Hypothesis-driven Case Analysis in 3D-Space as a Support for Forensic Casework

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**Abstract:** Interpreting the evidence found at a crime scene is essential in reconstructing the circumstances of a crime and, hence, solving it. In this paper a classical hypothesis-driven approach is combined with computer-aided modeling. Hereby, the paper focuses on the advantages of 3D models and their added value in the reconstruction of a case by visually supporting the analysis of evidence found at a crime scene. Using the example of blood patterns, it is explained what the static part of an evidence is and how the interpretation of this part, with the help of an interpretation function, results in additional information about the dynamic part of evidence. Further it is explained how this concept can assist the classical hypothesis-driven approach of reconstructing a crime. By using 3D models it is possible to improve the analysis of the formation of evidence and especially the time line. Thus, 3D-models can aid classical forensic casework with a new computer-based approach.

**Keywords:** Forensic Casework; 3D Modelling; Hypothesis; Evidence Highlighting; Bloodstain Pattern Analysis (BPA)

1 The concept/definition of evidence in forensic casework based on a real example

When working a case all evidence and witness reports need to be analysed objectively and conscientiously in order to reconstruct the circumstances of a crime and as a result form hypotheses. These then have to be defended in front of a court of law using the available evidence. In order to ensure the objectivity during this process, several models have been proposed of how to handle the information [AA12; Ag11; Ah02; Mo17; Sa17]. Evidence found at a crime scene is used as a foundation in all of the models.

However, it is not clear what should be collected as evidence when working at a crime scene. In 1789 Quistorp first mentions that all the evidence and other circumstances in connection with a crime should be examined by an expert [Qu89]. The definition used by German

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law enforcement agencies states, that all visible or latent material changes that could be connected to a criminal event and can contribute to solving a crime should be considered evidence. This means, that all changes at a crime scene can be defined as evidence [Ge86].

Interpreting the meaning and chronological order of evidence found at a crime scene presents some limitations and risks, as it might be misinterpreted based on subjective assessments. Consequently, it can take longer until a case is solved and important details might be ignored. A study from 2017 has shown that prior knowledge of a crime scene can lead to evidence being treated significantly different [EPV16]. A logical evidence evaluation system is recommended for an objective assessment. Furthermore, even though misinterpretations of evidence may not be avoided it can be minimized by logically linking the evidence [SML18].

A basic representation of common analysis models is shown in Figure 1. In investigative procedures analogous conditions are attached to the process of hypothesis development. Scientific methods are used to generate information from the evidence (data, facts, numerals). Scientific methods are procedures, algorithms and systems that have been evaluated and meet a well-defined standard. Information are summarised into case-specific hypotheses and explanations and leads to the actual hypothesis, which is evaluated in the course of an iterative process. Fig. 1 shows a hypothesis cycle for the reconstruction of a crime scene. Information and the resulting knowledge provide the basis for the verification or falsification process of forensic hypotheses. [LS17] The hypotheses cycle can be continued until the circumstances of the crime are reconstructed to a satisfactory degree.

Fig. 1: Procedure of a classical analysis of a case. The hypotheses cycle represents an iterative process. The starting point is the formulation of hypotheses, followed by the analysis of the evidence in order to gain new data to model possible scenarios. The results are then evaluated and the original hypotheses can be accepted or rejected. [LS17]
Based on a real case, analyses and procedures of this concept will be explained in more detail in this publication. The case is a homicide from 2005 [Re18]. The victim was a middle-aged woman who was killed by several blows to the head in her apartment. In 2015, an extensive analysis of the case was performed. The data basis was formed by files, photographs and autopsy reports. During the investigation process from 2005 numerous evidence were found, especially blood traces. In order to gain a better understanding of the crime scene conditions at the time and to be able to analyse the relationship of individual evidence, a true-to-scale 3D model of the crime scene was created by an on-site visit. Due to the fact that the crime was committed in 2005, the actual crime scene was no longer in its original state and only the floor plan could be digitized. Based on the data mentioned above the victim, the evidence in form of the blood traces and pieces of furniture were enriched as digital models itself in the created 3D model of the floor plan. This made it possible to create a scale model of the entire crime scene. The case itself was chosen because the added value of the procedures presented here can be particularly emphasized and were explicitly applied to this case. Because of the usage of the hypothesis-driven approach in combination with the 3D model of the crime scene with the enriched blood traces, it was possible to formulate hypotheses and to chronologically order the sequence of events of the crime. On the basis of the case this mentioned combination of a hypothesis-driven approach of analysing a case and three-dimensional data is introduced. More detailed information on the procedure above, in particular on the significance of the static and dynamic part of an evidence (inspired by [Mu21]), can be found in the following chapters.

2 Static and dynamic part of evidence

In this paper we want to bring additional attention to an extension of the classic term of evidence: the static and the dynamic part of evidence.

In many cases this distinction, allows the development of new hypotheses without increasing the amount of the collected evidence. In this context, the static part refers to the appearance, condition and geometry of the evidence at the time of its collection. Examples include the shape and color of a blood pattern, the type and quantity of minutiae on a collected fingerprint or the material composition of a foreign synthetic fiber found on a carpet. In the presented model from Figure 1, the static part would form the basis for the first iteration of hypotheses. In our opinion, the dynamic part of evidence can provide information that should not be underestimated and refers to the formation of pieces of evidence. This means, that one has to consider why a piece of evidence was found at a certain location and how it was formed. The dynamics of how a piece of evidence was formed often provides a context about the relationship of different pieces of evidence to each other. Thus, it is also possible to reconstruct the circumstances of a crime. In the examples mentioned above the dynamic parts could be the calculated convergence area of the blood patterns and the order of their origin, the reconstruction of the position of the fingerprint-leaving person at the scene or the object, from which the synthetic fibre originated, and its current location.
For a better explanation of the formalisation of the presented hypothesis-driven approach a crime scene with crime events is given. These events have left evidence at a fixed point in time. This point in time can be defined as the true time of origin of the evidence, where each evidence has its individual true time of origin. In addition there is also the point in time when the evidence were secured at the crime scene. It should be noted that a secured evidence consists of the two parts, the static and the dynamic part like mentioned above. By analysing these two parts, it is possible to approximate the time of origin of an evidence through a hypothesis-driven approach with the aim of getting as best as possible to the true time of origin of the evidence.

In mathematical terms all evidence, defined as $E = \{e_k\}$ ($k \in \mathbb{N}$ and $k = 1...n$ with $n =$ number of secured evidence $e_k$) (see 6) from a crime scene are secured at a fixed point in time $T_S$ ($S =$ secured). The true time of origin of the evidence is defined as $t_o^{e_k}$, which should be approximated as best as possible through the approximated time of origin $t_o$ of the evidence $e_k$, definded as $t_o^{e_k}$, by analysing the evidence $e_k$. On the description level these evidence $e_k$ include a static part $e_{ks}$ and a dynamic part $e_{kd}$ (see 1). Based on the static part of evidence $e_{ks}$ the crime sequence should be analysed initially by a hypothesis-driven approach. This approach leads to an approximated time of origin $t_e^{o}$ (see 2), which results from the analysis of $e_{ks}$. This approximation of $t_e^{o}$ is done via $\Delta t_e^{o}$ an approximation step in relation to $T_S$. This results in an initial relation set $S$, which maps the relation between the evidence and their initially approximated time of origin defined as $S = \{e_k, t_e^{o}\}$, based on the analyses of the static part of evidence $e_{ks}$ (see 3). With the help of an interpretation function $I(e_{ks})$ to interpret the static part , additional information of the dynamic part $e_{kd}$ can be generated in the form of connected time shares $t_o^{e_k}$ and $t_o^{e_d}$ for the best approximation of $t_o^{e_k}$, by $t_o^{e_k}$. By analysing the dynamic part of evidence $e_{kd}$, the approximated time of origin of the evidence $t_o^{e_k}$ can be adjusted to $t_o^{e_k}$ based on the new information (see 4), where $t_o^{e_k}$ are the best approximations of the true times of origin $t_o^{e_k}$.

This results in an adapted relation set $S'$ with the evidence and the adapted time of origin $t_o^{e_k}$ defined as $S' = \{e_k, t_o^{e_k}\}$ (see 5). A formalized representation of these processes is shown in equation (1)-(5) and visualised in fig. 2.

\[\begin{align*}
\text{crime scene} \\
\downarrow \\
e_k := e_{ks} \cup e_{kd} \\
e_{ks} \Rightarrow T_S - \Delta t_{e_k} \Rightarrow t_o^{e_k} \\
S = \{e_k, t_o^{e_k}\} \\
e_{kd} := I(e_{ks}) \Rightarrow t_o^{e_k} \pm t_o^{e_d} \Rightarrow t_o^{e_k} \\
S' = \{e_k, t_o^{e_k}\}
\end{align*}\]
Fig. 2: Schematic representation of the formalisation presented in (see 1-5) based on three example evidence $e_1$-$e_3$. Through a hypothesis-driven approach, it is possible to approximate the time of origin for each individual evidence at the crime scene. This approximation is initially based on the static part of an evidence by an approximation step $\Delta t_{e_k}$ in relation to the time of securing $T_S$ of the evidence. By interpreting the static part of the evidence through an interpretation function $I(e_k)$, information about the dynamic part of the evidence is obtained in the form of connected time shares $t_{e_k}^{o,s}$ and $t_{e_k}^{o,d}$. Based on this new information, approximated times of origin $t_{e_k}^{o}$ of evidence can be further adjusted to $t_{e_k}^{o,s}$ to best approximate the true time of origin.
Only by analysing both parts of the evidence it is possible to get as close as possible to the true time of origin.

Nowadays, methods of 3D modelling are increasingly used to support the documentation of crime scenes because the technology allows investigators to make analyses at a later point in time [TSP19]. 3D modelling offers great added value in computer-assisted case analysis, especially in the possibilities of analysing a temporal sequence of events in 3D space. The following chapter first provides an introduction to the possibilities of digitising crime scenes, followed by a hypothesis-driven case analysis in 3D space based on blood traces of the presented case example.

3 Hypothesis-driven case analysis in 3D space based on blood traces

Modern visualization technology with software that is becoming increasingly user-friendly and constantly evolving hardware is finding its way into most areas of our everyday life. This is also the case in forensic casework, for which different tools can be used to digitally preserve crime scenes including complex evidence constellations [Be18; DLE16; Sp16; Sü19]. Many of these tools are already used routinely. However, despite their widespread use, they are often only used to create a simple model of a crime scene, which on itself offers only a limited added value. Currently, additional analysing options as well as the combination of these are rarely used. This means that the tools currently in use are mostly used to document a crime scene, at the best in 3D. Within such created 3D models, for example visual inspections and distance measurements between evidence are carried out. A possible limitation of the tools used may also be in the processing of cold cases. In these cases, there are usually no 3D data of the crime scene available, as 3D documentation may not have reached the necessary technical progress at that time. This means that a crime scene or the area where the crime took place in the past can theoretically be documented in 3D in the present, but a multitude of further process steps are necessary to reconstruct the actual crime scene in its entirety (e.g. including evidence) and thus to be able to use the added value of such models in combination with hypothesis-driven approach of case analysis like presented in this paper.

Within this publication, it will be shown how a combination of these two methods can improve forensic casework. Figure 3 shows a 3D model of a crime scene as it is already often created by crime scene investigators when processing the crime scene. The model shown here was created on the basis of on-site measurements at the crime scene. In open terrain, drones provide a means of creating aerial photographs. The refinement, texturing, and data enhancement of the 3D model presented here was done in the open source software Blender (https://www.blender.org/). Blender is a free open source 3D modeling suite that provides the entire 3D pipeline - modeling, rigging, animation, simulation, rendering, compositing, motion tracking and video editing. All secured evidences, possibly relevant to the crime, are included in the model. In order to keep the example as simple as possible, only blood patterns are of particular interest and used to illustrate the principle presented
in this paper. The blood traces secured at the crime scene were classified, if possible, according to the types defined in [BG08]. In order to optimally illustrate the principle of hypothesis-driven case analysis with the inclusion of 3D models, only those blood traces were used that could be clearly assigned to a type. This was crucial, as the dynamic part of the evidence is defined by the different processes of formation of different evidence, which can be used to extract information about the sequence of events. However, this is only possible if their type can be clearly determined. For example, a cast-off pattern found on the wall shows evidence of active violence and a pool of blood shows evidence of a blood spill that was influenced only by gravity. In this example all these secured and classified blood traces, corresponds to the defined \( E = \{ e_k \} \) with \( k \in \mathbb{N} \) and \( k = 1, 2, 3, 4, 5 \) (see 6).

\[
E = \{ e_1, e_2, \ldots, e_5 \} \quad with \quad (6)
\]

\begin{align*}
e_1 & := \text{wipe pattern} \\
e_2 & := \text{cast-off pattern} \\
e_3 & := \text{drip pattern} \\
e_4 & := \text{contact pattern} \\
e_5 & := \text{pool of blood}
\end{align*}

Even though this is just a basic model and no additional information has been added, it can already offer some advantages for the criminal investigator. With a 3D model it is possible to virtually walk through the crime scene without the risk of changing anything. This makes it easier to examine individual pieces of evidence and their position (static part of the evidence). Furthermore, the relationship of the individual pieces of evidence to each other is easier to see in the model, as one is not limited to classical crime scene photographs as it is often not possible to capture all the relations between the pieces of evidence. Additionally, it is possible to discuss preliminary hypotheses about the time of origin of evidence directly in the model, which corresponds to the defined initial relation set \( S = \{ e_k, t^{\sigma_k}_e \} \). It is also easy to share the findings as the model can be easily sent to other devices, where it can be viewed by others.

All these advantages thus allow better recognizability and assignability of individual evidence. The static part of evidence (appearance, condition and geometry) and especially the dynamic part of evidence (formation dynamic) can be captured and displayed more easily in the 3D model. Thus, 3D modeling becomes a helpful tool for investigators, supporting a hypothesis-driven case analysis.

Fig. 3A shows possibilities of using a 3D model to analyse the evidence of the crime scene of the presented real case example. Highlighting is used in order to quickly identify the blood traces and to form knowledge-based hypotheses about their origin. Here, it can be
Fig. 3: A: 3D model of a crime scene, where the black squares show the different blood patterns on the ground and wall of the crime scene. The different blood patterns are: $e_1$: wipe pattern $e_2$: cast-off pattern $e_3$: drip pattern $e_4$: contact pattern and $e_5$: pool of blood. The contact pattern shown is a part of trousers belonging to a witness who was allegedly at the crime scene. Even such blood traces, even if they were not found directly at the crime scene, can be classified in the chronology of the formation of blood traces. All these different blood patterns represent the static part of the evidence. B: 3D-Model after interpretation of the static part of evidence resulting in the area of origin (dynamic part). C: The different pieces of evidence were highlighted in different colors in order to visualize the chronological order. The coloring of the blood traces depends on the time of origin. Blue marked blood traces are younger than red marked ones. The smaller figures left- and right-handside of C ($C_1$ - $C_5$) represent the colored blood traces and serve as a better overview.

seen that the overview of the scene makes it easy to record and evaluate the position of the individual blood traces in relation to each other. Thereby, it is possible to create different categories in which individual blood traces can be grouped together. These categories can be easily identified, for example by using different colors for each category. This makes it easy to identify relationships between blood traces by using visual highlighting and to present these to a third party.

Analysing the static part of evidence (appearance, condition and geometry) in our example, it quickly becomes clear that the blood pool must have been created after the active blood traces on the walls, provided that all blood stains originate from the same person. The size of the blood pool says that the blood loss was fatal, so it is possibly the final position of the corpse. An origin of the evidence on the walls by active force impact on the victim walking around after the blood pool origin is therefore not plausible. Under what circumstances the contact pattern was created is not yet clear. After evaluation of the static part of evidence, a
first hypothesis about the time of origin of evidence arises, which can be summarized as the following relation set $S$ in (see 7).

$$S = \{ e_1, t^{e_1}_o; e_2, t^{e_2}_o; e_3, t^{e_3}_o; e_5, t^{e_5}_o \}$$ (7)

By using a model as shown in Fig. 3A it is easier to gain new knowledge from the given evidence. For example, by logically combining the location of the individual blood traces and their relationship to each other, it is possible to determine the dynamic part of the evidence. In the hypothesis-driven approach presented here, this corresponds to the interpretation of the static part with the help of an interpretation function. An example of this is the interpretation of the shapes of several blood traces and their relation to each other, which allows to determine the so-called area of origin [Gr21] (Fig. 3B), the location of the blood source at the time of trauma. Fig. 3C shows this new information with the help of color spectrum, where blue represents the piece of evidence that was formed first and red the one that was formed last. With the help of the color spectrum, it should be made clear how the blood traces were created temporal in relation to each other, independent of the time of securing.

This hypothesis of the sequence of events is based on the following knowledge-based analyses of the pieces of evidence in relation to each other and by including and by interpreting data (static part) recorded at the crime scene to gain new information (dynamic part). The static part of the blood traces corresponds to the position, shape and arrangement of the secured blood drops. These were interpreted with the help of an interpretation function, i.e. analyses were carried out with regard to the distance between individual blood drops and other blood patterns, as well as with regard to impact angles and direction. From this, calculations of the so-called area of origins were made. These area of origins correspond to the defined dynamic part of an evidence.

The cast-off pattern (evidence $e_2$) between the small picture on the wall indicates that the victim must have been standing near this position and was hit with great force. Therefore in comparison to the other secured blood traces this blood pattern was probably created in an initial phase of the crime act. In this case, interpreting the position of the blood traces to each other using the interpretation function $I(e_k)$ results in the determined area of origin, which can be used to adjust the approximated $t^{e_k}_o$ to $t^{e_k}_o$ of the evidence $e_k$. On this basis it was possible to derive that the cast-off pattern (evidence $e_2$) may have been originated first in relation to the other evidence (see 8). The approximated time of origin of the other evidence are not yet adjusted at this point.

$$t^{e_2}_o < \forall \in t^{e_k}_o \text{ with } k = 1, 3, 4, 5$$ (8)
Interpreting the location and geometry of $e_1$ and $e_3$ it comes to light that the wipe pattern is located on the wall just behind the drip pattern near the hand of the victim. Possibly, the wipe pattern was created when the victim was still alive but with blood adhesion on its hand. These adhesions could have occurred due to possible defensive postures and resulting injuries to the hands, thus leading to the secured blood drops which created the drip pattern. The blood drops had a circular shape due to a possible orthogonal angle of impact. Consequently, the use of the interpretation function $I(e_k)$ to interpret the location and shape of the blood traces resulted in the knowledge that the drip pattern was created slightly staggered up to the same time as the wipe pattern was created (see 9).

$$t^{e_1}_o \leq t^{e_3}_o$$  \hspace{1cm} (9)

The time of origin can also be adjusted for $e_5$ using an interpretation function ($I(e_k)$). The size and shape of the contact pattern indicates that the trousers were touched by a large accumulation of blood. At the crime scene, there is only one such accumulation of blood, namely $e_4$, the blood pool. This consideration leads to the assumption that the contact pattern on the trousers of the witness was possibly created after the victim was found in the floor (see 10).

$$t^{e_5}_o < t^{e_4}_o$$  \hspace{1cm} (10)

After interpreting the static part of all evidence $e_k$ with the help of the interpretation function $I(e_k)$ and analysing the dynamic part of all evidence $e_k_d$, the time of origin of the evidence were adjusted from $t^{e_k}_o$ to $t^{e_k_d}_o$. In summary this adjustment results in the following order of time of origin of the evidence $e_k$ (see 11).

$$t^{e_2}_o < t^{e_1}_o \leq t^{e_3}_o < t^{e_5}_o < t^{e_4}_o$$  \hspace{1cm} (11)

This results in the adapted relation set $S^*$ (see 12).

$$S^* = \{e_2, t^{e_2}_o; e_1, t^{e_1}_o; e_3, t^{e_3}_o; e_5, t^{e_5}_o; e_4, t^{e_4}_o\}$$  \hspace{1cm} (12)

The deduced timeline can now be used to formulate new hypotheses about the people involved and their actions at the crime scene. These new hypotheses can again be visualized in order to get closer to what happen at the crime scene and the actual timeline. Of course, the described procedure of extracting information from the dynamic part of the evidence is
also possible at the actual crime scene or with the help of crime scene photographs and crime scene sketches. However, the intention of this paper is not to point out the novelty of the proposed method, but to demonstrate that a 3D model can assist in this procedure. The 3D model offers the possibility to quickly transfer all results and hypotheses and to present them clearly. Therefore, it should be recognized as an extension to the forensic toolbox.

4 Summary

In summary, it should be noted that by gathering and analysing the static and dynamic part of the evidence it is possible to group pieces of evidence and in result formulate hypotheses about the chronological order in which the evidence was formed to approximate as best as possible the true time of origin of evidence. These new hypotheses should be compared with the situation found at the crime scene in an iterative process until no more questions arise. 3D models are a valuable tool to reconstruct and analyse cases in this way, as they allow a non-invasive and clear analysis of the evidence. By using colors to make the evidence more prominent as demonstrated in this paper, relationships between pieces of evidence as well as different hypotheses can be visually highlighted. This simplifies the presentation of the reconstructed circumstances of the crime between those working the case as well as in front of a court of law. Therefore, including the dynamic part, in addition to the static part, of the evidence when working a case using 3D models is an efficient method and it should be considered to use it more often in the near future.

References


