

Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer

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Week – 06

Lecture - 27

Depth from Defocus – 1

Hello, everyone. In this part of the course, we will discuss a technique known as depth from defocus. So this, as the name suggests, we will try to extract information from the extent of defocusing that is captured in an image. So this is basically an image-imaging based technique, and it has a lot of applications. But we will be focusing on a very particular application that is related to a measurement made frequently in the context of fluid mechanics. So, before diving deep into the technique that is depth from defocus, we will first try to understand the fundamentals of how a blurred image is formed.

Introduction

What is Image Blurring?

- Loss of sharpness or **detail** in an image.
- Commonly caused by limitations in the optical system or motion.

Applications and Challenges

- Image restoration, medical imaging, photography, etc.
- **Quantitative measurement from experimental images.**

Original Image (Left) Vs. Gaussian Filtered Image (Right)



With the advent of modern cameras that are easily accessible to everyone in the world, like each and every smartphone nowadays that consists of a very powerful camera, I think everyone in the world is now aware of terminologies like in focus, out of focus, or blurred images. From a general intuition, one can say that blurring relates to the loss of sharpness or details in any image. A scene, when captured, if it is blurred, then there is a loss of information; there can be many reasons for this blurring, some of which we will discuss. Apart from this, if you want to extend this idea of blurring or deblurring, it relates to image restoration.

One of the relatable examples could be security surveillance; apart from that, there is a

wide spectrum of applications. Medical imaging photography even includes astrophysical images that are captured at astronomical scales. So there is this restoration of information from a blurred image; a blurred signal is something that is very important. A natural extension of this idea, being a fluid mechanics person, is to estimate and establish quantitative measurements from blurred experimental images. So, as I discussed in the last slide, there can be a lot of reasons for blurring to happen.

Introduction



What is Image Blurring?

- Loss of sharpness or **detail** in an image.
- Commonly caused by limitations in the optical system or motion.

Types of Image Blurring?

Source: Zhang et. al, Int J Comput Vis, 2022



(a) Camera shake blur



(b) Out-of-focus blur



(c) Moving object blur



(d) Mixed blur

Defocus Blurring

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So, some types of image blurring I am depicting here are just to make you realize that you must have seen these kinds of images, but I just want to emphasize the reason behind this kind of blurring. So, the first image here, if I can just put on my pointer, is because of the camera shake blur. So, as the name suggests, this is because you shake your camera just before capturing an image. And this is one thing we all have experienced because of our shaky hands, or maybe we are sitting on a boat trying to capture a beautiful scene or something like that. And so you will see that, okay, things kind of look hazy.

Maybe there is a directionality in that haze. So, that is one kind of blurring that we are all familiar with. This second kind of blurring, which is actually what we are more interested in in this course, is this out-of-focus blurring or defocus blurring. So, this is related to the fact that when you have an optical system or a camera trying to capture an image, we all know from basic ray optics or even from intuition that there is a specific region where things look sharp and crisp spatially. In front of the camera, there is a particular kind of plane over which, if you place something, it will look very crisp; but if you move that object away from that plane, towards the camera or away from the camera, keeping the camera fixed, it will not.

You will see that it becomes more and more blurred, so you can also control the extent of blurring, like how it changes as you move away from that plane. But there is always a

blur, and this is known as out-of-focus blur, so this is also a very common kind of blurring. I think most of the people might be aware of it. We will discuss why this happens, and how we can then use the information about what kind of information is available in such blurred images to get some quantitative estimates. So, that will be the major focus of this part of the course.

Then there is this third kind of blurring, which is this moving object blurring or motion blur. This is also a very common form of blurring. If you can see here, this bus is moving in the right direction, and in the direction of motion, you will see the streaks. So here, most artists even use this effect to depict motion. But sometimes, this is not necessary.

We want to avoid it, especially in the case of experimental imaging. Say you have an object. If you want to track an object by capturing a sequence of images and then tracking where it went through that sequence of images. But if this streak is formed because, say, the object is moving at extremely high speed, then a streak will be formed, and it becomes very difficult to define where the object was because the streak is like a hazy blur, which makes things challenging in certain ways. Artistically, it looks good; then there is this mixed blurring, where there can be multiple modes of blurring superimposed.

Say you have a defocused scenery. So what you are trying to capture is not in your plane of focus. Then you also shake your camera, and maybe the objects are even moving. So I think this is a perfect picture depicting all of them. And there can be even more categories of blurring that I am not explaining here.

But these are the basic categories, I think, to which everyone can relate. And some of them we even try to avoid in experiments, like we try to avoid this camera shake blur and the moving object blur. Depending, or obviously depending on the context of the problem, this is something that is very important, and this out-of-focus blur, or the defocus blurring, is something that we will focus on mostly. So, one of the motivations for the implementation of this technique would be dispersion side measurement. So, by dispersion, we mean particles dispersed in a fluid phase.

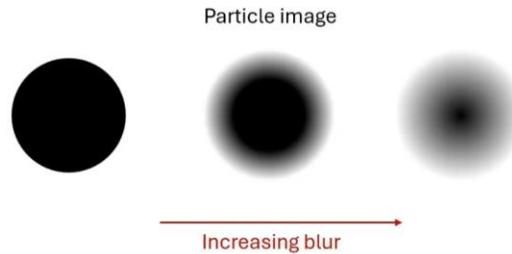
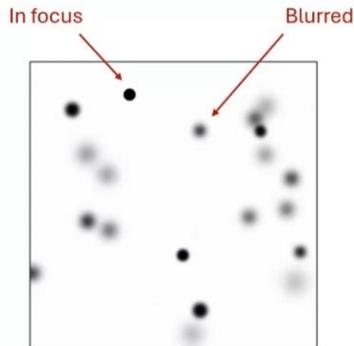
Motivation – Dispersion size measurement



Dispersion?

- Particulate entities dispersed in a fluid phase

- Liquid in gas – Droplets
- Gas in liquid – Bubbles
- Liquid in liquid – Emulsions
- Solid in gas – Dust
- Solid in liquid – Colloids
- Solid on Solid – Target dots/Pattern



Source: Xu et. al, EXIF, 2024

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And by particles, it's still not a very strict definition because in a conventional way, by particle we mean solid particles, but here particle means discrete isolated objects. So it can be like a dispersion of liquid in a gas, which are droplets or sprays, or gas in a liquid, which are bubbles, or liquid in a liquid, which are like emulsions where both of these liquids are usually immiscible. Or you can have solids in gas like dust or like these kinds of pollutant particles in the air. You can have solids in liquids, like colloids, such as mud or some slurry, in a particular concentration limit, but something like that. You can also have solid on solid, which is kind of unconventional.

So it can be a textured pattern. So you can have a speckled or dotted pattern over a surface. So it is also kind of a solid entity dispersed over a surface, something like that. And here is one demonstrative image of droplets dispersed in a volume. So it is an image of a spray.

So you can see, depending on the position of these spray droplets, it can either be out of focus. So this spray droplet is in focus. Because it aligns with the plane of focus of the camera. But this is way beyond that, and that's why it looks blurred. These are even further apart from the plane, and that's why they look extremely blurred.

So you can see here that each of these droplets or particles is blurred by a different degree of blurring. And that is represented here. This is a particle image when it is in focus, and when you move that particle away from this plane of focus, you see that it becomes more and more blurred. So clearly, here, if you want to extract the size of this particle, it's pretty easy; you can use a lot of image processing algorithms to estimate the size of this particle. I will just say two approaches, two of them: one is.

You can directly enclose this within a rectangle or square, whatever, and you can then just estimate the distance from this point to this point or this point to this point, and that will give you a diameter. Another approach is estimating the area, and then knowing that this is kind of a circle, you can use the formula for the area of the circle to estimate its radius or diameter. Because there is a sharp interface here, things are easy. But there is no sharp interface here.

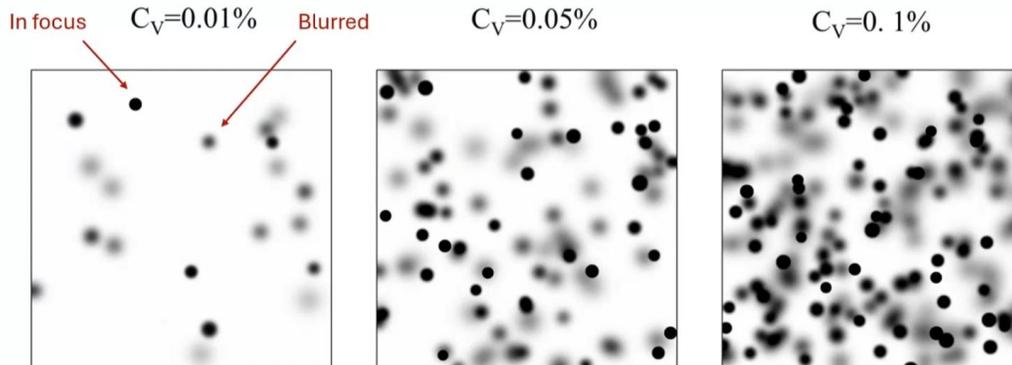
It's a gradual variation. So where should you take that size? Then, that's a challenge. And as you increase the blur, it becomes even more challenging. And it becomes even more challenging if you simply increase the volumetric concentration of the droplets or, basically, if you have a denser spray or dispersion. So clearly here, these particles are sparsely spaced. But here you can see that there are these overlapping images, so that itself is a different category of challenge altogether.

Motivation – Dispersion size measurement



Dispersion?

- Particulate entities dispersed in a fluid phase



Source: Yuet et al. EFM 2024

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However, we will focus on this part of the problem: identifying the size. So that is the final goal: identifying the actual size of this blurred particle and estimating where it lies in the depth direction. That is the motivation. Here are some of the ideas for which this problem of estimating the dispersion size is relevant. So the first problem is actually something that I am working on.

So here we see the secondary atomization of a droplet because of shock waves, and you can see it generates a lot of tiny droplets; from this image, it definitely cannot be measured. So we take images at slightly higher magnification and then, as I have shown in the last slide, the dispersion of particles in the volume; there you will have some particles in focus and most of them not in focus. These kinds of depth from defocus

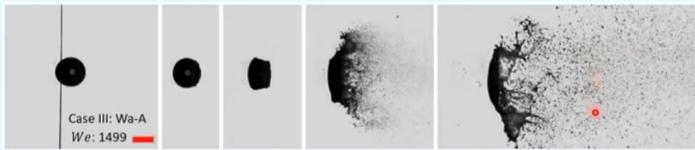
arrangements are extremely important to measure sizes. Here are also other applications, like fuel injection or droplets generated. Rupturing a bubble, when a bubble ruptures, leaves a trail of droplets; it is also very difficult to measure these sizes because it leaves a tail as it moves in and out of the plane of focus, so there are a lot of droplets that are not in focus.

Motivation – Dispersion size measurement



Fluid Mechanics

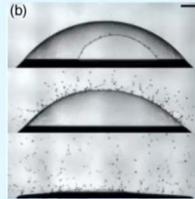
Shockwave droplet interaction



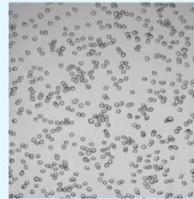
Fuel injection in supersonic flow



Surface bubble rupture

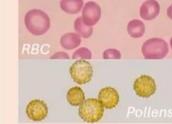


Bubbly flows

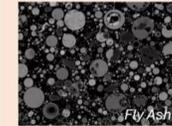


Other fields

Microbiology



Powder



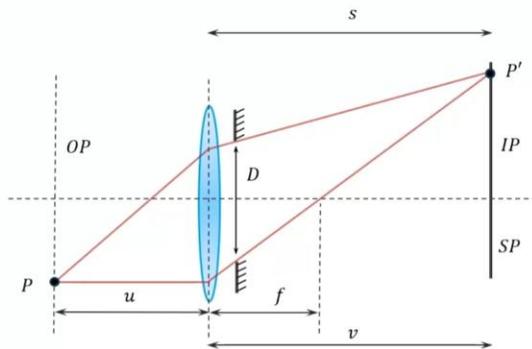
Computer Vision



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Then you can also have bubbly flows, biological entities dispersed in a fluid medium, or powder or particles dispersed in air or liquid. Then you can have these target dots on a surface that is 3D. So you have a depth effect. So if you take a normal image with focus on this surface, you will find this surface to be blurred and the other surfaces to be blurred. So this kind of scenario keeps on repeating in a lot of problems where we want to estimate either size or depth, or both of these dispersed entities.

Hence, we want to develop a technique that makes this easier. So, now let us dive into the fundamentals of image formation through ray optics and then extend these ideas to how a blurred image is formed. So, that is how we are depicting image formation through a schematic here. So there are a few major components associated with this; this depicts basically an imaging system. You have a lens, an aperture coupled with the lens, an opening diameter of d for this aperture, and then you have a sensor plane.



- Light rays passing through a lens form an image on the sensor.
- *OP* – Object Plane
- *IP* – Image Plane
- *SP* – Sensor plane
- Thin lens formula

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$
- Aperture limits the cone of light that passes through the lens.
- A **point** source *P* forms a **point** image *P'*
- This means *P* is in **focus**.
- *IP* and *SP* aligns.

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Basically, this consists of an array of sensors that receive the light signals and convert them into a digital signature. which is then finally converted into an image that we can see on our computers or digital devices. And then there is one more thing called the image plane. So basically, this is the plane over which the image is formed. Then you have this plane called the object plane, the plane over which the object is placed or the plane of focus.

So, basically, we will use this interchangeably. We consider a point source for simplicity and clarity. Usually, all the objects that we see are clusters of point sources. You can imagine it that way. So this *P* is a point source, and you can see we can trace rays, and these rays intersect at this point *P'*.

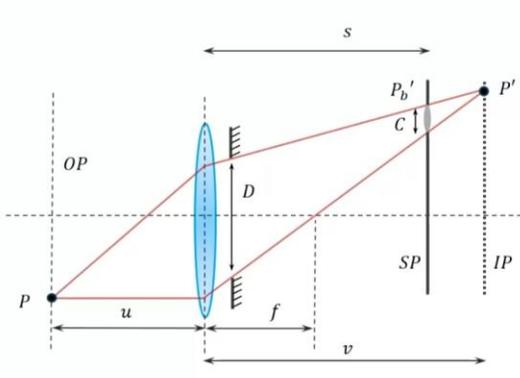
So this *P'* is your image for this object *P*, and this lies on the imaging plane, which is exactly aligned with your sensor plane. By this, we mean that this system is configured in a way that point *P* is in focus and forms the image exactly on the sensor plane, so that whatever image is being captured by the camera is in focus. There are also these other terminologies that I'll just reiterate; this is something you already know from the basics of optics, but I'm just reiterating because that makes things easier. So then there is this distance of the object from the lens *U*, the distance of the image from the lens *V*, the distance of the sensor plane from the lens *S*, and the focal length of the lens. These are the basic terminologies that are clear.

Now we will talk in terms of things being in focus or not being in focus. So, first of all, what is the role of aperture? Aperture limits the light, the cone of light that will pass through. So basically, these two look like a line, but if you can imagine this in a three-

dimensional way, the lens is circular and the aperture hole is typically circular. So this will form, these are just the two lines for the part of the cone that will pass through the aperture. If you reduce the aperture, this cone will become shorter, and we will discuss that.

Just in a few slides, apart from that, these terms are related by this thin lens formula, so this will be very useful in a lot of discussions that we are going to have. The only thing that is important here is that a point source generates a point image, so that tells us that point P is in focus for this system as the imaging plane and the sensor plane align. Now we will start making our camera like the configuration of our camera or the object; it's just a relative configuration, and see how things turn out to be. So the first thing that we will do is just adjust the camera focus. What do I mean by adjusting the camera focus? I am just modifying this parameter.

Shifting the sensor plane – adjusting camera focus



- IP and SP not aligned.
- A point source P forms an image P'_b spread over a circle.
- This is called a blur circle.
- This means P is **out of focus**.
- From geometrical similarity

$$\frac{D}{v} = \frac{C}{v - s}$$

- **Larger C, higher blurring.**

So whenever you try to say if you have a DSLR and adjust the focus of the camera, you are basically changing the relative orientation of the lens with respect to the sensor plane. So what you are changing is this parameter S. It can be more complicated than this, but in a very simplistic way, you can say that you are changing the S. So what happens now is that the imaging plane still remains the same as it was in the previous slide. So the image still forms at this distance v, but now you have shifted your sensor plane to this new position with a new s.

Okay, so now you can see that this imaging plane and the sensor planes are not aligned, and what your sensor will now capture is not a point; it will capture a circle, because this is a cone. I explained it in the last slide, right? So, as this is a cone, a plane cutting the cone will be a circle here. So this circle is now representative of the blur because your object is a point source, but now that information is spread out over a circle on the sensor

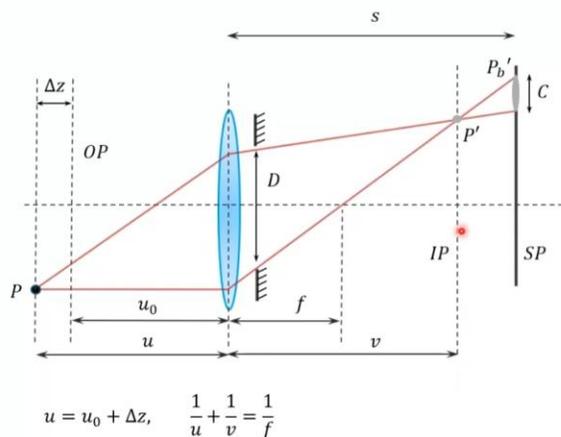
plane, so the image that is being captured in the camera will have blurring. Here, this smearing out of information or smoothing out of information is related to blur. So, that is what we will define as blurring the spread of point zone information over a circle.

This circle is known as a blur circle or circle of confusion, and there is a lot of terminology for this, but we will call it a blur circle in this course, and this kind of configuration now tells us that P is out of focus. So, what this means is that as we have changed S, there is a different U now for which the P will be in focus. So, basically, you have to shift P in this Z direction. So, this axis is the z direction. So, you have to shift P in the Z direction to adjust the focus now.

From simple geometric similarity, you can actually correlate these terms. This comes from the fact that this bigger triangle and this smaller triangle are similar. You can apply simple geometry to get this. I will not be explaining that in detail, but it is a simple exercise that you can try. Now, as I have discussed, if the C is larger, the size of this blur circle is larger, and the blurring will be higher.

So, basically, more is the spread of that point information over a larger area. So, it will be blurrier. So, it can be clearly deduced from the intuition. Now, let's go back to the first step and instead of modifying the relative orientation of the lens with respect to the sensor, what if we shift the particle away from the plane of focus so this OP actually represents the plane over which the particle was in focus in the earlier configuration, but we shifted that particle away from this plane by our distance Δz ? So clearly now we have changed u, so v will also change, or the plane over which the image will form will change. But as we are not shifting our sensor plane, there is a mismatch between the imaging plane and the sensor plane, so the system is again not in focus.

Shifting the point P – Object depth effect



- IP and SP not aligned.
- A point source P forms an image P'_b spread over a circle.
- This is called a blur circle.
- This means P is out of focus.
- From geometrical similarity

$$\frac{D}{v} = \frac{C}{s - v}$$
- Larger $|\Delta z|$, higher blurring.

You can see that these rays, after forming an image here, will cross each other and lead to the formation of a circle, as we have seen in the earlier case as well. So this lateral shift of the particle in the optical axis direction, which we will mark as Z , leads to a blur circle formation, and again a point source forms an image that is spread over a circle, and we call this again a blur circle, and this means that the image is not in focus. Here again you can use geometric similarity between this triangle and that triangle. To reduce this relation, which looks very similar to the previous relation, and from intuition, we already know that increasing this Δz or moving away in the depth direction from this object plane leads to more blurring, and by more blurring, we mean a higher value of c . So, now we will try to reduce the relationship between this Δz and this blur circle diameter c .

Here, we will mostly invoke the thin lens formula to reduce that. So, in the initial configuration, when things were in focus, we had this formula where the image forms for $v = s$ and $u = u_0$, and we can substitute to get this formula; in the modified configuration, where the particle is shifted by Δz , we have u equal to $u_0 + \Delta z$, as you can see geometrically here. And substituting that in the sine lens equation, we get something like this. Now, from geometrical similarity, we can write d by v like this formula. I just have mentioned "mod" here because you can see in the last two configurations, in one of the cases we got $s-v$, and in the other we got $v-s$.

Shifting the point P – Object depth effect

$\frac{1}{u_0} + \frac{1}{s} = \frac{1}{f}$, $u = u_0 + \Delta z$, $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

- From geometrical similarity

$$\frac{D}{v} = \frac{C}{|s - v|}$$
- Combining and simplifying

$$C = \frac{DM}{f} |\Delta z|$$
- Where M is the magnification

$$M = \frac{v}{u}$$

So actually, it is much more. It is practical that we put a mod sign here, and then even if you change s without changing the even for when Δz is 0, you can still implement this formula. So, this is a more generic formula. So what we will do now is use this relation and these three relations, combine them, and rearrange them to get something like this. So this is something that I want you to do as an exercise because this is just simple algebra, nothing else. The only thing that was invoked here is this parameter m , which is nothing but magnification, and you must now know from simple ray optics or geometric

optics

that

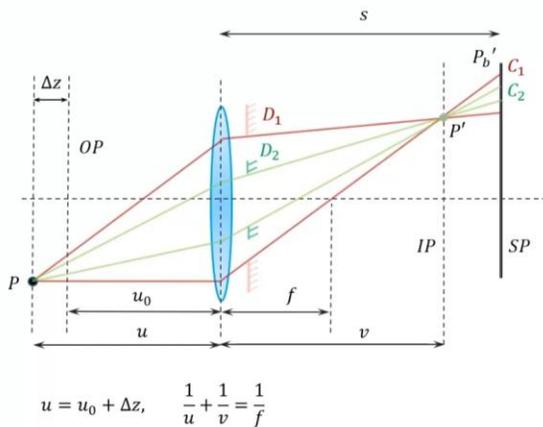
$m =$

$$\frac{v}{u}$$

Because of this mod sign that we have kept here, we get this mod sign here still preserved. So this is a very important relation which relates your blur circle diameter c with. The aperture diameter d , as well as your depth Δz , is a very significant equation that will play an important role when we are trying to deduce Δz from images; this actually tells us the way in which things will progress. We will try to estimate this c in some way from the images of blurred particles, just for example. Blurred particle images, and we will try to use that to reduce Δz and somehow also use this information to reduce the actual size of the particles or droplets.

So, that is the motivation, and I want to re-emphasize that this equation is really important. Now, with the same previous configuration, let us see the effect of aperture size on the blur circle. So here you can see that there are two aperture sizes that we have considered for the same configuration in which the particle has an offset from the object plane. In the first case of the aperture diameter D_1 , which is larger, if we trace these led lines that represent the ray of light, you can see that it leads to the formation of a blur circle with a diameter of C_1 . If we reduce the aperture size, what happens is that we are reducing the cone of light that is passing through.

Shifting the point P – Aperture effect



- IP and SP still not aligned.
- The blur circle size changes as Aperture changed.
- The extent of **out of focus** affected.
- From geometrical similarity

$$\frac{D_i}{v} = \frac{C_i}{|s - v|}$$

$$\frac{C_2}{C_1} = \frac{D_2}{D_1}$$

- **Smaller aperture, less blurring**

So although all the other parameters are not changed, you can clearly see that u_0 , u_f , and v — all these parameters are not getting changed because of the change of the upper aperture diameter. However, you can clearly see that as the cone of light passing through the aperture has reduced, the blur circle diameter has also reduced. So clearly, for a larger aperture, we see that the blur circle diameter is large. For a smaller aperture, we see that the blur circle diameter is small; what it tells us is that for the same shift, Δz , if you have

a smaller aperture, the amount of blurring will be less. So, this is very crucial information, and if you have ever used a DSLR, you know that you can adjust the aperture.

To change the depth of field. So, depth of field is something that is related to this. So, this is something that explains what I will come to later. But here, clearly, aperture affects the amount of blurring, and a smaller aperture means less blurring. Using the earlier equation that we have derived, we can actually correlate this blur circle diameter with the aperture diameter. We see it is directly proportional because v , s , and all these other parameters are not changing.

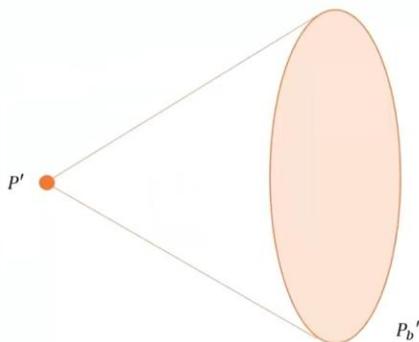
It clearly tells us that this relation will come from this, and this is also an important relation used in two-camera depth from defocus approaches, where you take two simultaneous images with different aperture opening sizes and things like that, so you need to know this relation, which is very important. So, this is the image that depicts the depth of field that I was talking about in the earlier slide. What do you mean by the depth of field? Basically, it means how much of the image is not blurred in the depth direction. So, when the aperture opening is very small, as we have seen earlier, only the cone of light that passes through the imaging system is very small, so the blur circle diameters are also very small. Even for a very large Δz , the blur circle diameter c will still be small, so the amount of blurring is very small.

Here, you can see that in this tape, you can see only at the farther end; like very far away, you will see some blurring. But for most of the depth region, you will see that everything is almost in focus. As you keep opening the aperture, the amount of blurring increases with depth. So, basically, even a slight increase in depth will lead to large blurring. So clearly here you can see that only things are in focus, but everything apart from that is blurred.

It forms an image that looks focused, so here this is a solid target dot; actually, these are both experimental images, and if we remove that target dot away from this plane by an amount Δz , we see that the actual imaging plane of the focused image is here, but we have our sensor plane here. So, the blur circle's diameter here is C and the radius is R . It's just the same thing. And where we see, then the image becomes blurred. So, clearly you can significantly observe the sharpness and smooth variations in this image.

So, this is in focus, and this is blurred. We have seen that for out-of-focus objects with higher depth from the object plane, the size of the blur circle is larger, which means that the blurring is greater. Thus, we have seen that c is proportional to Δz , and we have also observed that the aperture size regulates the blur; therefore, for larger aperture openings, we have larger blur circle diameters, which means more blur. Blurring can be explained in terms of point spread functions, which is something that will be a point of discussion in the next lecture. Just to glance over this idea, which will be mostly discussed in detail in the last lecture, this blur circle that we were talking about will schematically look something like this. So this was your point, and this point's information is now spread over this circle.

Blur Circle

- When a point source P forms an image P'_b spread over the blur circle.
- This leads to image blurring.
- **Larger C , higher blurring.**
- The points source's intensity (energy) is redistributed in a particular way over this circle.

$$E_p = \iint E_c(r) dA$$

- This is called a **Point Spread Function**.

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So if I assume that there is an associated intensity or energy of light with this point that is redistributed over this circle. So clearly from the law of conservation of energy, you can say that this energy here should be the same as the energy integrated over this. So you can write it in this form, maybe. So this E_p represents the energy at this point, and E_c is now not of constant value.

It depends on the position. So at each position, you will have a value of energy or intensity, and you can integrate it over this area, and that should match with this. So, this is basically the redistribution of energy. So this spatial dependence here is the spatial

dependence of energy or the distribution of energy. This is something that is explained using a point spread function. So, the point spread function, as the name suggests, is a functional form that represents how that point information is spread over an area.

So, this is something that we will discuss in detail in the next lecture, which will also tell us how to use this point spread function to simulate blurred images and explain how we can use those concepts to deblur an image. So, that is all for this lecture, and let us discuss the point spread function in the next one.