DETERMINING WIND VELOCITY FROM IMAGES OF RAINDROPS

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DECLARATION

I hereby declare that the work in this study is my own except for quotations and summaries which have been duly acknowledged.

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KUHAN MUNIAM
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ABSTRACT

This study develops the method of determining wind velocity from images of raindrops. The motivation of this study was to develop a new method of finding wind velocity. In this new method, digital images or videos of raindrops are processed using computer stereo vision to extract information about the rain inclination. The rain inclination is the used to compute the wind velocity. The rain inclination changes with height (and time) due to acceleration from the force exerted by the wind on the raindrops. A simple experiment was conducted to demonstrate that it is possible to determine rain inclination from digital images. The inclination of falling water was found using two perpendicular two-dimensional digital images. This implies that it is possible to determine rain inclination from digital images. Some equations relating wind velocity and the trajectory of a raindrop are derived using Stokes’ Law. Extensive use of fluid mechanics is required to derive accurate equations. Some hypothetical setups of systems that use this method are described. Wind velocity can also be determined from stereoscopic videos of raindrop trajectory. Disdrometers may be used instead of digital cameras when applying this method.

Keywords: rain inclination, raindrop, wind velocity, camera, digital images, stereoscopic vision, computer stereo vision, epipolar geometry, wind force, disdrometer, pinhole camera model, fluid mechanics.

Kata kunci: kecenderungan hujan, titisan hujan, halaju angin, kamera, imej digital, penglihatan stereoskopik, komputer penglihatan stereo, geometri epipolar, daya angin, disdrometer, model kamera lubang jarum, mekanik bendalir.
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CHAPTER 1

INTRODUCTION

In an equatorial country like Malaysia, it rains throughout the year. Watching the rainfall is common. In this study, the researcher focuses on the relationship between rain inclination and wind velocity. The researcher describes a method of obtaining information about the wind velocity by analysing digital images of rain.

OBJECTIVES

The objective of this study is to present a method. Specifically, it seeks:

i. to develop a method of determining wind velocity from digital images of raindrops.

ii. to explore the potential applications of this method.

HYPOTHESIS

The velocity of wind can be determined from digital images of raindrops.
OPERATIONAL DEFINITIONS

i. RAINDROP
In this study, raindrop refers to a drop of water falling through the atmosphere.

ii. WIND VELOCITY
In this study, wind velocity is the speed and direction of air motion.

iii. DIGITAL IMAGES OF RAINDROPS
In this study, digital images of raindrops refer to two-dimensional (2D) pictures captured by digital cameras.

iv. VIDEO
In this study, video is considered to be many consecutive digital images taken within short period of time of each other.

v. RAIN INCLINATION
In this study, rain inclination is the angle between the instantaneous velocity of a raindrop and the vertical.
CHAPTER 2

LITERATURE REVIEW

According to The Free Dictionary, cant means the “angular deviation from a vertical or horizontal plane or surface; an inclination or slope.” (quoted from http://www.thefreedictionary.com/cant)

According to Wikipedia, “Computer stereo vision is the extraction of 3D information from digital images, such as obtained by a CCD camera. By comparing information about a scene from two vantage points, 3D information can be extracted by examination of the relative positions of objects in the two panels. This is similar to the biological process Stereopsis.” (quoted from http://en.wikipedia.org/wiki/Computer_stereo_vision)

“Epipolar geometry is the geometry of stereo vision. When two cameras view a 3D scene from two distinct positions, there are a number of geometric relations between the 3D points and their projections onto the 2D images that lead to constraints between the image points. These relations are derived based on the assumption that the cameras can be approximated by the pinhole camera model.” (quoted from http://en.wikipedia.org/wiki/Epipolar_geometry)

“The pinhole camera model describes the mathematical relationship between the coordinates of a 3D point and its projection onto the image plane of an ideal pinhole camera, where the camera aperture is described as a point and no lenses are used to focus light. The model does not include, for example, geometric distortions or blurring of unfocused objects caused by lenses and finite sized apertures. It also does not take into account that most practical cameras have only discrete image coordinates. This means that the pinhole camera model can only be used as a first order approximation of the mapping from a 3D scene to a 2D image. Its validity depends on the quality of the camera and, in general, decreases from
the center of the image to the edges as lens distortion effects increase.” (quoted from http://en.wikipedia.org/wiki/Pinhole_camera_model)

“A stereo camera is a type of camera with two or more lenses with a separate image sensor or film frame for each lens. This allows the camera to simulate human binocular vision, and therefore gives it the ability to capture three-dimensional images, a process known as stereo photography.” (quoted from http://en.wikipedia.org/wiki/Stereo_camera)

“Orthographic projection (or orthogonal projection) is a means of representing a three-dimensional object in two dimensions. It is a form of parallel projection, where all the projection lines are orthogonal to the projection plane, resulting in every plane of the scene appearing in affine transformation on the viewing surface.” (quoted from http://en.wikipedia.org/wiki/Orthographic_projection)

“In 1851, George Gabriel Stokes derived an expression, now known as Stokes' law, for the frictional force – also called drag force – exerted on spherical objects with very small Reynolds numbers (e.g., very small particles) in a continuous viscous fluid. Stokes' law is derived by solving the Stokes flow limit for small Reynolds numbers of the generally unsolvable Navier–Stokes equations:[1]

\[ F_d = 6\pi \mu R v_s \]

where:

- \( F_d \) is the frictional force acting on the interface between the fluid and the particle (in N),
- \( \mu \) is the dynamic viscosity (N s/m²),
- \( R \) is the radius of the spherical object (in m), and
- \( v_s \) is the particle's settling velocity (in m/s).

If the particles are falling in the viscous fluid by their own weight due to gravity, then a terminal velocity, also known as the settling velocity, is reached when this frictional force
combined with the buoyant force exactly balance the gravitational force. The resulting settling velocity (or terminal velocity) is given by:[2]

$$v_s = \frac{2}{9} \left( \frac{\rho_p - \rho_f}{\mu} \right) g R^2$$

where:

- $v_s$ is the particles' settling velocity (m/s) (vertically downwards if $\rho_p > \rho_f$, upwards if $\rho_p < \rho_f$),
- $g$ is the gravitational acceleration (m/s$^2$),
- $\rho_p$ is the mass density of the particles (kg/m$^3$), and $\rho_f$ is the mass density of the fluid (kg/m$^3$)." (quoted from http://en.wikipedia.org/wiki/Stokes’_law)

According to Beard, K.V. et al. (1982), in the study of “Raindrop Canting”, “a theory for canting has been developed from the response of raindrops to shear produced by homogeneous, isotropic turbulence. The model predicts small canting angles, with the tangent of the angle having a Gaussian probability distribution about a mean value of zero. Previous reports of large canting angles above the surface layer were based upon interpretations of microwave measurements which were found to be sensitive to the assumed drop shapes and size distributions. However, past measurements using a circular polarization radar technique, sensitive to canting but not to drop shapes and distributions, yielded a narrow distribution of canting angles with a mean near zero in agreement with theoretical expectations.”

“Wind-Driven Rain is described as raindrops falling through a wind field at an angle from the vertical under the effects of both gravitational and drag forces. Wind-driven raindrops gain some degree of horizontal velocity and strike the soil surface with an angle deviated from vertical. Additionally, the distribution and intensity of rainfall on sloping surfaces differs depending on wind direction and velocity.” (Erpul, G.; 2003)

Chandrasekar V. et al. (1989) wrote that “Two-dimensional PMS (Particle Measuring Systems, Inc.) probes are widely used in cloud physics research (Knollenberg 1981).
However, the application of advanced image processing techniques for hydrometeor feature extraction and image classification has not found widespread use in the context of 2D-PMS ages. Duroure (1982) used the method of Fourier descriptors (FD) to extract shape discrimination parameters of an image. Rahman et al. (1981a,b) developed classification methods for hydrometeors using statistical pattern recognition techniques. They found that incomplete images were difficult to classify. Chandrasekar et al. (1988, henceforth referred to as CCB) used FD methods to accurately compute axis ratios of raindrops imaged by a 2D probe with optical axis mounted horizontally rather than the conventional vertical orientation. Thus, raindrop images are elliptical rather than circular; the conventional circular images are frequently sized using the algorithm developed by Cooper (1980). Harris—Hobbs and Cooper (1987) classified raindrops and graupel particles using the cirmethod; i.e., a circle was fitted to the image perimeter and the variance of the measured data about the fitted circle was used for classification. Cooper et al. (1983) used a variant of this technique on elliptical raindrop images to estimate the canting angle of the image.

However, Chandrasekar, V. et al. (1989) did a study on “Fourier and Moment Methods Applied to Two –Dimensional Raindrop Images”. “Two-dimensional PMS precipitation probes mounted with horizontal optical axis have been previously used to study the shapes of hydrometeors such as raindrops and graupel. Fourier and moment descriptors have been applied to such images for the purposes of parameter estimation (axis ratio, canting angle) of raindrops, and for classifying raindrops in a raindrop/graupel mixture. Simulations have been used to evaluate these techniques. Their results show that axis ratios of raindrops can be accurately estimated using both Fourier and moment methods. They also show that the canting angle of the raindrop image can be accurately estimated using the moment method. Two image classification techniques were applied to data from below the melting level in a convective storm for classifying raindrops and graupel.”

In 1999, Helming, K. carried out a study titled “Wind Speed Effects on Rain Erositivity”. According to Helming, K., “The kinetic energy of rainstorms plays a paramount role in surface sealing, runoff, and erosion processes. Typically, the kinetic energy rate is calculated based on terminal velocity of vertically falling raindrops. Few studies have investigated the effect of wind speed on raindrop velocity, rainfall energy and on inclination angles of raindrops.” Helming, K. (1999).
The paper “reports an attempt to determine (i) the effect of wind speed on the kinetic energy of rainstorms, (ii) the relationships between rainstorm intensity and wind speed, and (iii) raindrop impact angle distributions with respect to wind speed, inclination angle, and soil surface geometries. Rainfall amount and wind speed were measured over 24 months. The kinetic energy and the inclination angle of the wind-driven rain were determined with trigonometric functions combining the horizontal wind speed with the vertical drop velocity. The distribution of raindrop impact angles was determined for various soil surfaces represented by digital elevation maps.

The results showed: 1) The rainstorm kinetic energy, determined with respect to the wind speed, reached a maximum of 3.5 times the value of the kinetic energy without the wind speed factor. On average, the portion of the raindrop energy derived from wind speed accounted to about one fourth of the total rain energy. 2) There was no association between rainstorm intensity and wind speed. 3) Soil surface roughness was more important for raindrop impact angle distribution than wind speed. The results suggest that wind speed has considerable effects on rainstorm energy, and thus impacts surface sealing and soil erosion processes.” (Helming, K., 1999)

Lynch, B. et al. (2011) wrote that “As a raindrop falls, it forms a shape different from popular belief; the resulting shape from all of the forces causes the raindrop to form almost a perfect sphere at diameters under 1.25mm and at larger diameters the sphere flattens out into an oblate spheroid which is somewhat similar in shape to that of a hamburger bun. When a drop reaches diameters above 8mm it starts to break up into smaller pieces therefore giving us a range up to 8mm for the starting diameter of a raindrop. As a rain drop falls, it attains a constant velocity where it experiences no acceleration. This is called terminal velocity, when the forces of gravity are opposed equally by the resistive forces on the raindrop.”

According to Schonhuber et al. (2000), “natural raindrops have a significant impact on polarisation properties of tropospheric wave propagation. Although analyses of differential weather radar returns have widely been investigated, interpretation of crosspolarreflectivities from rain still could be improved, if statistically reliable knowledge
on raindrops’ canting and orientation angles would exist. To the authors' knowledge up to now relevant observations had not been carried out under field conditions on a continuous basis. However, with a 2D-Video-Distrometer, an imaging precipitation gauge, measurements were performed, which allow the determination of raindrops' canting and orientation angles.”

Kruger A. et al., (2001) described the “design and operation of a two-dimensional video disdrometer (2DVD) for in situ measurements of precipitation drop size distribution.” “The instrument records orthogonal image projections of raindrops as they cross its sensing area”. It “can provide a wealth of information, including velocity and shape, of individual raindrops”. The Two-Dimensional Video Disdrometer (2DVD) “is a sensitive optical instrument that is exposed to rain, high humidity, and possibly high temperatures. These and other issues such as calibration procedures impact its performance. Under low-wind conditions, the instrument can provide accurate and detailed information on drop size, terminal velocity, and drop shape in a field setting, and the instrument’s advantages far outweigh its disadvantages”.

In 2006, Blocken, B. et al. did a study titled “On the validity of the cosine projection in wind-driven rain calculations on buildings”. From the study, “Wind-driven rain (WDR) is one of the most important boundary conditions governing the hygrothermal performance and the durability of building facades. Information concerning the quantity of WDR falling onto building facades is an essential requirement as a boundary condition for Heat-Air-Moisture transfer analyses and for building facade design. The WDR relationship is most often used. It applies the cosine projection to take into account the effect of varying wind direction on the WDR quantity or intensity. In the recently developed numerical simulation methods, it is tempting to apply the cosine projection to reduce the computational expense. In this study, the validity of the cosine projection is investigated based on 3D numerical simulations of WDR with CFD. It will be shown that the cosine projection, although generally accepted, is not strictly valid and that it can give rise to significant errors.”
Another study was done in the 21\textsuperscript{st} century on raindrops by Bringi, V.N. (2008). It “presented the canting angle distribution of raindrops derived separately from a 2D video disdrometer and from an S-band advanced polarimetric radar. In the former case, measurements were made in both natural and artificial rain. The canting angles showed a symmetric distribution about 0deg with a standard deviation (\sigma_{\beta}) of 7deg-8deg in low wind conditions and 12deg in moderate wind conditions. In the radar-based estimates, the histogram of \sigma_{\beta} derived from data obtained during a light stratiform rain event with embedded convection shows the mode to be around 7deg, with a significant positive skewness. Around 16\% of occurrences exceeded 10deg and 3.3\% exceeded 15deg.”

Lynch, B. et al. (2011), in his study on “Modelling the velocity of a raindrop” created a mathematical model of a falling raindrop and derived the motion of the raindrop as it is affected by air resistance. The researcher took the non-spherical shape of the drop into consideration to produce an accurate model.
CHAPTER 3

METHODOLOGY

Primary data was obtained from observation, experimentation and formulation. The researcher observed rain and noticed that the orientation of the observed raindrops changed when looking from left to right. The researcher conducted an experiment on deriving inclination of falling water from digital images. The researcher also derived some basic formulae which describe the trajectory of raindrops.

Secondary data on the topic of raindrops were gathered from reference books, journal articles, seminar papers, published theses, newspapers and the like.

SCOPE AND LIMITATIONS

The scope of this study is general. It can be applied in any part of the world.

This study is based on researcher’s observation, library research and the internet. It only applies to two-dimensional digital images.

A limitation on this study is the limited time available to complete it and the dry weather during the period of time available to complete the study which caused the author to be unable to produce experimental data using digital images of rain.
THE EXPERIMENT

An experiment was conducted to demonstrate the method of finding the inclination of falling water from digital images. The materials used were a water hose, a tap, some water, and a camera.

Image capture

Two perpendicular walls as shown in Figure 1 were chosen as the location for the experiment.

Figure 1: Two perpendicular walls were chosen as the location for the experiment.

Two digital images of water falling from a hose are taken perpendicular to each other as shown in Figure 2 and Figure 3. Figure 2 shows the first setup, which is denoted as setup $\alpha$ and Figure 3 shows the second setup, which is denoted as setup $\beta$. In each setup, the hose had a unique position. Thus, the inclination of the falling water was different at the fixed height above the ground at which it was computed.
Figure 2: Two digital images of water falling from a hose in setup $\alpha$ are taken perpendicular to each other.

Figure 3: Two digital images of water falling from a hose in setup $\beta$ are taken perpendicular to each other.
Image analysis

The digital images are then analysed to find the inclination of the falling water as shown in Figure 4 and Figure 5. When analyzing the images of the falling water, it is assumed that the digital images of the falling water are orthogonal projections of the falling water. Thus, epipolar geometry is not used in the computations involved in the image analysis. The digital images were printed and measurements were made on the printed images using a ruler to determine the lengths of some sides of the triangle formed by the vertical, the horizontal and the gradient of the water falling from the hose. The measurements were recorded on the digital image using a computer. The length of the vertical and horizontal sides of the triangles in each image was measured. Uncertainties are not included in measurements and calculations. Thus, it is assumed that all measured and calculated values are exactly correct.
Figure 4: Image analysis of images of setup α.
Figure 5: Image analysis of images of setup $\beta$. 
Calculation and Formulations:

The angles $\alpha_1, \alpha_2, \beta_1$ and $\beta_2$ are calculated as follows.

\[
\alpha_1 = \tan^{-1}\left(\frac{1.2}{5.2}\right)
\]

= 0.227 rad

\[
\alpha_2 = \tan^{-1}\left(\frac{0.5}{3.9}\right)
\]

= 0.128 rad

\[
\beta_1 = \tan^{-1}\left(\frac{1.2}{4.7}\right)
\]

= 0.250 rad

\[
\beta_2 = \tan^{-1}\left(\frac{0.5}{3.1}\right)
\]

= 0.160 rad
A schematic diagram showing the components of the inclination and the velocity vector components of the falling water is shown in Figure 6.

Figure 6: Schematic diagram showing the components of the inclination and the velocity vector components of the falling water.
Next, the inclination of the falling water in setup α, which is the resultant angle, $\alpha_r$ formed by the angles $\alpha_1$ and $\alpha_2$ is found.

A geometric interpretation of the angle $\alpha_r$ is shown in Figure 7.

![Figure 7: The geometric interpretation of the angle $\alpha_r$.](image)

The derivation of the angles $\alpha_r$ and $\beta_r$ are as follows.

\[
\sqrt{(X^2_{\alpha} + Y^2_{\alpha})} = H \sqrt{(\tan^2 \alpha_1 + \tan^2 \alpha_2)}
\]

\[
tan \alpha_r = \frac{H \sqrt{(\tan^2 \alpha_1 + \tan^2 \alpha_2)}}{H} = \sqrt{(\tan^2 \alpha_1 + \tan^2 \alpha_2)}
\]

$\alpha_r = 0.259 \text{ rad}$

Similarly, it can be shown that

$\beta_r = \tan^{-1} \sqrt{(\tan^2 \beta_1 + \tan^2 \beta_2)}$

$= 0.2933 \text{ rad}$
Discussion

The experiment demonstrates the method of finding rain inclination from digital images. The method of finding the inclination of falling water from digital images can be applied to other falling fluids and not just raindrops. This method uses the two perpendicular orthogonal projections that the falling water forms in the image to derive the inclination of the falling water. It can be applied to raindrops to find the rain inclination from digital images.

This method uses computer stereo vision. ‘3D information is extracted from digital images taken from two vantage points by examining the relative positions of the objects in the two images.’ (paraphrased from http://en.wikipedia.org/wiki/Computer_stereo_vision)
A schematic diagram of using orthogonal projections to find the inclination of falling water is shown in Figure 8.

Figure 8: Schematic diagram of using orthogonal projections to find the inclination of falling water.
Derivation of equations relating wind force and the trajectory of raindrops:

When deriving the wind velocity from the rain inclination, equations relating wind force and the trajectory of raindrops are needed. This is because wind velocity is related to wind force (and the characteristics of the raindrop, such as mass, diameter, shape and canting) and the rain inclination is related to the trajectory of the raindrops (the function describing the rain inclination is the gradient function of the function describing the trajectory of the raindrops.) These equations are then derived with the assumption that the raindrop obeys Stokes’ law and that the only forces acting upon the raindrop are the drag force, gravitational force and force exerted by the wind on the raindrop. Since Stokes’ law was used in deriving the equations relating the trajectory of the raindrop and the force that the wind exerts on the raindrop, the assumptions made by Stokes’ law apply to the derivation of the equations.

“Stokes' law makes the following assumptions for the behavior of a particle in a fluid:

- Laminar Flow
- Spherical particles
- Homogeneous (uniform in composition) material
- Smooth surfaces
- Particles do not interfere with each other.”

(quoted from http://en.wikipedia.org/wiki/Stokes'_law)

It is also assumed that the raindrops are “spherical objects with very small Reynolds numbers (e.g., very small particles) in a continuous viscous fluid.” (quoted from http://en.wikipedia.org/wiki/Stokes'_law)
The following assumptions are also made: “the raindrop fell from a cumulonimbus cloud at low altitude and therefore the changes in air pressure, air density and gravity are ignored. The raindrop is also falling with other drops and therefore the surrounding humidity is high enough that the evaporation of the raindrop as it falls will be negligible and therefore ignored.” (quoted from Lynch, B. et al., 2011)

Figure 9 shows a force-body diagram of the forces acting on the raindrop.

![Force-body diagram of the forces acting on the raindrop.](image)

\[
\sum \vec{F} = m\vec{a}
\]

\[
\sum F_x = F_d \sin \theta - F_{\text{wind}} = ma_x
\]

\[
\sum F_y = F_d \cos \theta - F_{\text{wind}} = ma_y
\]

From Stokes’ law,

\[F_d = 6\pi \mu R v_s\]

“where:

- \(F_d\) is the frictional force acting on the interface between the fluid and the particle (in N),
- \(\mu\) is the dynamic viscosity (N s/m²),
- \(R\) is the radius of the spherical object (in m), and
- $v_s$ is the particle’s settling velocity (in m/s).” (quoted from http://en.wikipedia.org/wiki/Stokes'_law)

Thus, we get the equations describing the relationship between the trajectory of the raindrop and the force that the wind exerts on the raindrop.

\[
\frac{d^2x}{dt^2} = \frac{6\pi\mu R v_s \sin \theta - F_{\text{wind}}}{m}
\]

\[
\frac{d^2y}{dt^2} = \frac{6\pi\mu R v_s \cos \theta - F_{\text{wind}}}{m}
\]
We can use digital images obtained from a stereo camera to find the rain inclination. Thus, a system involving a stereo camera may be used compute wind velocity. The images from the stereo camera are processed using computer stereo vision to obtain the rain inclination. ‘The stereo camera provides two digital images from two vantage points. 3D information (the rain inclination) can be extracted by examination of the relative positions of objects in the two images.’ (adapted from http://en.wikipedia.org/wiki/Computer_stereo_vision)

Wind exerts a force on raindrops. Wind has different velocities at different heights. So, the force that the wind exerts on the raindrops varies with height. During a raindrop’s trajectory, the varying force exerted by the wind will cause the raindrop to accelerate in varying directions. The acceleration is equal to the rate of change of velocity with respect to time. The force that the wind exerts on the raindrops depends on factors such as the shape of the raindrop and the wind velocity.

If data on raindrop shape, velocity and trajectory is gathered from a stereo camera, the wind velocity can be computed. Trajectory of the raindrop is recorded by stereo cameras to and data about the rate of change of velocity with time is calculated from the trajectory of the raindrop. Usage of high quality cameras allows for the determination of raindrop size, shape, canting and trajectory from the digital images.

Formulae need to be derived to find accurate relationships between the characteristics of raindrops, such as size, shape, and canting, and the flow of wind around the raindrop. Then, equations describing the relationship between the wind velocity and the force exerted by the wind on a raindrop should be found. The information obtained from the raindrop would be sent to a computer which would compute the wind velocity from the characteristics of the raindrop. Once these equations are derived, the method of determining wind velocity from images of raindrops will become possible.
The wind velocity does not have to be calculated over a large height. Thus, a camera system may be placed close to each other and compute the wind velocity from the small change in velocity of the raindrop over the small height. The camera must have high resolution so that these small changes can be computed precisely. In addition, a more precise method would be for the camera system to actually measure the velocity of the raindrop continuously during its trajectory.

An ideal working system using this method would use stereo cameras to record a video of the trajectories, diameter, size, shape and velocity of falling raindrops. It would use computer stereo vision to ‘extract 3D information from digital images’ (paraphrased from http://en.wikipedia.org/wiki/Computer_stereo_vision) and epipolar geometry to accurately compute the measurements of the raindrops. It would then compute the wind velocity using the information obtained from the video.
A similar system would use 2D video disdrometers to determine the rain inclination and to obtain other information about the raindrop at different heights. The information can then be computed to find the wind velocity.

Figures 10, 11, 12 and 13 illustrate several setups which use cameras to determine wind velocity. The cameras in Figures 10 and 12 capture digital images of raindrops, whereas the cameras in Figures 11 and 13 capture digital images of water falling from a dripper. In Figures 11 and 13, wind is allowed to travel between the roof and the cameras so that the trajectory of the water falling from the dripper will change due to the force exerted by the wind on the falling water. The benefit of using drippers and roofs instead of relying on raindrops is that the setups can be used to measure wind velocity in non-rainy weather. The digital images of the camera must be sent to a system which can compute the wind velocity from the digital images. The setups in Figures 10 and 11 use perpendicular cameras, while the setups in Figures 12 and 13 use side-by-side cameras (each camera in Figures 12 and 13 may be individual digital cameras or may represent a lens of a stereo camera with two lenses).

Figure 10: Setup using perpendicular cameras without roof.
Figure 11: Setup using perpendicular cameras with roof.

Figure 12: Setup using side-by-side cameras without roof.
Figure 13: Setup using side-by-side cameras with roof.
CHAPTER 5

CONCLUSIONS

SUMMARY OF FINDINGS

The findings of this study reveal the method of determining wind velocity from images of raindrops. The study also demonstrates that it is possible to determine rain inclination from digital images. Usage of stereo cameras to determine wind velocity is also possible.

RECOMMENDATIONS FOR FURTHER RESEARCH

Further research into use of this method to produce accurate and reliable wind data should be done because:

1. This method may be integrated with future or current technologies of determining wind velocity. For example, stereo cameras may be used to obtain wind velocity. 2D video disdrometers may be used instead of digital cameras to find the rain inclination.

2. This method is a pioneer: we should take into account that the other methods of obtaining wind data such as those used by aircraft are older and thus have been refined for increased accuracy. Thus, we may similarly expect that further research on this method may make it competent, if not better than current methods of obtaining wind data.
Applications of this method include the following:

1. To create a program which can determine the direction and magnitude of wind by calculating the angle of raindrops on two-dimensional photographs obtained from digital cameras. A diagram of the function of the program is shown in Figure 14.

![Diagram showing the function of the program](image)

Figure 14: A schematic diagram illustrating how the program would work.

2. By matching up wind velocity and location data from digital images with information stored in weather databases, the time that the picture was captured may be known. Weather databases can store information about the movement of wind in different locations.

3. Extensive use of fluid mechanics is required to derive accurate equations which describe the relationship between wind velocity, the characteristics of a raindrop and the rain inclination. More research has to be done to find these accurate equations.
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