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PROJECT SUMMARY

1) Introduction

Crime scene reconstruction is the process of determining the events that occurred during a crime using the physical evidence present at the scene together with scientific methodology and deductive reasoning. There are many techniques that could be used during this reconstruction process, such as DNA evaluation, fingerprint identification, shoeprint identification, etc. The reconstruction method addressed by the present research is blood-spatter analysis. In this method, residual bloodstains at the scene of a crime are used to determine the point of origin of a particular bloodletting event and the type of trauma that led to the bloodstain (e.g., gunshot, blunt force, sharp object, etc.). The determination of these factors assists crime-scene analysts in their efforts to establish the sequence of events that occurred during the crime.

The size of a bloodstain is quantitatively described using the area of the stain's circular or elliptical shape. The shape is further quantified by its aspect ratio as well as the number of spines and satellite drops around the outer contour of the bloodstain. The size and shape of a typical bloodstain is the result of a complex fluid dynamical process in which a blood droplet impacts and spreads over a solid surface. Thus, the observed characteristics of a bloodstain depend on the physical characteristics of the surface itself, which includes its wetting properties and roughness, the impact angle with respect to the surface and impact speed of the blood droplet just prior to impact, and the physical properties of the blood droplet, which includes the droplet size and its material properties, such as viscosity and surface tension. The objective of a forensic blood spatter analysis is to use the observed size and shape of a bloodstain to infer the impact conditions of a blood droplet, i.e., its impact angle, impact speed, and size. The goal of the present research is to provide a rigorous scientific study of the fluid dynamics of droplet spreading that will support the reconstruction techniques used in a blood spatter analysis.

2) Major goals

This research was a combined experimental and numerical study of the motion of a liquid droplet with the density, viscosity, and surface tension of blood impacting an inclined planar surface of well-defined roughness and wettability. The main research goals are:

a) quantify the effects of the initial droplet size, speed, and impact angle, and the surface roughness and wettability on the final observed fully spread droplet-shape patterns over a broad range of parameters appropriate to forensic science, and

b) analyze these data to provide simplified, but relevant phenomenological models of droplet spreading and splashing that can be directly used by practitioners in the field of forensic science to predict droplet impact parameters using simple bloodstain measurements.

3) Experimental Work

The experimental work in this research program has resulted in the successful design and build of an acoustically actuated droplet generator that followed the design described by Visser et al. (2015). A sketch of the device is shown in Figure 1. The small cylindrical tank is a pressure vessel that contains the blood simulant. A small sapphire orifice plate attached to the bottom of the tank acts as an outlet for the liquid. The tank is also attached to a high-pressure nitrogen tank through a controllable relief valve (not shown). The high-pressure gas forces the blood simulant

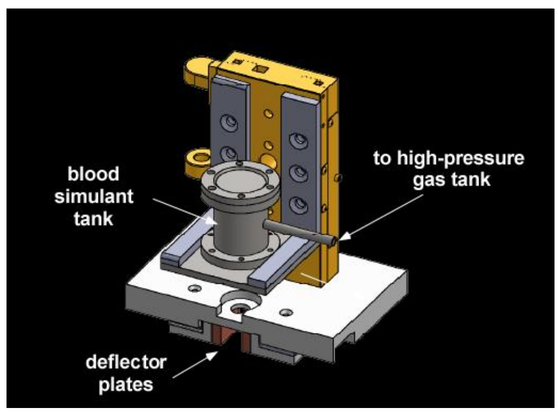

Figure 1: *Sketch of the acoustically actuated droplet generator.*

out of the tank through the sapphire orifice to form a high-speed liquid jet with a prescribed speed determined by the pressure set by the relief valve.

A piezo-electric acoustic actuator (piezo) is attached to the top of the blood simulant tank (sound chamber) as shown in Figure 2. The actuator vibrates the tank at a prescribed frequency in order to initiate a controlled capillary instability of the liquid jet that produces a stream of small droplets with a diameter determined by the acoustic frequency. Each of the small droplets in this stream has a zero charge and are undeflected as they pass through a uniform electric field maintained between a pair of high-voltage deflector plates (see Figure 1). The liquid stream then enters a collection tank located next to the target surface for disposal.

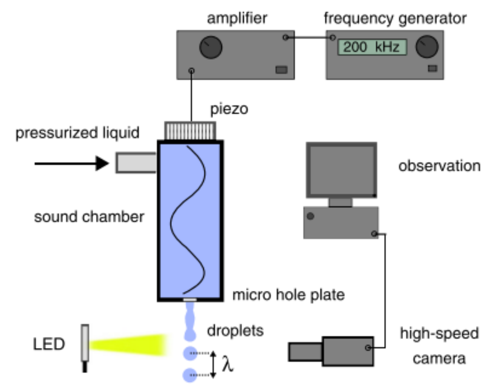

Figure 2: *Sketch of the operation of the acoustically actuated droplet generator.*

When a droplet impact event is desired, a charging electrode located near the point where the jet starts to breakup (see Figure 2, electrode not shown) is switched on for a brief time so that only a single droplet is charged. As this droplet passes through the electric field between the deflector plates (Figure 1) it is deflected to the side and impacts the target surface. This impact event will be observed and recorded with a camera using high-speed laser-pulse illumination.

At this point the student working on the project resigned from the Ph.D. program effective January 31, 2022. A short-term research engineer was not found to continue the experimental work and so this phase of the project was halted.

An outline of any future experimental work for this project is as follows.

1. Produce target surfaces of varying roughness. Use glass surfaces roughened by sandblasting with different sizes of sand grit. These surfaces will be measured with a profilometer to provide a direct measure of the magnitude of the surface roughness and to ensure its spatial uniformity.
2. Build a device to hold the target surfaces at defined inclination angles relative to the incoming droplet for the droplet impact studies.
3. Assemble a laser-pulse illumination system with several mirrors to obtain images of a droplet just before impact and the resulting spreading event that occurs on the surface. The data collection will be computer-controlled to aid in the execution of each droplet-impact event and the experimental measurements of the impact pattern.
4. Conduct a series of droplet impact studies. The primary measurements will be of the droplet impact speed and shape just before impact and the subsequent droplet-spreading event. Of particular interest will be the quality of the data. Every effort will be made to ensure that the system can create reproducible droplet impact data with minimal uncertainty. This will include measurements of droplet fluid properties, impact parameters, target surface parameters, and droplet spreading parameters. The goal is a relative uncertainty in the final data of about 3%.
5. Develop a set of simple experimental correlations that accurately fit the experimental data. These correlations will be simple enough to be used by forensic practitioners to accurately determine the droplet impact parameters from measurements of bloodstains. The data from these correlations will be used to reconstruct crime scenes from blood spatter evidence.
6. Prepare this work for publication in the fluid dynamics and forensics literature.

4) Numerical Work

The numerical work in this research program has produced a numerical simulation of high-speed droplet impact and spreading over a solid surface. The simulation was written using OpenFoam, an open source CFD code. This three-dimensional, time-dependent simulation assumes symmetry about the midplane and uses the appropriate fluid properties for a Newtonian blood simulant. One result for a 5° impact angle (measured from the vertical) is shown in Figure 3. This image shows a spreading droplet taken at a time near the point of maximum spreading. The red arrow in the figure is the projection of the impact velocity on the solid surface (not to scale). The larger spreading speeds (red color) and the thicker rim occur on the downstream side of the droplet (upper right side of the image). The central blue area is where the droplet has formed a thin layer of slow-speed liquid. This behavior has been seen in many other studies, such as Gordillo et al. 2019 and Eggers et al. 2010.

The model also predicts that after the droplet is fully spread it will retract and rebound from the surface, a behavior typically seen in high-speed droplet impact on hydrophobic surfaces (Yarin 2006). This behavior was not observed in our previous droplet impact experiments, (Lockard 2015 and Smith et al. 2015). The reasons for this rebound in the current simulation need to be explored and resolved before the model can be used for blood spatter predictions.

Figure 3: *The velocity magnitude in a fully spread droplet after impact on a planar surface with a 5° impact angle. The droplet is assumed to be symmetrical about the midplane. The red color on the rim of the droplet indicates a larger speed. The red arrow is the projection of the impact velocity on the solid surface (not to scale).*

At this point the project end date was reached and this phase of the project was halted.

An outline of any future numerical work for this project is as follows.

1. Resolve the rebound behavior seen in the OpenFoam droplet impact simulation.
2. Perform parameter studies to produce droplet spreading data for the same parameter ranges used in the experimental work.

3. Compare this data to the experimental data obtained earlier and to other experimental data sets found in the literature.
4. Extend the simplified droplet spreading model previously used by Smith et al. 2015 from 1-D to 2-D. Validate this model with both the experimental data from this program and the numerical data obtained from the OpenFoam model. The advantage of this simpler 2-D model is the ease with which it can be developed into an online tool for use by forensic investigators.
5. Prepare this work for publication in the fluid dynamics and forensics literature.

5) References

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PARTICIPANTS AND COLLABORATING ORGANIZATIONS

Individuals that worked on this project

Marc K. Smith, Co-PI

Contribution to project: Advisor for the numerical work and the overall execution of this project.

G. Paul Neitzel, Co-PI

Contribution to project: Advisor for the experimental work.

Grace Chambers, Graduate student

Contribution to project: Design, build, and test the experimental apparatus used for this project.

Ardalan Javadi, Research scientist

Contribution to project: Write the OpenFoam numerical simulation of droplet impact.

Other organizations that worked on this project

None

CHANGES IN APPROACH

The major change in approach for the experimental phase of this project was in the design of the droplet generator. The initial design was a blood simulant chamber with a small capillary tube inserted into the chamber from below. The blood simulant would flow into the capillary tube to form a liquid-air meniscus. When the chamber is struck from above, the resulting acoustic wave in the liquid would cause the meniscus to deform and produce a small liquid droplet that is ejected downward inside the tube and out into the atmosphere. A major design goal for this work was a relative uncertainty in the data of less than 3%. This goal calls for repeatable droplet ejection events to within this uncertainty.

The impact-driven droplet generator did not meet this goal and it even had difficulty reaching the droplet ejection speeds called for in this project. After three different design iterations to address this repeatability issue it was finally abandoned. The next attempt was a droplet generator based on laser-induced cavitation in the blood simulant. This design easily reached the required droplet ejection speeds, but it was abandoned because of the same repeatability issues. The final version of the droplet generator used a high-speed liquid jet that was acoustically excited to induce a capillary instability that enabled the formation of a stream of liquid droplets. When desired, an individual drop was electrically charged and deflected to the impact surface for observation and measurement. This droplet generator is described in more detail in Section 3 of the Project Summary above.

Much of the work described above was delayed because of COVID concerns in 2020-21. The student working on the experiments also had health issues and took time off in the Fall 2021 term. She returned in January 2022, but within a few weeks she resigned from the Ph.D. program. Plans to hire a short-time research engineer for this work did not succeed. As a result, the experimental phase of this work was stopped at the point described above.

The major change in approach for the numerical phase of this project was in the design of the numerical simulation. During previous work (Contract 2013-DN-BX-K003), the authors developed a single phase, compressible flow simulation based on a wavelet-adaptive multi-resolution method that ran on a GPU. The initial numerical work in the current project was to update the previous simulation with a dual time-stepping method to enable the simulation of an incompressible flow and then to include the level-set method to handle the multiphase aspect of the droplets. However, this work was abandoned when a research engineer with the appropriate skill set was not found. Instead, a new simulation was started in Fall 2022 using the open source CFD code OpenFoam. That work is described in more detail in Section 3 of the Project Summary above.

OUTCOMES

The major accomplishment of the experimental portion of this research project is the design of a droplet generator capable of delivering a single high-speed liquid droplet to strike a solid surface. This impact event serves as an experimental simulation of the creation of a bloodstain. A prototype of the design was built and it performed as described. Further work is needed to include the inclined impact surface and the laser-pulsed illumination system and video cameras for the data collection phase of this work.

The major accomplishment of the numerical portion of this research project is the building of a droplet impact simulation using OpenFoam, an open source CFD code. The simulation produces a reasonable droplet impact event up to the point of maximum droplet spreading. However, the droplet then rebounds from the surface, which has not been observed in earlier bloodstain problems. Further work is needed to address this rebound problem in the model and then to conduct data collection runs over the parameter range of interest to this project.

ARTIFACTS

No publications, conference papers, databases, or other products were produced during this project. No dissemination activities were conducted during this project.