Autonomous Systems for Forensic Applications: Sensing, Interaction, and Sustainability

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Abstract:

Forensic science has emerged as a crucial area of application for robotics, which ha s transformed from an intensive academic field into a transformational instrument across m ultiple sectors. Advances in artificial intelligence, computer modeling, sensing, and article, which looks at the state of robotics in forensic science today.When functioning inthe sensit ive, complex environment of crime scenes, robots must prioritize accuracy,non-contamination, safety, and contextual integrity maintenance. The technological foundations of autonomy in relation to scene investigation, developments in human-robot interaction for effective collaboration with investigators, and new efforts to develop r obotic systems that are both sustainable and forensically sound are all discussed in this arti cle, which looks at the state of robotics in forensic science today.

We examine key applications, such as digital forensics, aerial mapping, hazardous material handling, and evidence collecting, and we evaluate the ethical, legal, and technical concerns that must be resolved for results to be accepted in court. It is emphasized that the future generation of intelligent, dependable forensic robots must combine sophistic ated perception, strong control, human-centered design, and forensic-grade processes.

Keywords: *Robotics in forensics, Crime scene investigation, Autonomous robotic systems, Artificial intelligence, Human–robot interaction.*

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1. Introduction

The field of robotics has seen swift advancement, emerging as a cornerstone of contemporary technological development. Although its effects on manufacturing and logistics are widely recognized, its incorporation into forensic science marks a noteworthy transition from organized industrial settings to chaotic, evidence-sensitive crime scenes. Robots operating in these high-stakes areas must be accurate, minimize contamination, guarantee operator safety, and maintain the chain of custody and evidential integrity in addition to being autonomous and intelligent. [1][2].

This study looks at new developments in robots that are especially designed to satisfy the demanding specifications of forensic investigations. It starts by describing the fundamental technologies that make autonomous forensic operations possible, such as precise state estimate for mapping and scene reconstruction, mobility and planning for non-invasive evidence collecting, and navigation in difficult and complicated situations. The important facets of human–robot interaction (HRI) that enable efficient cooperation between robotic systems and forensic investigators at crime scenes are then covered in the study.

The increasing significance of sustainability in forensic robotics is covered in detail, with a focus on energy efficiency for prolonged field operations and the use of materials that avoid cross-contamination.

The practical effects of these improvements are demonstrated by applications in environmental forensics, hazardous evidence management, and crime scene recording. An evaluation of the upcoming legal, ethical, and technological difficulties is presented at the end of the conversation, highlighting the need for multidisciplinary methods that connect robotics, forensic science, and law.

2. Essential Technologies for Autonomous Forensics:

The capacity to see, map, and model a criminal scene without making any changes is crucial for robotic autonomy in forensic contexts. The foundation for producing dependable, spatially accurate 3D representations of a scene is probabilistic methods like Simultaneous Localization and Mapping (SLAM). [3], [4].

In order to maintain steady mapping performance even in complicated outdoor or crowded interior situations, modern forensic SLAM systems incorporate data from numerous sensors, such as multispectral cameras for latent evidence identification, high-resolution LiDAR for structural detail, and inertial units [5], [6]. Robots can now automatically identify possible evidence objects and rebuild the scene geometrically thanks to developments in dense and semantic mapping, which helps investigators make decisions.

For non-invasive scene engagement, motion planning is essential. Robots can explore complicated environments without disturbing evidence because to sampling-based techniques like RRT* [7]. Optimization-based planners include real-time limitations to provide steady, sensitive motions for robotic arms handling fragile objects in order to acquire exact evidence [8], [9].

Deep learning speeds up forensic analysis. CNNs enable end-to-end methods for systematic scene scanning, complex item recognition (e.g., identifying weapons or shell casings), and terrain appraisal for safe robot movement [10], [11]. Advances in lightweight sensing and control in aerial forensics have enabled drones with autonomous aerial mapping capabilities, which provide fast overhead views for scene reconstruction and search pattern optimization [12].

3. Human-Robot Interaction in Forensic Investigation

For seamless incorporation into forensic operations, investigators and robots must communicate effectively. Shared control, intuitive teleoperation, and user-centered system design that enhances rather than replaces human knowledge are the key topics of HRI research in this field [13], [14]. The focus on machines that can help with precise, repetitive activities like sample preparation or microscope scanning under human supervision is shown by the rise of collaborative robots, or "cobots," in laboratory settings.

Evidentiary safety is one aspect of forensic HRI safety that goes beyond physical touch.To handle sensitive evidence without causing harm, robots are built with compliant frames and force-sensitive joints [15], [16]. Natural language instructions for hands-free operation and augmented reality interfaces that superimpose digital scene models on the actual world are examples of interaction modalities that enable investigators to intuitively guide robots to particular locations of interest.

Effective HRI guarantees that robots act as force multipliers for long-term involvement, such as in extensive crime scene searches or mass catastrophe scenarios, lowering investigator fatigue and preserving consistent performance.

4. Towards Sustainable and Forensically-Sound Robotics

Concerns about forensic integrity and operational lifespan are critical as robotic deployment in forensics grows. In order to enhance battery life during lengthy investigations, research into efficient motors, power-aware computation, and optimum motion techniques has been prompted by the severe energy restrictions faced by mobile robots at extended scenes [17], [18].

Sustainability also includes taking cross-contamination prevention into account when choosing and designing materials. Components that are robust, chemically inert, and readily decontaminated are given priority by researchers [19]. Modular designs make it simple to repair contaminated components without having to throw away the entire system. Additionally, research into the use of single-use, biodegradable coverings for sensors and manipulators that come into direct touch with evidence is expanding [20].

In order to make sure that the deployment of forensic robotic systems does not unintentionally damage the areas they are deployed to examine, life-cycle assessment techniques are now being utilized to quantify the ecological footprint of these systems from production to disposal [21]. By deploying several low-power units that collaborate to provide redundancy and thorough coverage with minimum individual energy consumption, swarm robots provides a path toward sustainability for large-area searches (e.g., finding scattered evidence in a field) [22].

5. Results and Discussion

5.1 Real-World Forensic Applications:

Crime Scene Documentation and Reconstruction: Scene documentation is being revolutionized by robots. Millimetre-accurate 3D scene models are produced by mobile ground platforms with LiDAR and high-resolution cameras, maintaining the spatial connections between evidence pieces [5], [6]. Large-scale events like traffic accidents or mass tragedies may be accurately mapped and recreated thanks to aerial drones' quick overhead photographic capabilities [12].

Hazardous Evidence Collection: The safe handling, disruption, and disposal of hazardous devices is made possible by the well-established use of explosive ordnance disposal (EOD) robots [23]. Teleoperated robotic arms can gather samples in CBRNe (Chemical, Biological, Radiological, Nuclear, and Explosive) disasters without putting human investigators in danger.

Specialized Forensic Specialties:

• **Environmental and Aquatic Forensics:** While keeping thorough logs of retrieval location and depth, autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) make it possible to search for and retrieve submerged evidence from lakes, rivers, and seas [24].

• **Forensic Anthropology:** Robots with accurate excavation tools and ground-penetrating radar (GPR) can help locate and exhume buried remains while maintaining stratigraphic context, which is essential for figuring out the time and conditions of burial [25].

• **Digital Forensics:** In laboratory settings, robotic systems can automate the imaging of many digital storage devices, guaranteeing a reliable, repeatable, and recorded chain of custody for digital evidence [26].

5.2 Enduring Difficulties and Forensic Issues:

Despite substantial progress, there are still many obstacles to overcome before robots can be fully integrated into forensics. Since evidence gathered by robots must be accepted in court, legal and ethical issues are crucial. To meet norms of evidence and endure judicial examination, this calls for transparent, verified algorithms, strict calibration, and unambiguous record of a robot's activities [2]. Robots that collect large amounts of visual and geographical data from private land also raise data privacy concerns.

The high price of specialist devices, the difficulty of integrating them into accepted forensic procedures, and the requirement for intensive training are examples of technical and operational challenges. Technically speaking, there are still difficulties in creating robots that can function dependably in the wide variety of environments seen in forensic work, from fallen buildings to impenetrable woodlands. Standardization and confidence: The creation of uniform testing and certification for forensic robots is necessary to promote confidence among investigators, legal experts, and the general public. For a system's results to be seen as trustworthy and authoritative, clear information of its capabilities, limits, and error rates is crucial.

6. Conclusion and Future Directions

Systems that combine high degrees of spatial intelligence and autonomy with operational safety, legal resilience, and ethical integrity are the way of the future for forensic robots. Sophisticated sensing for evidence identification, strong control for delicate manipulation, non-contaminating and sustainable engineering techniques, and interaction models focused on the investigator's workflow are all necessary to realize this vision. The next ten years will be shaped by emerging technology. In order to provide clear logs of robotic decision-making during evidence collecting and foster trust for courtroom applications, Explainable AI (XAI) will be essential [27]. Robots will be able to process complicated sensor data (such as hyperspectral photography for blood detection) in real-time at the site thanks to advancements in edge computing [28].

Improved shared autonomy will make human-robot collaboration more smooth, enabling an investigator to command a robotic helper or a swarm of drones with ease. Robots with biologically inspired mobility will be able to reach tight or unstable settings, while advancements in soft robotics will open up new possibilities for handling incredibly delicate evidence without causing damage. Responsible innovation, rooted on cooperation between roboticists, forensic scientists, and legal specialists, will be crucial to guaranteeing that new technologies improve the pursuit of justice as robotic systems become commonplace instruments in forensic research.

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