Sketch-Based Modeling and Immersive Display Techniques for Indoor Crime Scene Presentation

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Abstract. The reconstruction of crime scene plays an important role in digital forensic application. Although the 3D scanning technique is popular in general scene reconstruction, it has great limitation in the practice use of crime scene presentation. This article integrates computer graphics, sketch-based modeling and virtual reality (VR) techniques to develop a low-cost and rapid 3D crime scene presentation approach, which can be used by investigators to analyze and simulate the criminal process. First, we constructed a collection of 3D models for indoor crime scenes using various popular techniques, including laser scanning, image-based modeling and software-modeling. Second, to quickly obtain an object of interest from the 3D model database that is consistent with the geometric structure of the real object, a sketch-based retrieval method was proposed. Finally, a rapid modeling system that integrates our database and retrieval algorithm was developed to quickly build a digital crime scene. For practical use, an interactive real-time virtual roaming application was developed in Unity 3D and a low-cost VR head-mounted display (HMD). Practical cases have been implemented to demonstrate the feasibility and availability of our method.

Keywords: Forensic science · Indoor crime scene presentation
3D model database · Sketch-based retrieval · Rapid modeling
Immersive display

1 Introduction

In case of criminal incidents, the first phase of inspection and investigation is to rapidly record a complete, objective crime scene representation without erroneous information [1]. In comparison to traditional methods, i.e., verbal descriptions, hand-drawn sketches, photos, videos, etc., the use of 3D crime scene presentation is more intuitive and effective [2, 3]. Although 2D photos, videos and spherical photographs have been used in the courtroom, there are challenges in using these resources to describe and present the crime

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scene because these resources only provide information from a given view [4, 5]. 3D presentation enables investigators to virtually experience the crime scene, measure the distances between different objects and simulate the criminal activity. A powerful and effective way of presenting a 3D crime scene was proposed in this context.

In recent studies of forensic investigation, the use of a terrestrial laser scanner (TLS) or RGB-D camera has become a popular technique for the acquisition of 3D models of indoor crime scenes and evidence. The time-of-flight laser scanner, structure-light scanner and triangulation-based scanner have been used to acquire both the large-scale geometric information of crime scenes and the small-scale geometric information of evidence and victims [1, 3, 4, 6, 7]. These noninvasive scanners can be used to accurately generate a digital model after registration of range images and mesh processing. However, these devices are always expensive and the generation of digital models from unorganized point clouds is always based on manual and expert procedures. It is difficult to widely promote the application of this technique in local police stations. To address this problem, another type of modeling method is to produce a realistic 3D digital model from a series of images, the procedures for which comprise camera calibration, dense point-cloud computation, surface reconstruction and post-processing [8–11]. The quality of a reconstructed model depends largely upon the algorithm used to calculate feature correspondence and camera calibration. Furthermore, it is time consuming and expensive to use these optical device based methods.

Considering investigators would like to quickly represent the spatial information of crime scenes, the use of professional software, for example AutoCAD, 3Ds Max, SketchUp, etc., is the most common, intensive and powerful technique for 3D crime scene representation [12–15]. However, one potential problem of this technique is that investigators have no professional training or experience in producing 3D models using software. In addition, this work is tedious and time consuming, because hundreds of 3D models should be generated for a crime scene.

We have observed that in traditional practical crime investigations, policemen are often tasked with recording the indoor layout in hand-drawn sketches. Inspired by this observation and existing literature, this article presents an effective way to build a digital indoor crime scene to record the spatial relationships of objects for crime analysis and presentation. Additionally, rather than relying on sketches of the layout and objects, investigators can directly obtain a 3D scene using our system and explore this virtual scene anywhere and at any time.

2 Materials and Methods

2.1 A Specialized 3D Model Collection

The high quality and large number of 3D models in the collection improved the presentation of the 3D crime scene. By collecting more categories and a larger number of models in each category, one can retrieve a larger number of appropriate objects. In this study, we used existing laser-scanning, image-based modeling and software-modeling techniques to generate 3D models. We have constructed a 3D model database including crime-related models and common models in indoor scenes.

Some objects that appear in a crime scene are unique and cannot be replaced by the existing models in the database. Thus, we used laser-scanning and image-based modeling techniques to capture real data of critical evidence. We used a high-precision hand-held laser scanner HandySCAN 700 (Creaform Company, Canada) to reconstruct 3D models of objects. The benefit of this laser scanner is that it automatically produces complete single mesh models, without the procedure of manual range-image registration in other scanners (e.g., Vivid 910 laser scanner). Figure 1 shows some examples of 3D models captured by laser scanner. In addition to some crime tools there are two shoes and soles (usually very important evidence) in this figure. The main benefit of this technique is that it acquires high-quality 3D models with more details. However, the high cost of the device prohibits its widespread use.

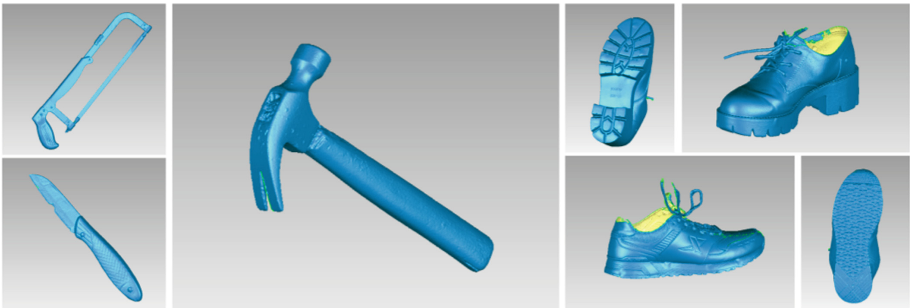

Fig. 1. 3D models capture by laser scanner. (Crime-fighting tools and shoe soles.)

The structure-from-motion (SFM) technique is used as a substitute in cases in which the laser scanner cannot be used. Inputting a set of photos of the object, a powerful and free tool called VisualSFM [16, 17] was used to generate a dense 3D point cloud with color. Figure 2 shows some examples of 3D models acquired by the SFM technique.

Fig. 2. 3D models reconstructed by SFM technique. Left: a chair with clothes on it. Middle: a mass of clothes. Right: a plush toy. (Color figure online)

To construct a mesh model from point clouds, the open-source software Meshlab was used to realize surface reconstruction and post-processing [18]. In Meshlab, the normal vector at every point was estimated and the Poisson surface reconstruction algorithm was used to generate a mesh model. This technique is easier to use than 3D scanning since it is convenient to acquire multiple photos for evidence.

To extend the number and categories of 3D models, we collected 3D models from online public-domain galleries, such as the Google 3D Warehouse, which offers thousands of models online [12], and the public database from literature [19]. As a supplement, some models were created by professional designers using geometric modeling software. Figure 3 shows some examples of 3D models created using commercial software (SketchUp, 3Ds Max). Figure 3(a) shows 3D models of furniture. Moreover, the victim's posture plays a significant role in crime investigation. Thus, multiple types of human models with various postures are available in our database to ensure that the most similar one to the real situation would be found (Fig. 3(b)). In summary, we offered a total of 2,564 models and 18 categories in our collection, including windows, doors, home appliances, furniture, human bodies, and criminal tools. Table 1 lists the main types of models from different sources in our database. The decisive evidence refers to some material evidence which play a decisive role in the real investigation.

(a)

(b)

Fig. 3. A collection of 3D models in the crime scene. (a) Furniture models with various shapes. (b) Human models with various postures.

Table 1. 3D model database.

Source	Online libraries	Open literature	Software modeling	Laser scanning	Image-based modeling	Total
Indoor models	1,123	659	361	0	18	2,161
Murder related	240	0	135	12	6	393
Decisive evidence	0	0	2	3	5	10
Total						2,564

2.2 Method

I. Sketch-based indoor scene modeling

It is a challenge to rapidly obtain the appropriate model from large collections of 3D models since public collections are often insufficiently annotated [20]. To address this problem, the content-based retrieval technique is a powerful and effective tool. The general idea of the sketch-based method is that the user retrieves the desired model through the input of a hand drawing. In this study, our sketch-based retrieval was divided into two stages: offline index and online query. To save time in a real-time query, we perform the computation offline as much as possible. Figure 4 shows the framework of our algorithm and Fig. 5 shows one of the retrieval results. The input sketch is shown on the upper left, and the first couch model is the most similar model in the database. The key steps of our algorithm are described below.

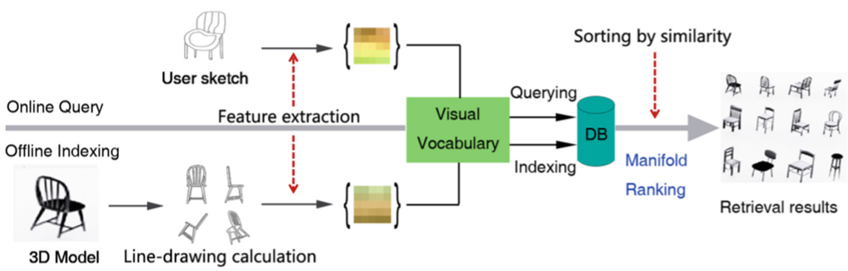

Fig. 4. The framework of our sketch-based retrieval algorithm.

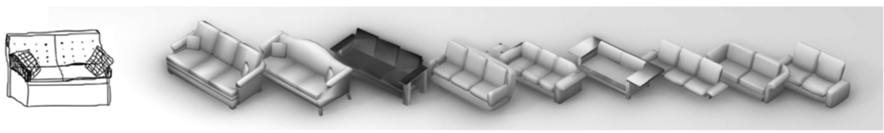

Fig. 5. Retrieval results using sketch-based technique. The left figure shows an input of hand drawing by user. Right figure shows the first nine most similar models.

Step 1: Line-drawing calculation. The essence of 3D model retrieval is to evaluate the similarity between hand-drawn sketches and models. Towards this end, 3D information should be first projected into 2D images. 2D line drawings are extracted from 102 viewpoints of geodesic geometry for each model in the database, reflecting the visual information as much as possible. Different from most of the previous line-drawing extraction algorithms, which were only available for homogeneously distributed dense meshes, we proposed a depth map-based difference-of-Gaussian (DoG) method to extract lines, including the boundaries and creases formed by differences in depth. The information in the depth buffer is used to generate depth images with different Gaussian parameters, called D1 and D2, and the line drawing is generated by calculating the inverse of binary image, i.e., the Gaussian difference of D1 and D2. To overcome the saw tooth noise problem, the Bezier curve approximation is used to perform the line stylization and obtain a smooth contour line [22].

Step 2: Feature extraction. We used a spatial, high-dimensional local feature-description algorithm to extract features. As a type of short-time Fourier transform, Gabor transform is sensitive to the edges of an image. It can provide good selection for frequency and orientation. In addition, the Gabor filter is similar to the mammalian visual system in the expression of frequency and orientation. It is suitable for sketch retrieval requests. Thus, we use an algorithm called the Space Pyramid of Gabor Local Feature Extraction and obtain better results [20]. Next, we define a set of Gabor filters $g_i(i = 1, 2, \ldots, k)$ to calculate the basic transform of the feature region, and the information on the spatial distribution is obtained in the space pyramid of the image. For each g_i and image I, a convolution computation is employed to obtain a response image R_i:

$$R_i = \|\mathrm{idft}(g_i * \mathrm{dft}(I))\| \tag{1}$$

where * denotes point-wise multiplication, and the function dft() and idft() respectively denote the discrete Fourier transform and the inverse discrete Fourier transform. A grid-sampling method is used for feature-point sampling. For a local shape feature, we divide the region into $n \times n$ cells C_{rc}, in which r and c respectively denote the row and column coordinates. The descriptor in the i direction is a feature vector of size $n \times n$.

$$F(r, c, i) = \frac{1}{N} \sum_{(x,y) \in C_{rc}} R_i(x, y) \tag{2}$$

where N denotes the sample number for which $R_i(x, y) \neq 0$ in the i direction. The local feature is a $k \times n \times n$ dimensional vector.

Step 3: Sorting by similarity. We employed TF-IDF [21] to calculate the similarities of feature vectors among various models. In an ideal situation, the first-place model is the desired model, and then we import it into the crime scene. As the retrieval algorithm is not the focus of this work, readers can find more complete algorithm details in our other work [22].

II. System interface

Our system was developed on the basis of open-source software SweetHome3D licensed under the GNU General Public License [23]. We developed the sketch-based algorithm in Microsoft Visual Studio in C++ and exported to a Dynamic-link library (dll) file. This dll file was imported as a plugin on a new user interface implementing sketch-based function. Our proposed 3D crime scene representation system contains five modules (see Fig. 6): (a) the user draw a sketch of the desired from any viewpoint at the left-top area, and the retrieval results are displayed on the bottom, sorted according to similarity; (b) a 2D plan view that referring to the ichnography, can be loaded into this module as a base map where the layout of the indoor scene and the selected model can be transformed to the designated location (translation, rotation and scale); (c) a 3D display view where the 3D model scene corresponding to the 2D plan view is displayed and the user can observe the scene from any view and roam the scene as a virtual character; (d) a model classification and viewing tree in which a collection of 3D models is classified according to the given classification scheme and every model can be selected and viewed; and (e) a scene management interface where the parameters and statues of every model can be edited.

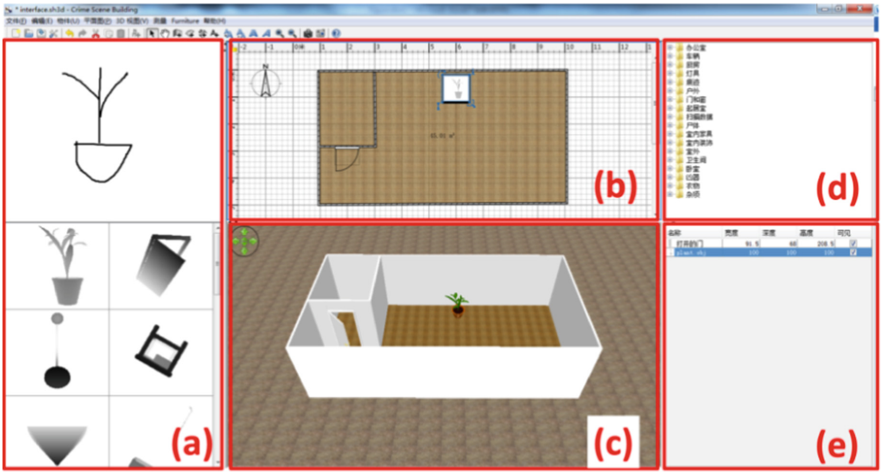

Fig. 6. Interface of our system. (a) Sketch retrieval interface. (b) 2D plan view. (c) 3D display view. (d) Model classification and viewing tree. (e) Scene management interface.

The major advantage of our system is that simple 2D sketches can be rapidly transformed into a complex 3D crime scene. In the first stage, users need to draw a sketch on the sketch-retrieval interface to obtain the desired objects from the database directly. Second, the retrieved models are placed on the 2D plane view and the corresponding 3D scene is simultaneously rendered on the 3D display view. The user can either view the 3D scene from any directions or roam in it anywhere and at any time. In the scene-management module, users can adjust the parameters and status of the chosen model, including visibility, texture, object position and size. Another notable feature of our system is that it is easy to measure the distance between two objects (Fig. 7). In the 3D scene shown in (a), the distance between the body and the murder weapon can be easily measured by connecting them with a line as shown in (b). Finally, the 3D crime-scene representation can be exported as a standard .obj files.

(a) (b)

Fig. 7. The distance measuring function of the system.

III. Immersive display

As a supplement to the virtual roaming function provided by our system, a helmet-mounted display (HMD) device, such as HTC Vive, can be used to increase the immersive VR effect. This device has a high resolution of pixels, resulting in a resolution of pixels for each eye. HTC Vive provides a pair of handheld controllers and positioning-system tracking display, which allow the user to move within a certain scope and interact with the virtual scene using the handle [4]. These advantages are very suitable for the virtual representation of crime scenes.

Utilizing the encapsulated SDK in the cross-platform game engine Unity3D (Unity Technologies, San Francisco, USA), we developed a VR roaming system for crime scenes. The 3D model scene built with our proposed sketch-based indoor-scene system can be imported into Unity3D and real-time interactive virtual-experience systems are developed using Microsoft Visual Studio C#. In comparison to the traditional PC screen, the immersive display offers a larger viewing volume and more realistic experience. With the headset and handle, the investigator can enter the crime scene in digital space, observe 3D models of physical evidence, and analyze the case from a more intuitive angle.

3 Illustrative Example

To demonstrate the availability and effectiveness of our system, we quickly present an example of how to create an acceptable 3D crime scene for presentation from series of 2D sketches. We took a criminal case happened fifteen years ago as an example;

specifically, three adults and one child were killed in an apartment (Fig. 8). The only remaining visual documents for this case are several low-resolution photos and a hand-drawn floor plan of the crime scene. Using our system, we can rapidly reconstruct this indoor scene and develop a roaming system in VR space.

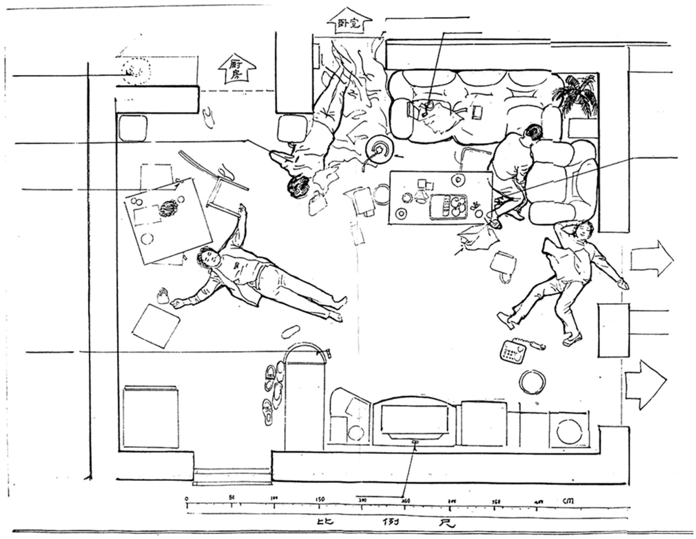

Fig. 8. The floor plan of the crime scene in our example.

Although very few visual records of this case are available, the floor plan is a crucial piece of physical evidence for crime-scene reconstruction. By importing the hand-drawn floor plan into our system as a base map, we obtained the measurements and layout information of 3D models (Fig. 9a). Then, the user dragged the mouse to draw 2D shapes of walls on the 2D plan view according to the tracing lines of the imported base map, and the 3D scene was rendered in the 3D display view in real time (Fig. 9b). To enable the accurate representation of the 3D crime scene, the user scaled each shape according to the real measurement values, i.e., user defined the length, height and width of the indoor scene. The main contribution of our approach is the sketch retrieval function in this system. Figure 9c shows an example of retrieving the sofa. The retrieved model was imported into the 2D plan view and placed at the designated location, according to the base map. All the textures of imported models can be exchanged according to the real scenario (Fig. 9d). These steps were repeated until all objects were imported and transformed to the correct locations.

Figure 10 shows the 3D scene of this crime that was constructed using our system, which consisted of a total of 58 digital models and was rebuilt in a total of 13 min. The top two screenshots are bird's eye view and the bottom two are roaming perspective.

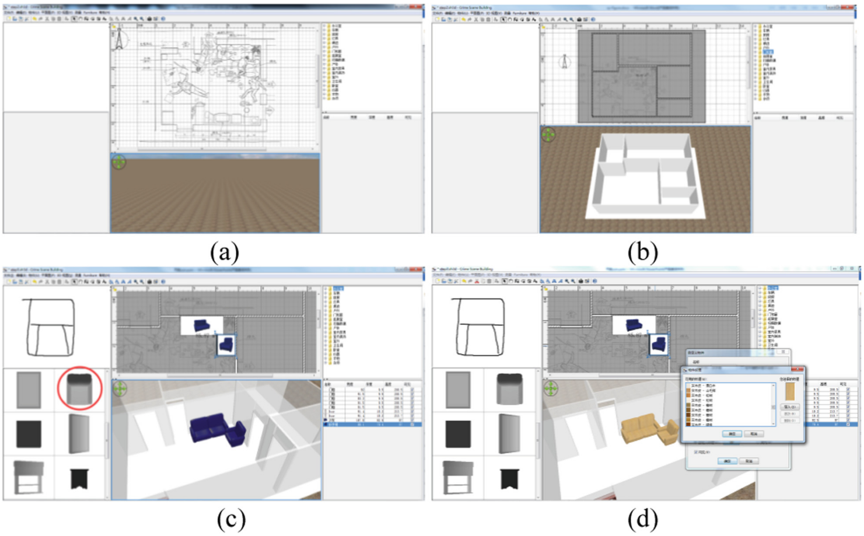

Fig. 9. Sketch-based modeling for the indoor crime scene. (a) Importing the hand-drawn floor plan as a base map. (b) Reconstruct the walls. (c) Retrieving 3D models by sketches. (d) Changing the textures.

Fig. 10. The creation of 3D indoor crime scene using our system.

To virtually experience this crime scene in an immersive display, the created crime scene can be exported as a standard .obj file, and an interactive virtual roaming system was developed in Unity3D, enabling investigators to experience the crime scene from a fixed viewpoint or different views to examine more details of the evidence of interest. Figure 11 shows the immersive roaming effect using HTC Vive. In this application, the user can intuitively simulate and analysis the shooting and walking routes of the criminal in the virtual space.

Fig. 11. Interactive crime scene experience in the immersive display using HTC Vive. Left: photo of the experiencer. Right: real-time screenshot.

4 Discussion

In comparison to traditional recording approaches, e.g., 2D hand-drawn sketches, photos, videos, 3D digital scenes and animations have been used to enhance clarity and understanding in crime-scene investigation [2, 3, 7, 12, 14]. Although the laser-scanning technique provides life-like and accurate 3D models of crime scenes, it has limitations for widely promotion. For one hand, the devices are expensive. For another hand, it is still a great challenge to convert dense triangle meshes (more than hundreds of thousands of triangle meshes) into a simplified model to meet the requirement of real-time virtual experience. Another limitation is that many crime scenes cannot be entered after the criminal incident. In this situation, investigators need to model the scene manually. Clair et al. introduced the application of the easy-to-use modeling software SketchUp (version 8) to generate 3D indoor crime-scene models [12]. It was an extremely time-consuming process to generate every model. To solve this problem, Howard et al. constructed a collection of 3D models and generated the non-critical areas of digital crime scenes using the existing models [14].

One of the contributions of our work is utilizing multiple techniques to construct a large collection of 3D models for indoor scene. The 3D models with complex structures and more details, e.g., guns, knives, shoe soles, etc., were generated by laser-scanning or image-based modeling techniques. To enable real-time rendering of this model in Unity 3D, the open-source Meshlab software was used to convert this 3D model to a simplified model and texture.

Another contribution of our work is the sketch-based model retrieval. Because of the large number of models in the collection, investigators have become more comfortable and it has become easier to generate a crime scene by our method. However, it is also a challenge for investigator to rapidly obtain the desired model from datasets. Compared with the traditional text-based retrieval methods, the 2D hand-drawn sketch-based approach has much more potential in our application since few annotations are available for each 3D model. In this paper, we propose a sketch-based approach to obtain a suitable model with geometric structure similar to that of the real object from the database. To achieve real-time retrieval, we have extracted and archived the feature lines of every model in advance. Because of this main part of our work, crime scenes can be rebuilt quickly using policemen's hand-drawn sketches rather than those of professional designers.

To better provide a crime-scene model, a multi-participant, large-screen stereoscopic projector system [14], an immersive display VR headset [4], and the augmented-reality technique have been used in previous studies [24]. In our article, we provided a general system covering the functions of rebuilding an indoor crime scene and rendering it in 3D space. To realize immersive display, the rebuilt scene model was imported into Unity 3D to develop a VR roaming system in HTC Vive.

There are still some limitations of our approach. We have successfully extended the crime scene model database, but both the number of category in the database and the number of models in each category are insufficient for crime-scene presentation. We will continue to generate multiple kinds of models to build an extensive crime-scene model database. A system allowing the user to retrieve multiple 3D models at the same time is also helpful in practice.

5 Conclusion

Based on the 3D model collection, a sketch-retrieval based modeling system was developed. Because of the TF-IDF algorithm, our method achieves high retrieval accuracy and time efficiency. Using our approach, police investigators can rapidly record the spatial relationships of objects while constructing a digital model of the indoor crime scene. In comparison to laser-scanning and software-modeling techniques, the main advantage of our method is that it is low cost and rapid, making it very suitable for criminal investigation. In terms of digital forensics and educational training applications, the immersive-display we developed has broad prospects because of the VR interactive experience in the crime scene.

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