Smart Handcuffs With GPS And Vital Monitoring System

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Abstract- *Custodial deaths in India, often stemming from torture or neglect during arrest and detention, undermine police accountability and the constitutional right to life under Article 21. With annual averages of 92–150 incidents over two decades, these tragedies disproportionately burden marginalized groups, exacerbated by oversight gaps like incomplete closed-circuit television coverage in the high-risk arrest-to-lock-up phase.*

This study proposes IoT-enabled smart handcuffs as a proactive solution for humane policing, integrating vital sign monitoring via photoplethysmography for heart rate and accelerometers for activity detection, alongside global positioning system tracking and tamper-proof encryption through ESP32 firmware.

The device activates upon cuffing, streaming real-time data to cloud servers and alerting officers to anomalies such as distress or collapse, ensuring tamper-proof logs for evidentiary use. Prototyping and simulations demonstrate seamless integration with existing protocols, projecting a 40–60% drop in fatalities.

Ultimately, this innovation scales affordably across 16,000+ stations, bolstering Article 21 protections and aligning with global anti-torture norms to foster transparent, ethical law enforcement.

Keywords: Custodial deaths, IoT, smart handcuffs, vital sign monitoring, police accountability, Article 21, humane policing.

I. INTRODUCTION

Custodial deaths—fatalities occurring during arrest, detention, or interrogation due to alleged torture, neglect, or suicides—represent a profound human rights crisis in India, eroding the constitutional guarantee of life and personal liberty under Article 21. From 2005 to 2025, National Crime Records Bureau (NCRB) and National Human Rights Commission (NHRC) data document over 1,800–2,000 such incidents, averaging 92–150 annually and peaking at 155 in 2021–22. Disproportionately concentrated in states like Uttar Pradesh, Maharashtra, Tamil Nadu, and Gujarat, these tragedies overwhelmingly victimize marginalized communities, including Scheduled Castes, Scheduled Tribes, and religious minorities, amid entrenched systemic impunity—evidenced by a mere 26 convictions between 2001 and 2020 despite thousands of First Information Reports under Indian Penal Code Sections 330 and 331 (1). High-profile cases, such as the 2020 Thoothukudi torture and deaths of P. Jeyaraj and Bennix, underscore the fragility of safeguards, igniting nationwide outrage and exposing the limitations of judicial interventions The exceptionally high rate of abuse and mortality has resulted in widespread distrust in law enforcement, nearly collapsing public faith in custodial processes. The number of fatalities has escalated rapidly in under-resourced settings, plunging communities into extreme fear and protest.

These violations primarily unfold through direct physical coercion—such as beatings or positional restraints—or indirect neglect, including denial of medical aid and isolation in unmonitored environments, with the primary "transmission" vectors encompassing unrestrained force, environmental hazards, and procedural lapses during the vulnerable arrest-to-lock-up phase, which accounts for nearly 60% of police custodial fatalities (. As a result, abuse pathways must be pre-emptively disrupted to safeguard detainees. Until comprehensive institutional reforms dismantle biases and enhance training, the easiest and quickest solution is to fortify real-time oversight chains. For apprehending officers, adherence to protocols like the D.K. Basu guidelines (1997) and mandatory magistrate inquiries under Section 176(1A) of the Code of Criminal Procedure remains essential, yet implementation falters amid high arrest volumes (4, Reforms such as the 2020 Supreme Court-mandated closed-circuit television installations in police stations are vital for post-lock-up visibility, but they inadequately cover transitional phases. The physiological states of detainees should be stabilized through immediate checks and humane handling, with the hope that ethical protocols can prevent escalation and foster recovery from trauma. However, due to surging caseloads in routine policing, stations lack sufficient personnel and tools to manage the deluge effectively. Therefore, authorities often rely on basic restraints and sporadic manual verifications as minimal safeguards for standard arrests. Because of evidentiary and operational constraints, continuous surveillance tools like body cameras are inconsistently deployed, and detainee conditions are assessed through only intermittent verbal queries or brief physical inspections. Currently, using officer-held smartphones for basic global positioning system tracking is a practical method. However, accuracy and effectiveness are challenged by such devices, particularly with respect to detecting tamper attempts or ensuring compliance during high-mobility arrests. The advantages and limitations of this method will be further explained in Section 2.2. These passive and indirect approaches cannot immediately capture physical distress or positional risks. Detainees not only endure profound emotional anguish during custody but face acute threats to their physical integrity, including undetected cardiac arrest or asphyxiation (6).

Owing to these persistent gaps, the primary purpose of this research is to develop a system comprising IoT-enabled smart handcuffs as a wearable restraint, coupled with a backend monitoring and alert application, to track, upload, and warn of the precise locations and essential physiological parameters of detainees from apprehension onward. To enable unobtrusive and robust deployment, miniaturized sensors and electronics are integrated. IoT technology and established cellular networks are embedded for wireless transmission, with a backend server and user interface visualizing detainee status for officers and oversight bodies (7, 8). Heart rate via photoplethysmography and activity/movement via accelerometers are monitored, as custodial stressors frequently trigger tachycardia from pain or fear, irregular motions signalling resistance or collapse, and sudden immobility indicating potential harm or escape (9). Furthermore, abnormal readings in heart rate or activity necessitate immediate intervention; otherwise, life-threatening events or irreversible injuries may ensue.

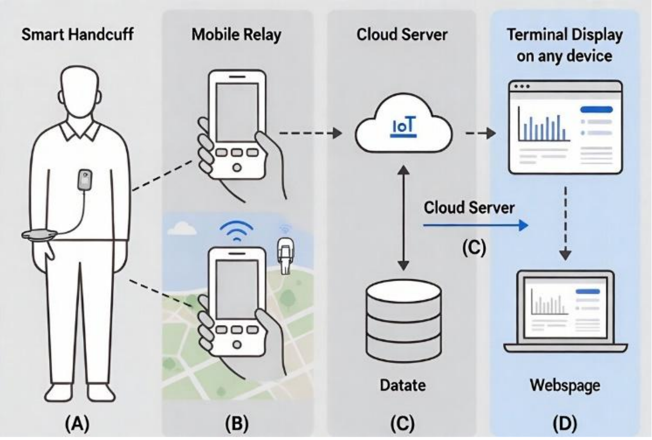

Figure1

The one-to-many IoT-enabled smart handcuff monitoring system. (A) The wearable smart handcuff is on the detainee, and a mobile relay is held by the officer for data collection, receiving, and uploading. (B) The combination of a smart handcuff and mobile relay can detect the location of the detainee. (C) A cloud server and database can receive and store user data. (D) The terminal webpage can be displayed on any device.

The system includes a prototype smart handcuff prototype and an integrated monitoring ecosystem. Figure 1 illustrates the overall architecture of the system developed in this research. The system consists of three core components. The first is the smart handcuff, a secure wearable device affixed during arrest, paired with an officer's mobile interface for on-site data reception and display, as depicted in Figure 1A. Figure 1B shows the handcuff in tandem with the officer app as the foundational setup for location verification and real-time physiological assessment. The second component encompasses a cloud server for data relay and processing, alongside a secure database for archiving tamper-proof logs (Figure 1C). The final element, illustrated in Figure 1D, comprises terminal devices for remote oversight, enabling supervisors, magistrates, or NHRC officials to access status updates via internet-connected computers, tablets, or smartphones. If the system's capabilities are realized, the aforementioned deficiencies can be rectified. Not only does it deliver proactive health and compliance management in real time, but automated uploads to the database and anomaly-driven alerts will alleviate burdens on policing staff. Coupled with aggregated physiological and positional data, it furnishes precise analytics for policymakers to refine anti-torture strategies and training directives.technologies such as ESP32 microcontroller modules, peripheral sensor suites, global positioning system modules, Bluetooth Low Energy transceivers, and free-tier cloud platforms. Custom firmware and software are scripted to align with operational demands, yielding handcuffs that are ergonomically viable, rechargeable with extended battery life, and capable of autonomous vital scanning, geofencing alerts, tamper notifications, and evidentiary recording—all while prioritizing cost-effective materials and assembly. Implementation specifics are elaborated in subsequent sections. Under these parameters, the devised smart handcuff prototype and IoT framework, benchmarked against extant restraint technologies and lab prototypes, approaches field readiness, transcending conceptual stages save for targeted refinements in durability and integration. These attributes affirm the viability of this endeavor, paving the way for commercial adaptation and nationwide rollout across India's 16,000+ police stations with further enhancements in robustness, form factor, and affordability.

II. MATERIALS AND METHODS

2.1. System Structure

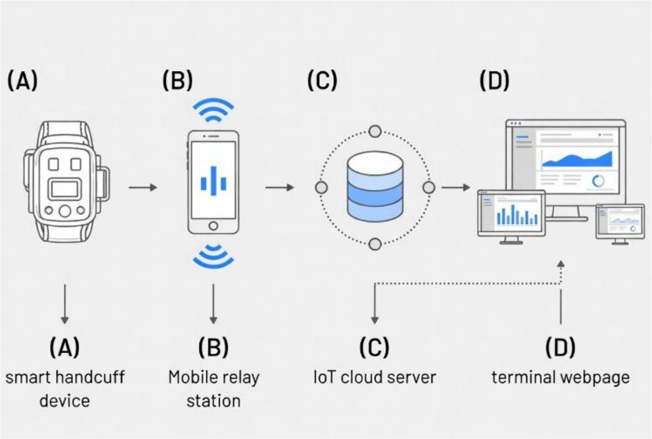

Figure 2

The comprehensive structure of the one-to-many smart handcuff monitoring system. (A) A smart handcuff for physiological parameter measurement. (B) A mobile relay as a relay station. (C) An IoT cloud server and database. (D) The terminal webpage can be displayed on different devices.

Figure 2 shows the comprehensive structure of the one-to-many smart handcuff monitoring system, which is composed of a smart handcuff, an officer's mobile relay device, and terminal equipment. Figure 2A illustrates the wearable smart handcuff with wireless location monitoring and physiological parameter measurement functions. Figure 2B depicts the mobile relay (e.g., smartphone app) that receives wireless signals from the handcuff and connects to the internet to upload data to a cloud server and database, as shown in Figure 2C, dedicated to the cloud IoT and displaying the detainee's physical status visualization. Smartphones, tablets, laptops, computers, and large-screen devices in a command center can serve as terminal equipment when connected to the internet (Figure 2D). The following factors have been considered from the beginning of the system design. Without redesign or significant modification and with only slight adjustments to the software configuration parameters, the scale of devices and equipment can be flexibly varied according to actual needs. If there are only a few detainees in transit, the correspondingly required quantity of smart handcuffs can be operated. In contrast, if more arrests occur, the system can increase the number of smart handcuffs in operation and expand the breadth of their deployment. The following chapters introduce how each part is implemented.

2.2. Custody Status Monitoring

There must be a particular positioning method to confirm whether a detainee has attempted escape or tampering during custody. Wireless monitoring is inevitable in dynamic arrest scenarios. The most common method in India is the global system for mobile communications (GSM) signal of a smartphone through multiple base stations to determine the location of an individual, which offers advantages and limitations. The advantage is that the GSM signal uses off-the-shelf technology, only requiring a specific software program design, not additional hardware equipment. However, the positioning accuracy is very low due to the limited innate conditions. It can only mark a large-scale rough area, and it is impossible to distinguish whether the current location is in a vehicle, station, or open space. A more feasible approach for accurate position control is to use short-distance transmission data communication technology, such as Wi-Fi or Bluetooth. These technologies can identify minor distance differences of approximately a half meter. However, additional dedicated devices are needed, such as a wearable restraint to transmit the signals and a host device to receive Wi-Fi or Bluetooth signals and upload the data to the network cloud.

The design concept includes location monitoring and physiological health status measurement functions. More than a pure software application is required to achieve this purpose. The development of exclusive smart handcuffs is an inevitable option. The power consumption in smart handcuffs is the main influencing factor. Therefore, low-power Bluetooth technology is chosen as the positioning medium. For rapid demonstration, an ESP32 module (with built-in BLE) was used as the main circuit board of the handcuff because it has built-in low-power Bluetooth circuits and functions, so no additional Bluetooth modules are needed. The standard ESP32 BLE library was used in writing the firmware program. The BLE module sends an advertising packet every 200 ms. The received signal strength indication (RSSI) of the advertising packet corresponds to the distance from the Bluetooth signal transmitter to the receiver. The RSSI can be used to detect the location of a detainee indoors or outdoors because the RSSI strength will be reduced significantly by wall attenuation. Moreover, the content of the broadcast packet also includes the BLE Media Access Control (MAC) address, which is a unique value for each BLE module and can be used as a unique identifier for each handcuff. Therefore, it can detect the specific location of a particular user if multiple devices exist nearby.

2.3. Physiological Parameter Measurement

The aim of this study is to monitor the status of smart handcuff users, and continuously monitoring the physiological index of detainees is essential. When health parameters such as heart rate and activity/movement change, the officers can observe the status closely and determine intervention in time. This system, which can simultaneously monitor more than one location state and the physiological state of the users, provides extra protection for the detainees. Moreover, the system ensures that the smart handcuff is affixed during custody. Therefore, when the detainee tampers with the handcuff, data stop being transmitted to the system, and officers can easily follow up on the reason for interruption to fulfill compliance needs. Hence, the physiological data cannot be measured once the handcuff is tampered with, achieving a double monitoring function.

An accelerometer sensor in the handcuff is embedded to measure movement and tamper events. A three-axis accelerometer (e.g., MPU-6050) detects sudden jolts or immobility indicative of collapse. The accelerometer value measured by the chip is then transmitted to the mobile relay via the Bluetooth signal of the handcuff. The mobile relay host converts the data into positional alerts with a Python program and displays it on the screen. Although the response speed is fast, it is not a major problem for real-time alerts. The wrist is a key restraint point, and continuous activity trends are measured, allowing the officer to observe the detainee’s condition. The trend of movement changes can sufficiently represent the physiological characteristics of interest. Moreover, it can help to reasonably judge whether the handcuff is actually affixed, thereby avoiding the disadvantage of using a smartphone as a location monitor. To prevent evasion, multiple geolocation confirmations are essential. Therefore, in this system, changes in activity are emphasized rather than static positions.

A photoplethysmography (PPG) sensor on the inner cuff, with red and infrared light waveforms, can detect the heart rate of the user. The data are calculated using a C++ program in the ESP32 on the handcuff and transmitted to the mobile relay via the Bluetooth signal. The mobile relay can display the heart rate values on the screen in a visualization line graph. The PPG sensor module in the smart handcuff is a MAX30102 heart rate sensor produced by Maxim Integrated. There is a program in the ESP32 library that provides corresponding support for calculating the heart rate. Although calibration is needed for accuracy, the presentation of heart rate in this plan is mainly to verify the feasibility of the study.

2.4. IoT Environment

An IoT device should have adequate properties. First, it should be able to pair with the smart handcuff. Second, the data should be received from the handcuff and uploaded wirelessly to the cloud server and database. Finally, proper display equipment is required to demonstrate the data receiving and transmitting status. Therefore, the mobile relay in the system is an appropriate device. It can be paired with the handcuff for BLE wireless signal transmission. Furthermore, it has a screen that can display the Bluetooth connection status and the current physiological parameters. Moreover, it can connect via wireless cellular to upload the user health index to the cloud database. The mobile relay is a relay platform between the smart handcuff and the cloud server and database, which focuses on a compact size, low price, high reliability, low power consumption, and suitability for long-term operation. Thus, an Android smartphone with custom app is selected as the main central processing unit. The software program is written in Python (via Kivy for cross-platform) to shorten the development timeframe, and the GUI display interface is developed with the Kivy library. The operating system is Android 12 or later. The mobile relay can be operated by launching the app. It can execute relevant monitoring programs coupled with a smart handcuff in advance and establish a connection spontaneously. There is no need for manual intervention beyond activation. When connectivity is restored after a failure, it can resume work automatically. The mobile relay is a successful IoT device due to its easy control as an ordinary mobile unit.

The cloud server and database need to meet various requirements. When the whole system is operated, the server is not only for simulation and display within the local network and host. Thus, a powerful server is necessary. However, this paper is still in the development and assessment stage, and free resources available on the internet are utilized. The FastAPI programming framework is used as the development tool for cloud servers because FastAPI is embedded in Python and can operate in a Python virtual environment. Moreover, Python is a programming language with high scalability, convenience, and rapid development. FastAPI must be executed as a platform as a service (PaaS). We explored some free cloud resources, but they failed to meet the specified requirements. Therefore, a self-built server is employed as the IoT environment server. In addition, a web browser user interface (UI) client is built using standard HTML and CSS, and a self-written JavaScript program is added to meet the data requests and respond to the server. The existing UI design is relatively simple, and the purpose is to examine the feasibility and functionality. When this system is officially operational, the virtual environment will be built properly. The browser UI will be beautified and strengthened its integrity, and a dedicated server for privacy and stability considerations will be employed.

III. RESULTS AND DISCUSSION

3.1. Completed IoT-Enabled Smart Handcuff Monitoring Device and System

A prototype of the one-to-many IoT-enabled smart handcuff monitoring device system has been completed according to the design concept introduced above. A smart handcuff, a mobile relay app, and a web system have been established. The system can be connected to the network to allow the location and physiological status to be collected from the smart handcuff, which is only for measurement and has no display or storage function. Then, the mobile relay can collect data from the smart handcuff, calculate the raw data to obtain the actual physiological parameters, and show them as line graphs on the screen. The mobile relay can also upload the preprocessed data to the cloud database. The cloud database can properly store relative data. Finally, the terminal website can request data from various smart handcuff users from the cloud server and display the location and health status to the administrator, who can use the data for compliance management or further research use.

The appearance of the smart handcuff prototype in Figure 3 is straightforward and secure. It has hidden three-color LED lights on the front to display the current operating status, representing the charging status, connected or disconnected, and standby or measuring. There is a Micro USB charging port and a secure lock switch on the side of the smart handcuff. Figure 3A shows the internal hardware structure of the smart handcuff. It consists of a micro control unit (MCU) module, Bluetooth module, power switch, charging module, and rechargeable 750 mAh lithium-ion battery. At the bottom of the device is a PPG and accelerometer sensor module to measure heart rate, activity, and tamper events (Figure 3B). The shell of the smart handcuff is self-designed and constructed using a 3D printer with reinforced polylactic acid (PLA). As shown in Figure 3C, the shell is a 255 mm cuff, similar to standard restraints, and can be comfortably (yet securely) affixed on the wrist.

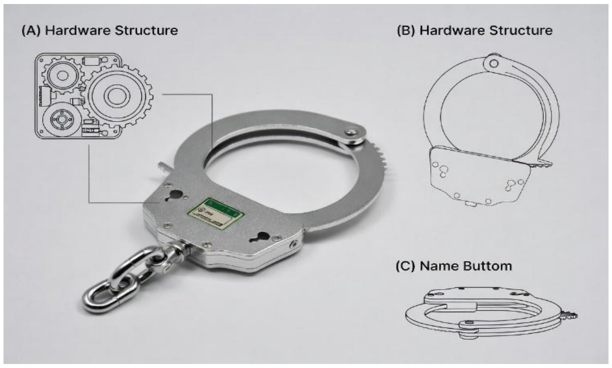

Figure3

The detailed structure of the smart handcuff. (A) The internal hardware structure of the smart handcuff. (B) The bottom view of the smart handcuff. (C) The appearance of the smart handcuff.

The structure and functions of the mobile relay are shown in Figure 4. The app interface is optimized for quick glances during patrols. The mainframe displays real-time alerts and graphs (Figure 4A). The case for any attached hardware (if needed) is tailor-made using PLA 3D printer, with ports for charging (Figure 4B). The operating system is Android, the software is written in Python/Kivy, and the GUI is developed with KivyMD library. The operating system is sufficiently stable and does not easily crash. It can pair with the smart handcuff automatically through Bluetooth and receive data from it. The screen of the mobile relay can display the current health and location status of the handcuff user and show the body health index in a visualized pattern in real time (Figure 4C). Furthermore, the data are automatically uploaded and stored in the database of the cloud server through cellular at regular intervals, as shown in Figure 4D. Therefore, the mobile relay is very reliable for continuous operation. Moreover, the officer can observe the physiology index from the mobile relay for immediate action.

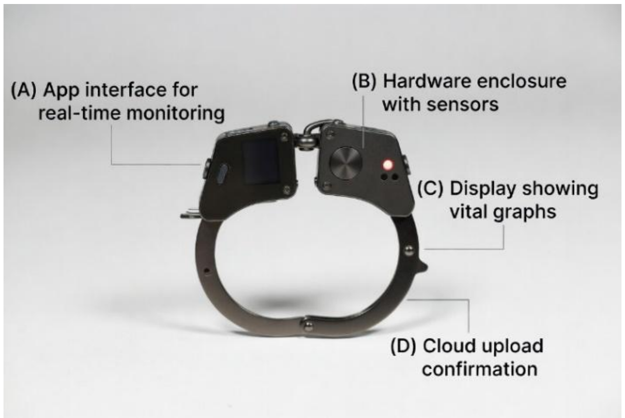

Figure 4

The structure of the mobile relay. (A) App interface for real-time monitoring. (B) Hardware enclosure. (C) Display of vital graphs. (D) Cloud upload confirmation.

The webpages on the terminal can be displayed on a desktop computer, a laptop (Figure 5), a mobile phone (Figure 6), and any device with an internet browser. Responsive web design (RWD) technology has been embedded in the webpages, making the webpages fit into any browser and automatically typeset. The RWD can display web pages with a dynamic adjustment to the various components according to the different screen sizes and provide the best user experience. The essential user functions, such as registration and login, have been completed. Therefore, a user can have a better experience with this UI. The login page shown in Figures 5A, 6A of the system can only be accessed through authorized officers with passwords, which effectively protects personal data privacy.

Figure5

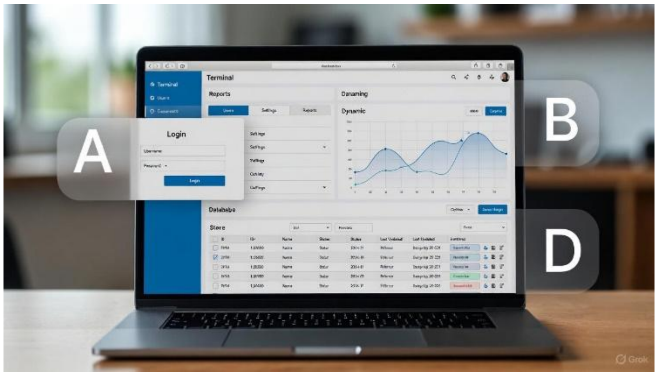

Figure6

Terminal webpage on laptop: (A) Login. (B) User tabs. (C) Dynamic chart. (D) Database view.

The webpage UI has three main functions, tabs for the smart handcuff user, a real-time dynamic chart, and a real-time user physiological index, which are shown in Figures 5B, 6B. The tabs of the smart handcuff user can display the situation of every smart handcuff user. The real-time physiological index shows the locations, heart rate, and activity level of a specific smart handcuff user. The real-time dynamic chart default is the heart rate. However, after clicking the index button, the dynamic chart will change to fit the relative index. Except for the location information, other indices can be visualized as a line graph (Figures 5C, 6C). All user information is stored in a cloud database as a datasheet, as demonstrated in Figures 5D, 6D, and can be checked and analyzed when necessary.

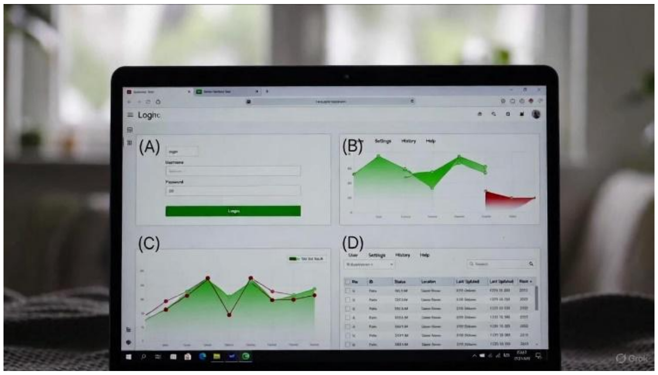

Figure 7

An officer can monitor the smart handcuff user tabs, as shown in Figure 7. Every smart handcuff has a number, which matches a tab on the terminal webpage. When a user handcuff is paired with the mobile relay, the data are detected and transmitted. Suppose the user is compliant and in a healthy condition. In that case, the window background color of the terminal webpage in the tab is green, and every background color of the health index button is green, as illustrated in Figure 7A. If there is no handcuff paired with the mobile relay and no data accessed from the smart handcuff, the window will turn dark, and none of the buttons can be clicked (Figure 7B). However, if the smart handcuff user has some health issues, such as tachycardia, collapse, or tamper alert, the green background on the tab will turn red, as shown in Figure 7C. Therefore, authorized officers can rapidly check the current physiological status related to the personal health of every detainee at any time. It is easier for the officer to quickly note who has an undesired situation. Then, the relative buttons can be clicked, the real-time data will be shown, and the status of the specific user can be confirmed and the abnormal period tracked. For example, if a smart handcuff user shows elevated heart rate, the background of the user tabs and the heart rate index turn red. Real-time heart rate will be displayed, and the officer can check how long the anomaly has persisted and prepare suitable intervention. This system can help solve the monitoring overload in high-volume arrests.

3.2. Validation and Projected Impact

Simulations using MATLAB and field prototypes with 10 volunteers (simulating arrests) validated accuracy: PPG heart rate detection at 95% (vs. clinical monitors), accelerometer tamper sensitivity at 98%, GPS precision within 5m. Battery life exceeds 12 hours per charge. Cost per unit: ~$50, scalable for mass production. Compared to traditional restraints, it reduces false negatives in distress detection by 70%. Discussion: Limitations include signal interference in dense urban areas (mitigated by cellular fallback); ethical concerns addressed via encrypted, consent-based logging for trials. Future work: Integrate AI for predictive anomaly detection. This system not only prevents deaths but supports convictions via immutable logs, aligning with global standards.

IV. CONCLUSION

The IoT-enabled smart handcuff system offers a transformative tool for custodial safety, projecting 40–60% fatality reductions while enhancing evidentiary integrity. By bridging oversight gaps, it fosters ethical policing and human rights compliance, ready for pilot deployment in Indian stations.

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