Article

Research on the Design and Optimization of Automated Data Collection and Visual Dashboard in the Medical Industry

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Abstract: With the ongoing advancement of medical informatization, automated data collection and visual dashboards have become critical for patient management, operational efficiency, and intelligent decision-making. Standardized data collection systems and display platforms improve the timeliness and accuracy of information gathering. To support diverse devices and complex use cases, system architecture, data transmission, display logic, and multi-terminal adaptation must be optimized to enhance data interoperability, boost efficiency, and maximize the value of intelligent healthcare systems.

Keywords: automated data collection; medical data acquisition; visual dashboards; real-time monitoring; medical industry; information system; hospital information systems; intelligent healthcare; multi-device compatibility

1. Introduction

With the continued advancement of smart healthcare and the digital transformation of medical institutions, the volume of medical data is expanding at an unprecedented rate. This trend imposes increasingly stringent requirements on the timeliness, accuracy, and systematic management of such data. Manual data entry methods are no longer adequate to support high-frequency monitoring, prompt clinical decision-making, and effective collaboration across functional departments. In contrast, automated data collection-enabled by a range of sensors, wearable technologies, and internet-connected devices-facilitates efficient and reliable data acquisition and transmission, thereby ensuring the continuous availability of critical information [1].

2. An Overview of Automated Data Collection and Visual Dashboard Design

2.1. The Basic Principles of Automated Data Collection

Automated data collection represents an advanced approach that leverages sensors, intelligent devices, and internet communication technologies to enable real-time and continuous acquisition and transmission of medical data without human intervention. This methodology plays a pivotal role within modern medical information systems and is typically structured around three core stages: perception, transmission, and integration.

In the perception stage, vital sign monitoring devices, wearable sensors, and embedded sensing modules within medical equipment are deployed to capture real-time physiological data such as heart rate, blood pressure, body temperature, and respiratory patterns [2]. Concurrently, the system monitors additional data streams, including the operational status of medical devices and the consumption of medications and medical supplies.

In the transmission stage, collected data is transmitted through modern data pipelines using technologies such as Apache Kafka, AWS Kinesis, or Google Pub/Sub.

These systems are designed to handle large volumes of time-series or event-based data with high durability, fault tolerance, and horizontal scalability. Depending on clinical requirements, data can be streamed in near real-time or batched for periodic processing. Message brokers enable decoupling between data producers (e.g., medical devices) and consumers (e.g., analytics engines or storage systems), ensuring flexible delivery guarantees and seamless integration with processing frameworks like Apache Flink, Spark, or cloud-native ETL tools [3].

In the integration and storage stage, data processed through edge computing or middleware platforms is further cleaned and transformed before being imported into core healthcare systems such as the Hospital Information System (HIS), Electronic Medical Record (EMR) system, or Clinical Decision Support System (CDSS). This structured data integration supports comprehensive data management and advanced analytics, thereby accelerating the development of smart healthcare and enhancing clinical efficiency.

2.2. The Value of Visual Dashboard Design

The visual dashboard serves as a data presentation layer built upon the medical information system, enabling the transformation of large-scale, complex, and dynamically changing medical data into intuitive visual formats such as charts, graphs, status indicators, and multi-dimensional reports. This facilitates rapid identification of key performance metrics, real-time monitoring of operational conditions, and early detection of potential risks [4].

By converting tabular, raw data or unstructured data into graphical representations, visual dashboards significantly improve the efficiency of data interpretation, reduce reliance on traditional spreadsheet formats, and enhance both the speed and accuracy of clinical insights. Their core advantages include accelerated information retrieval, improved trend recognition and predictive capabilities, and a more seamless human-computer interaction experience-making them particularly effective in decision-intensive scenarios.

In practical applications, dashboards are instrumental across various settings: in intensive care units (ICUs), they provide real-time visualizations of fluctuations in patients' vital signs; in outpatient clinics, they assist in optimizing physician scheduling and managing patient wait times; and in equipment operations, they display key metrics such as device status and failure rates [5]. These capabilities empower medical professionals to make informed decisions under time-sensitive and high-pressure conditions, improve service delivery, and advance the overarching goal of intelligent, data-driven healthcare.

3. The Design of Automated Data Collection and Visual Dashboard for the Medical Industry

3.1. Composition of the Acquisition System

An automated acquisition system typically comprises three layers: the sensing layer, the boundary layer, and the platform layer-forming a complete and efficient framework for medical data acquisition and management. The sensing layer is responsible for capturing raw data from a variety of sources, including embedded or external electrocardiogram (ECG) devices, patient monitoring systems, infusion pumps, and environmental sensors. It collects vital signs (e.g., heart rate, blood pressure, body temperature), equipment operation status, and environmental parameters such as room temperature, humidity, and ambient noise. This ensures comprehensive data collection without omissions of critical baseline information. The boundary layer, situated at edge devices or terminal nodes proximal to data sources, performs the initial processing of raw data. This includes data filtering, format translation, compression, and caching to reduce the computational load on the central system, enhance transmission efficiency, and improve system responsiveness. The platform layer functions as the system's central

processing hub. It interfaces with core hospital information systems-including the Hospital Information System (HIS), Electronic Medical Record (EMR), Picture Archiving and Communication System (PACS), and Laboratory Information System (LIS)-to perform data cleaning, normalization, integration, and structured storage. This layer ensures the availability, consistency, and interoperability of medical data for both clinical operations and research applications. (See Table 1)

Table 1. Correspondence Table of Components and Functions at each Level.

Hierarchy	Main equipment/modules	Core function
Perception layer	Heart rate sensors, monitors, pump equipment	Real-time collection of patient and equipment information
Edge layer	Data terminals, edge servers	Data preprocessing, caching and filtering
Platform layer	HIS, EMR and other systems	Data storage, invocation and business integration

The three-layer structure is interconnected and coordinated through standardized interfaces, enabling the intelligent layer to manage comprehensively and form a complete medical automatic data perception system. It also provides a solid path for its intelligent display, early warning analysis, and medical decision-making.

3.2. Data Transmission Mechanism

In medical automation systems, data transmission plays a critical role in bridging data acquisition endpoints with centralized processing platforms. It ensures seamless integration between front-end sensing devices and back-end systems, supporting the continuity, real-time availability, and security of medical data. The speed and reliability of data transmission directly influence system responsiveness, diagnostic accuracy, and the overall quality of patient care. Given the variability of medical environments, diverse communication protocols and transmission paths must be employed to accommodate different technical requirements and design constraints. Commonly used protocols include TCP/IP, which offers high-speed and stable data transmission, making it suitable for large data transfers and real-time remote monitoring systems. MQTT, known for low bandwidth consumption and energy efficiency, is ideal for portable and Internet of Things (IoT) devices that require lightweight, low-power data publishing. LoRa, which supports long-range, ultra-low-power wireless communication, is well suited for multi-floor or campus-wide medical deployments. Transmission methods may span local area networks (LAN), wireless networks (Wi-Fi), cellular networks (e.g., 4G/5G), and dedicated medical private networks. The combination of layered and complementary transmission architectures enhances data redundancy and adaptability. This design not only accommodates high system loads and emergency scenarios but also ensures the reliable, timely, and secure flow of clinical data across complex healthcare environments. (See Figure 1)
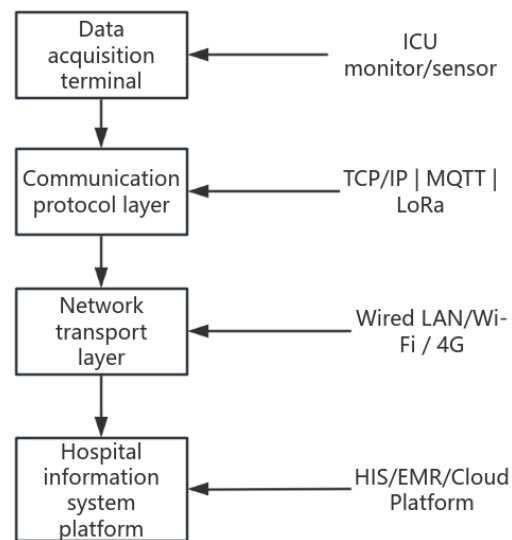
Figure 1. Medical data Transmission Mechanism and path diagram.

At the same time, it is required to have the capabilities of resuming from breakpoint, retransmission, local caching, etc. to deal with network instability or local hardware failure within several minutes. All transmission processes need to be encrypted, digitally signed and access authenticated.

3.3. Dashboard Design Elements

The visual dashboard acts as a critical interface between medical information systems and end users, significantly enhancing data utilization and improving user experience. It is generally composed of four core elements: content selection, visual representation, interface layout, and human-computer interaction design. The choice of what content to display and how to present it should be based on both the data's clinical relevance and user-specific requirements. In terms of content, key metrics should be prominently highlighted-for example, trends in vital signs, bed occupancy rates, medication administration status, and equipment utilization. Content can also be segmented by departmental responsibilities to align with operational workflows. For visual representation, appropriate chart types should be selected based on data characteristics. Time-series trends are best visualized with line or area charts; proportions can be conveyed through pie charts; and spatial patterns or density distributions are effectively represented with heat maps. A structured interface layout is essential. The main display area should focus on primary clinical data, while secondary data and alerts can be positioned in sidebars or footer panels to streamline navigation and minimize cognitive load. Regarding human-computer interaction, interactive elements such as dropdown menus, multi-layered visualizations, and context-sensitive hyperlinks can be incorporated. These features support data personalization and enable deeper exploration, thereby enhancing analytical capabilities and user engagement.

3.4. Platform Interconnection Design

The platform interconnection design is fundamental to enabling bidirectional integration between the automated data collection system and the hospital information infrastructure. It ensures seamless data exchange, protocol translation, and functional interoperability across systems. Data acquired through automated collection must be transmitted to platforms such as the Hospital Information System (HIS), Electronic Medical Record (EMR), Laboratory Information System (LIS), and Picture Archiving and

Communication System (PACS) via standardized interfaces to maintain data consistency and enable actionable workflows. To support this integration, middleware or API gateways can be employed to facilitate protocol translation, data formatting, and schema mapping across heterogeneous systems. These tools enable multi-platform communication, harmonized data exchange protocols, and interface-level compatibility. Moreover, the interconnection framework should support real-time event correlation-for example, automated alerts triggered by abnormal data, or synchronization of EMR updates with central management systems-thereby enhancing system responsiveness, operational coordination, and overall intelligence.

4. Optimization Strategies for Automated Data Collection and Visual Dashboard Design in the Medical Industry

4.1. Unify the Data Interface Standard

A major challenge in medical automation data acquisition systems is the lack of interoperability among heterogeneous devices and platforms, which significantly impedes integration and information sharing. Medical equipment often originates from different manufacturers and employs diverse data formats and communication protocols, resulting in poor compatibility and a slow pace of system integration. To enable coordinated operation across multiple devices and achieve high-level system integration, it is critical to standardize data interfaces and define clear mapping rules at the middleware layer. This process should begin with the adoption of internationally recognized standards-such as HL7, FHIR, and DICOM-to guide the formulation of regional interface specifications. These include standardized data encoding, communication protocols, and semantic conventions. The middleware layer acts as a crucial bridge, enabling automatic translation between incompatible communication protocols, data structures, and message formats. This enhances device accessibility and ensures smoother integration of heterogeneous systems. Moreover, incorporating modular interfaces supports greater system scalability, facilitates device-level flexibility, and simplifies future maintenance and functional expansion. (See Table 2)

Table 2. Matching Table of Common Medical Devices and Interface Protocols.

Equipment type	Manufacturer example	Communication protocol	Data format	Interface standard
Electrocardiogram monitor	Philips	TCP/IP	XML	HL7
Infusion pump	Mindray	RS232	CSV	Customize
ventilator	Dräger	MQTT	JSON	FHIR

In actual deployment, hospitals should take interface standards as the core technical indicators required for purchasing and establishing systems, achieve forward-looking standard unification and ensure constrained interconnection and interoperability.

4.2. Improve the Stability of Collected Data

The automated data acquisition system is the key to achieving continuous, timely and accurate collection of medical data. The existing bottleneck problems mainly include information loss, repetition and delay caused by the accuracy deviation of measurement instruments, unstable network transmission, environmental interference, poor anti-interruption processing ability of the system, etc., which seriously affect its quality and clinical judgment. To improve the reliability of data collection, the first step is to select a high-precision hardware system. Medical-grade sensors, industrial-grade embedded terminals, communication components with strong anti-interference capabilities should be given priority. The collection points should be set in areas not affected by high magnetic fields and signal shielding areas. Secondly, in terms of system construction, caching and

local storage functions can be added to achieve the effect of "resuming transmission from breakpoint" and provide emergency disaster recovery functions to avoid the phenomenon of data loss due to short-term network interruption or device restart. Edge processing methods can also be adopted to move some data analysis and sorting work down to the collection end, reducing the tasks of the central system and effectively improving the timeliness of collection. Finally, an online health check system is established to continuously monitor the equipment status, network links, and data integrity. (See Table 3)

Table 3. Comparison Table of Common Fault Types and Solutions.

Fault type	Problem manifestation	Cause analysis	Countermeasures and suggestions
Data loss	The chart is interrupted	The network is unstable and there is no cache	Enable the local caching and retransmission mechanism
Data duplication	Record the same indicator multiple times	Collection delay and repeated uploads	Set the timestamp deduplication logic
The equipment is disconnected	The signal is unresponsive.	Sensor damage	Introduce health detection and backup equipment switching

Through multi-level optimization of the collection process and stability design, not only the stability and fault tolerance have been enhanced, but also a basic data guarantee has been provided for the system support of subsequent processing, visualization and clinical auxiliary decision-making.

4.3. Streamline the Content Structure of the Dashboard

As the scope of medical data expands-both in type and in monitoring dimensions-visual dashboards have become increasingly prone to issues such as information redundancy, overcrowded visual elements, and repetitive logic. These factors hinder the ability of clinical staff to efficiently extract relevant insights, increasing cognitive load and the potential for diagnostic or operational errors. To improve usability and system efficiency, it is essential to simplify and restructure the content layout of medical dashboards. Optimization should follow three guiding principles: eliminating redundancy, emphasizing key information, and clarifying visual hierarchy. At the information filtering level, dashboards should be tailored to specific user roles. Indicators should be prioritized based on the professional responsibilities of the user, retaining only the most relevant and actionable information. Non-essential elements, including lengthy data tables and extraneous metrics, should be removed to reduce clutter. From a modular design perspective, the dashboard interface should be logically segmented into functional zones such as *real-time monitoring*, *historical trends*, *alerts and notifications*, and *device status*. This facilitates a clear structural hierarchy and streamlines information access. Regarding visual representation, design choices should prioritize clarity and intuitive understanding. Simple and effective formats-such as line charts for trends, card-style indicators for key metrics, and heat maps for spatial patterns-should be used in place of overly complex interactions, deeply nested views, or intricate dynamic visualizations. Additionally, features such as preset viewpoints, quick filtering mechanisms, and user-specific customization options can significantly enhance usability, allowing users to access critical information more quickly and effectively.

4.4. Optimize the Multi-Terminal Adaptation Performance

With the growing demand for mobile healthcare, remote monitoring, and multi-scenario data access, traditional interface designs limited to desktop platforms are no

longer sufficient. To accommodate the diverse and frequent usage contexts of modern healthcare environments, cross-device compatibility and screen adaptability have become critical design priorities. These factors directly affect system responsiveness and the timeliness of clinical interventions. To address this, modern medical visualization systems should adopt responsive design principles, leveraging front-end technologies such as HTML5 and CSS3 to ensure that interfaces can dynamically adjust to different screen sizes and interaction modes. This enables device-independent data visualization, allowing for consistent user experiences across desktops, tablets, smartphones, and dedicated medical terminals. For large-format displays-such as those used in control centers or nursing stations-simplified layouts and enlarged visual elements should be emphasized to maintain readability and support interactive engagement. Additionally, a hierarchical access strategy should be implemented, prioritizing desktop use for primary interaction, while supporting secondary access via mobile devices and self-service kiosks based on usage frequency and user preference. (See Figure 2)
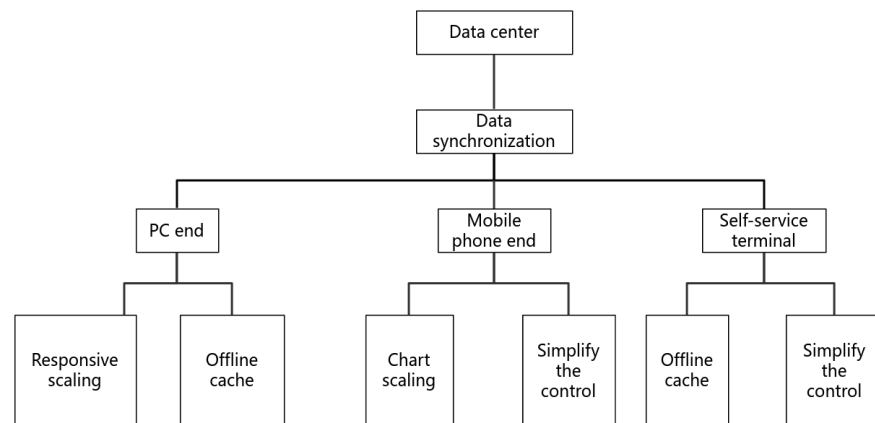

Figure 2. Structure diagram of the multi-terminal adaptation system.

The system also needs to achieve the level of data synchronization and recording the status and operations of users to ensure the consistency of operations and the continuity of information among various devices. In addition, to optimize the performance of mobile devices, the chart data needs to be compressed to reduce the amount of front-end rendering and avoid delays caused by lagging or loading. In the face of frequent network fluctuations, it is also necessary to comprehensively improve the compatibility of various platforms.

5. Conclusion

The integration of automated data collection systems with visual dashboards plays a pivotal role in enabling real-time intelligent monitoring, precise information management, and data-driven clinical decision-making within healthcare environments. By standardizing interface specifications, enhancing the reliability of data acquisition, and improving content organization to support multi-device adaptability, key challenges-such as system incompatibility, information overload, and poor terminal responsiveness-can be effectively addressed. These improvements significantly enhance operational efficiency and clinical responsiveness. Practical deployments across diverse healthcare settings have demonstrated that automated data collection and dashboard platforms are foundational components in the development of intelligent hospital infrastructure, supporting the transformation toward more efficient, connected, and adaptive medical systems.

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