techniques and ML-driven mechanisms. This ensures visualizations adapt to user requirements, addressing the challenge of information overload in time-sensitive scenarios. Furthermore, the framework prioritizes data privacy and confidentiality, making it a robust solution for data visualization in today's data-driven era.

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