Metal Additive Manufacturing
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Lecture-24
On-machine Sensing in MAM (Part 2 of 2)

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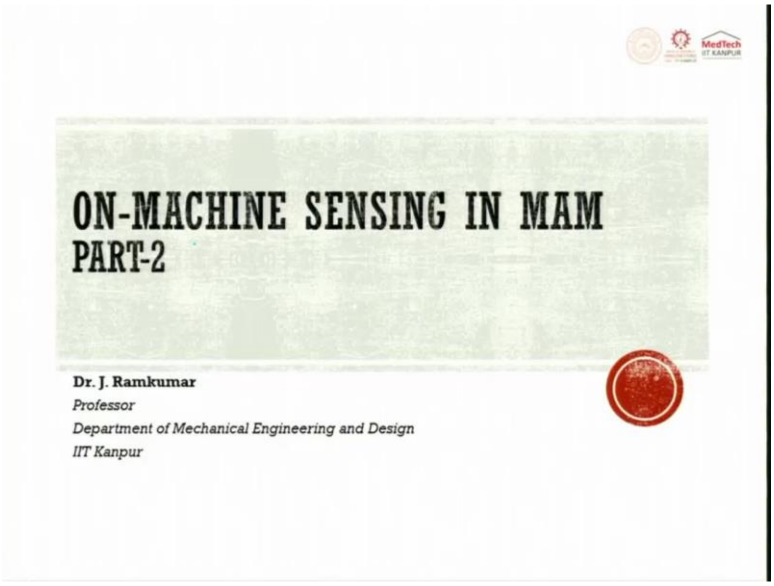

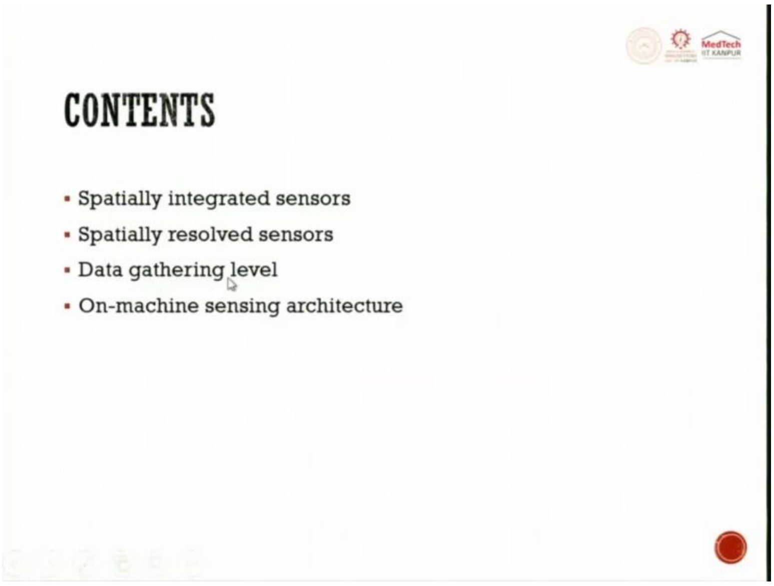

So welcome to the second part of on machine sensing in metal additive manufacturing. So, in this lecture, we will try to understand spatially integrated sensors, spatially resolved sensors, then we will try to see data gathering level and finally, we will see on machine sensing architecture.

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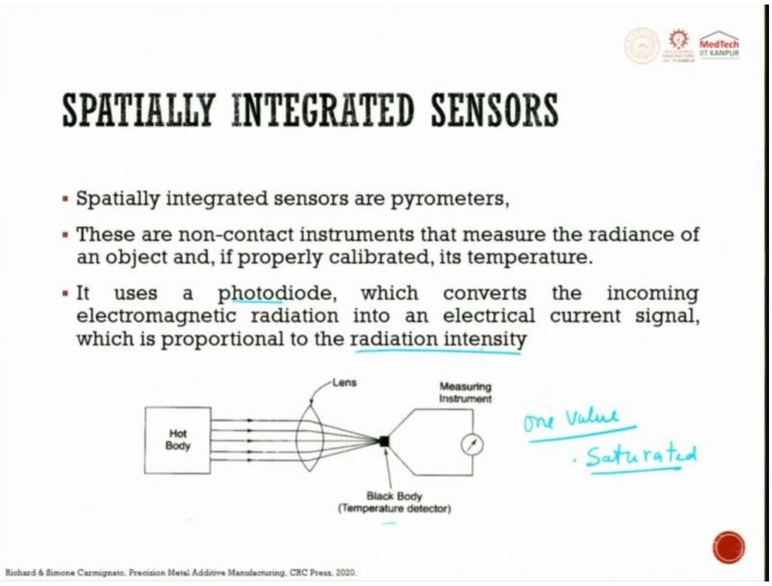

Spatially integrated sensors, spatially integrated sensors are pyrometers. So, if you see a pyrometer, this is the hot body, this hot body emits radiation passes through your lens which gets focused on to your black body or your temperature director. Then from here, we will try to measure the variation in voltage that in turn will be calibrated with respect to temperature. So spatially integrated sensors are pyrometers, one of the examples these are known contact instruments that measure the radiance of an object and if properly calibrated its temperature. So, we would like to use this pyrometer for measurement and it will already have inbuilt calibration undergone such that it measures and tells us the temperature.

Today you get all sorts of pyrometers. Infrared pyrometers, which is used to measure the temperature for a given spot it can be used in the railway stations, you would have seen the attender going across and measuring the temperature of the wheel, sometimes they measure the temperature of the spring, they used to measure it and then they used to find out if there is any deviations and other things, it can be used for that it can also be used for while grinding they wanted to measure the temperature that also can be done. But all these things are okay if you want to try to take one value, but if you want to take value with respect to time and there is a dynamic change happening then pyrometer has to be used with a word of caution.

It uses a photodiode, this photodiode converts the incoming electromagnetic radiation into an electrical current signal, which is proportional to the radiation intensity. What was earlier thought of like a temperature detector, today we are trying to integrate a photodiode, photodiodes are where the light falls on it on the falling of the light it tries to generate and millivolt or volt whatever it is the voltage and this voltage is already pre calibrated to the required measurement.

So, radiation intensity can be measured using photodiode, if we use a temperature detector and which measures only static value, sometimes as I told in the previous lecture, it gets saturated. What is saturation? It reaches a maximum value and then it freezes. So henceforth it displays the same temperature all through the life. So, then you should take it little cautious why is the temperature not varying, so either you switch on and switch off the system or try to refocus it and do it on any other system.

Today people use pyrometer exhaustively while doing experiments in machine tool Dynamics Lab or machine to lab or in central workshop or their research. But they should understand when you try to use this IR pyrometer, there will always be a factor called as MECVT factor. This MECVT factor is something like a weightage factor you have to multiply or add it to the value whatever is given and the moment you change the emissivity you see there is a change in the temperature displayed.

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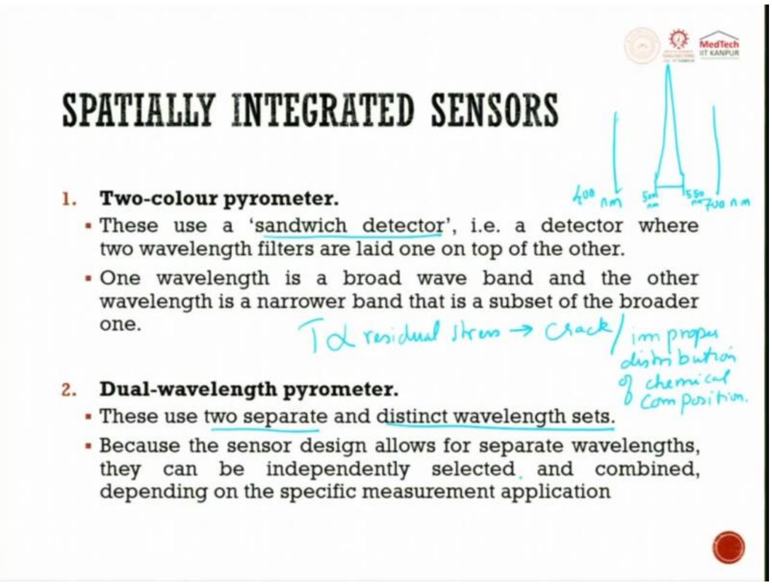

There are 2 colored pyrometer and there is dual wavelength pyrometer. So, 2 color pyrometer is these uses a sandwich detector, that is a detector where 2 wavelength filters are laid one on top of the other. So it is 2 color, one wavelength is a broad wave band and the other is a narrow wave band, that is a subset of the broad wave band, for example, if you are trying to so between 400 Nano metre to 700 Nano metre, this is a broadband and inside it you get it round about 500 Nano metre to 550 Nano metre. So, this is one wavelength is broadband which is 400 and 700, the other one wavelength is narrow which is a subset of the broadband which is 500 to 550.

So, these 2 colored pyrometer is basically a sandwich detector is there in the top, you will have one wavelength filter on the bottom, you will have the other one this is also exhaustively used for measuring the temperature. So, temperature is directly proportional to the residual stress getting developed, this leads to cracks and it also leads to improper distribution of chemical composition.

Next is dual wavelength pyrometer, dual wavelength pyrometer, this uses to separate and distinct wavelength set here it is broad than narrow. So here dual wavelength means, it there used to separate and distinct wavelengths sets because the sensor design allows for separate wavelengths, they can be independently selected and combined depending on the specific measurement application. So, you can have distinct wavelengths set, you can have a combined wavelength set the color pyrometer or dual pyrometer wavelength pyrometer is used for measuring the temperature on your hot body or on a hot surface. Because the sensor design allows for a separate wavelength they can independently select and combine depending on the specific measurement application.

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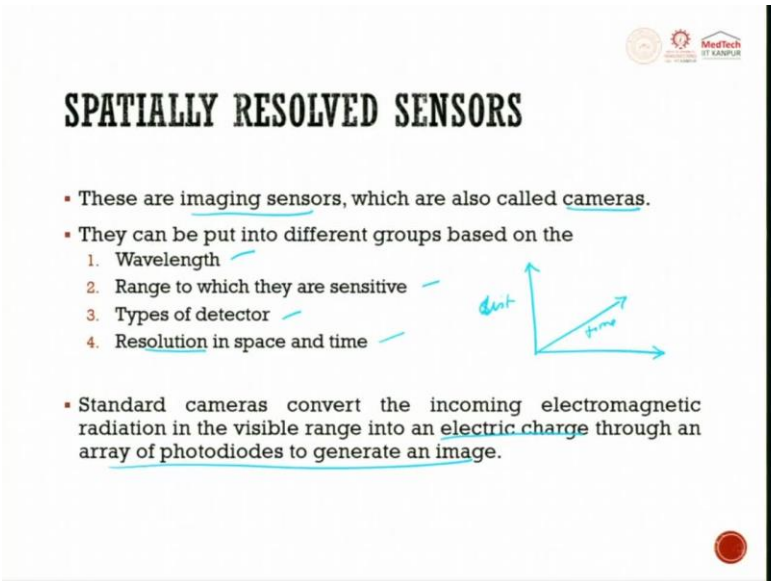

When we are talking about the spatially resolved sensors, these are image sensors which are also called as cameras, they can be put into different groups based on wavelength, range to which they are sensitive, type of detectors, and resolution space and time, resolution and time is seconds, resolution in space is microns. So you can have a resolution in space and time you can have 3 dimensional things you can have distance 2 you can have with respect to time and then you can have one more variable which is there, so you can try to plot and get the information, we generally use this for 3 dimensional flux.

Standard camera converts the incoming electromagnetic radiation in the visible range into an electric charge through an array of photo diodes to generate an image just very similar to that of your CRT. So from the intensity you get electric charge, from the electric charge you have set the array of photo diodes from this photodiode you get an image from the image you try to resolve spatially with respect to space as well as with respect to time, but for to meeting the requirements.

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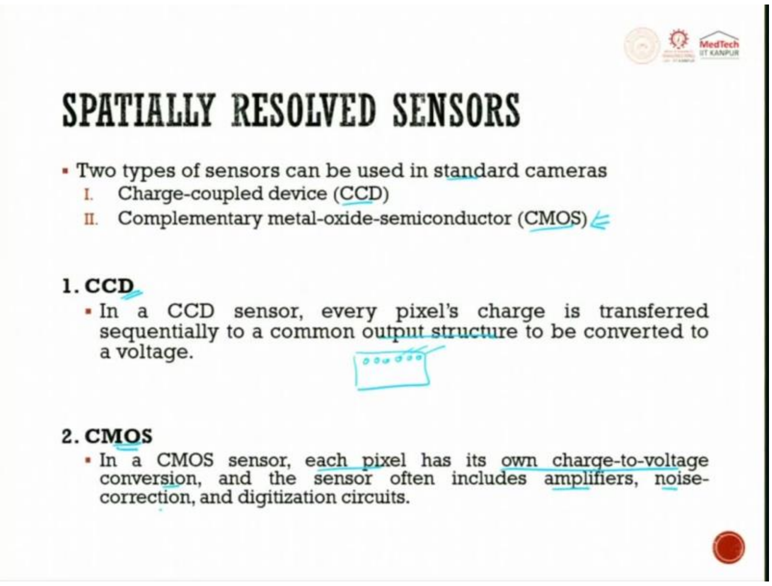

Two types of sensors that can be used in standard cameras they are CCD and CMOS, CCD are charge coupled device and CMOS is complementary metal oxide semiconductor cameras. So today we use exhaustively CMOS because the technology has very well matured and it is also economical in certain applications. In CCD sensor, every pixel charge is transferred subsequently to your common output structure to be converted into a voltage. Every pixel charge is transferred sequentially one after the other to your common output structure to be converted to a voltage.

When we talk about CMOS in CMOS sensor, each pixel has its own charge to voltage conversion, and the sensor often includes amplifier, noise correction and digital isolation circuit. CMOS is very much used today compared to CCD. So every pixel charge is transferred sequentially one after the other after the other to a output structure, but here has its own charge to voltage conversion and the sensor often includes amplifier, noise filtration and digitization circuit.

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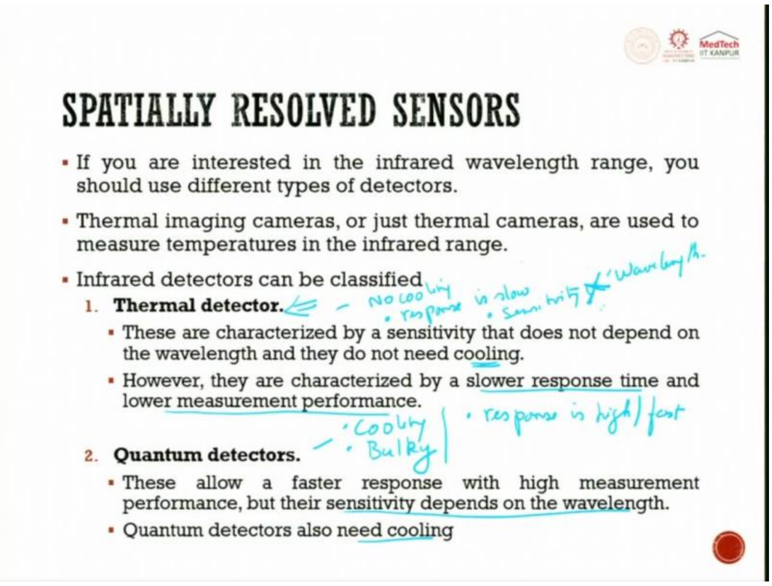

So if you are interested in the infrared wavelength range, you should use different types of detectors. Thermal imaging cameras are just thermal cameras are used to measure temperatures in the infrared range. Infrared detectors can be classified into two, one is called as thermal detectors, the other one is called as quantum detectors. So the thermal detectors these are characterised by a sensitivity that does not depend on the wavelength and they do not need cooling. It is very important in the thermal management system for all these devices are very-very efficiently made and their efficiency dictates the performance of the camera.

So the thermal detector these are characterised by a sensitivity that does not depend on the wavelength and they do not need cooling thermal detectors. However, they are characterised by slow response time and lower measurement performance. So what does it mean you our response is very slow and lawyer measurement performance happens, so because of this you always try to get average temperature through this detectors.

When we are working on quantum detectors, this allows you a fast response with high measurement performance, but their sensitivity depends on the wavelength, quantum detectors also needs cooling. So here quantum detectors it needs a cooling system so it is bulky and the response is extremely high, fast or high whatever it is. When we talk about this thermal detectors it no cooling, so it is not bulky, second thing is response is slow and the sensitivity is also poor sensitivity. So sensitivity is not dependent on the wavelength, this is very important you should know when we try to do it.

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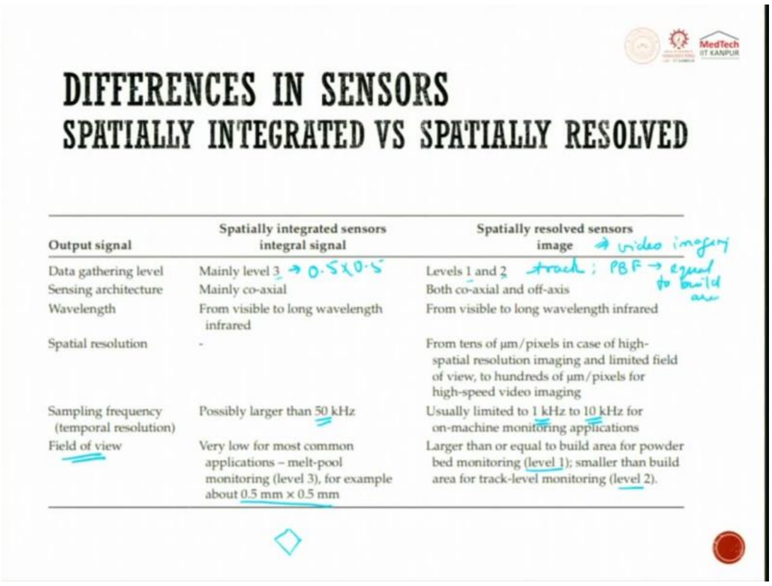

Output signal	Spatially integrated sensors integral signal	Spatially resolved sensors image
Data gathering level	Mainly level 3	Levels 1 and 2
Sensing architecture	Mainly co-axial	Both co-axial and off-axis
Wavelength	From visible to long wavelength infrared	From visible to long wavelength infrared
Spatial resolution	-	From tens of μm/pixels in case of high-spatial resolution imaging and limited field of view, to hundreds of μm/pixels for high-speed video imaging
Sampling frequency (temporal resolution)	Possibly larger than 50 kHz	Usually limited to 1 kHz to 10 kHz for on-machine monitoring applications
Field of view	Very low for most common applications – melt-pool monitoring (level 3), for example about 0.5 mm × 0.5 mm	Larger than or equal to build area for powder bed monitoring (level 1); smaller than build area for track-level monitoring (level 2).

So here we are trying to compare the output signals with the various spatial integrated sensors, integral signals and spatially resolved sensor images. Data gathering level it is main level phase 3, so it is level 1 and level 2, so it is simple it is heavy. Sensing architecture is mainly co axial here it is both co axial and off axial. The wavelength from visible to long wavelength infrared you can measure here from visible to long wavelength infrared you can do it here. Spatial resolution is nil from 10's of microns to pixel by pixel in case of higher spatial resolution imaging and limited field of view to 100's of micro metre per pixel for high speed video imaging, so this is used to for high speed video imaging.

Then sampling frequencies up to 50 hertz here we talk about one kilohertz to 10 kilohertz, so you can see lot of events happening. So you can try to get a bit that is why it is trying to take lots of events in a compressed time. So it can be used for high speed video imaging. So the field of view very low for most common application multiple monitoring for example, is about 0.5 to 0.5 you can do which is a very small way. So 0.5 millimeter t 0.5 millimeter something like this, this is 5, so 0.5 millimeter to 0.5 millimeter, so this will be the field of view you can do.

Here larger or equal to build the area for powder bed fusion that is level 1, smaller than build the area from track level monitoring is level 2. So these 2 it can do. So this will be for level 3, basically field of view, level 3 and level 2 is nothing but 0.5 into 0.5. So here it is going to be a track, track level monitoring, so it is used to for powder bed fusion of PBF build area, so it can try to do large areas also, so it build area.

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So this is a thermal imaging of MAM when you see it in real use. So this is a laser which goes down and one layer of information and in that one layer of information melting is happening. So you are trying to use a thermal imaging camera and try to take a temperature. So here this is hot this is hotter. And while it is doing it you see here, what is the influence it is also trying to create a temperature high here it is below the bed.

So you can see here you take such images and then now, if you have a highly computation thing you can try to draw a straight line and then try to find out what is your layer thickness, this you can make. And you can also see in the table also where does that temperature goes very high by this photo you can try to see what is the layer thickness does it heat only one layer does it pass through several layers, there is there as is touching between the layers happening, what happens while building itself what happens to the shrinkage does it try to create any poor or not, so all these things will be there. Suppose, if there is any pore which is getting formed. So in this itself you can see there will be a change in temperature profile.

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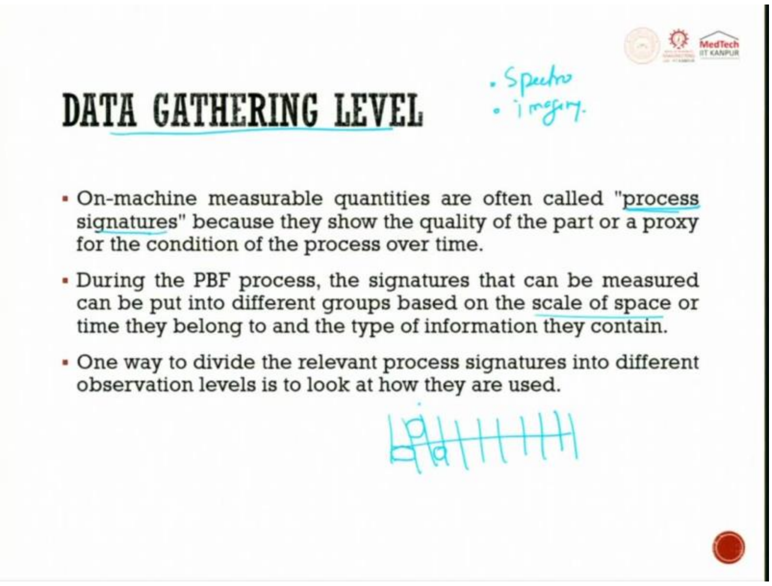

Once you have done spectroscopy, spectro or you are done imaging the next thing will be your data gathering level. On machine measurable quantities are often called as process signature like your signature, you have something called as process signature, if you are able to measure it online itself. Because they show the quality of the part or a proxy of for the condition of the process over time, we always try to call it as process signature. We will try to say process signature for the additive manufacturing process is very good.

During the powder bed fusion process, the signatures that can be measured can be put into different groups based on the scale of the space or time they belong to and type of information they contain. One way to divide the relevant process signatures into different observation level is to look at how they are used. So basically you have a data now you are splitting the data into small-small data's and then in each of these data's you are trying to make an inference and based on this or trying to average it out and then talk. One way to divide the relevant process signature into different observation levels is to look at how they can be used.

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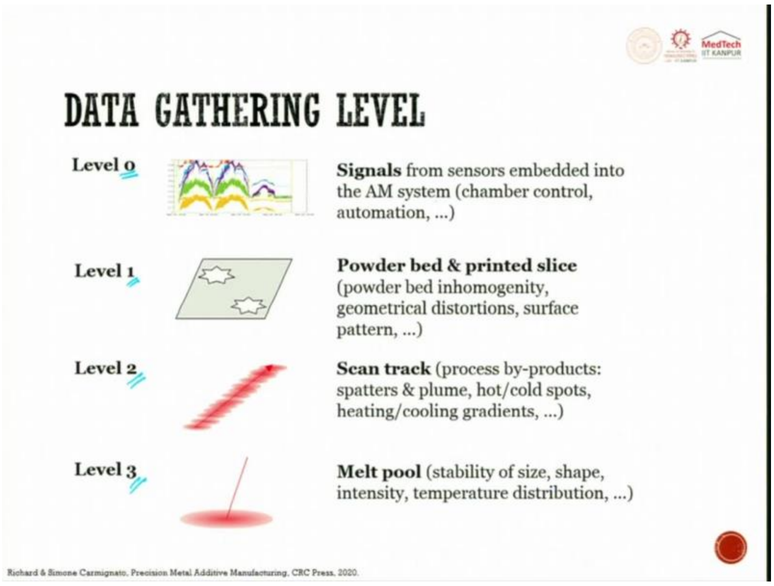

So this is level 0. Level 0 means signals from sensors embedded into an AM machine, chamber control automation they are all level 0 information. When we talk about level 1 information, it talks about powder bed and the printed slice, powder bed inhomogeneity geometrical distortion and surface patterns are seen in level 1. When we talk about level 2, it talks about scan track process by product, spatter, plume, hot and cold spots heating and cooling gradient all will be seen in level 2. When we are looking at level 3 we try to see the complete melt pool the stability of size, shape, intensity, temperature distribution, etc. etc.

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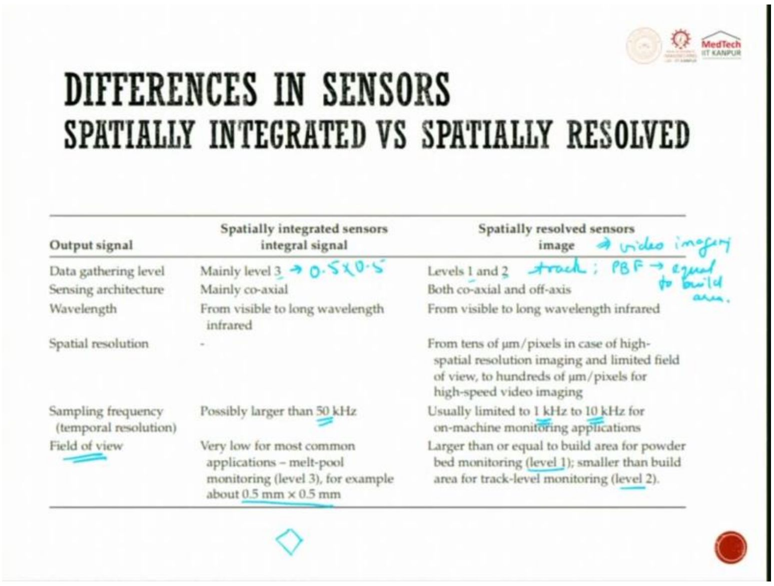

So when we go back to the graph of facial integrated sensors, integral sensors here you see level 3. So what is level 3 information? Level 3 information means it talks about the complete melt pool stability of size, shape intensity, temperature distribution. When we look at this spatial resolved sensor imaging, we try to take 1 and 2, 1 and 2 are nothing but powder bed and printed slice and scan track will be seen in 1 and 2 these 2 are images this is completely you see about the melt pool.

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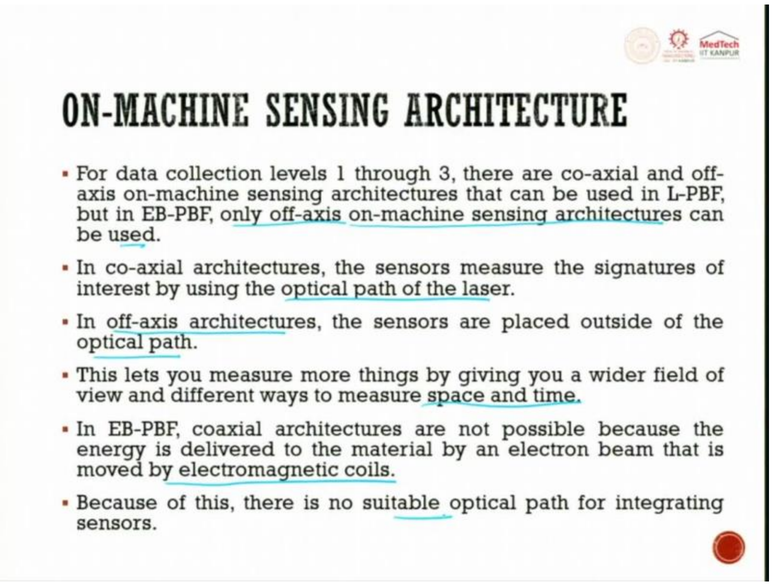

So all machine sensing architecture for data collection levels 1 through 3, there are co axial and off axis on machine sensing architectures that can be used in laser powder bed fusion, but in electron beam powder bed fusion only off axis on machine sensing architecture can be used because you are trying to put a vacuum and you are trying to close the machine. A co axial architecture, the sensor measures the signature process signature sensors measure the signature of interest by using optical path of the laser.

The off axis architecture, the sensors are placed outside the optical path in off axis architecture outside the optical path, this lets you measure more things by giving you your wide field of view and the different ways to measure space and time. So when we talk about electron beam, it is always off axis. Electron beam powder bed fusion co axial architectures are not possible because the energy is delivered to the material by the electron beam that is moved in by electromagnetic coil. Because of this there is no suitable optical path for integrating sensors.

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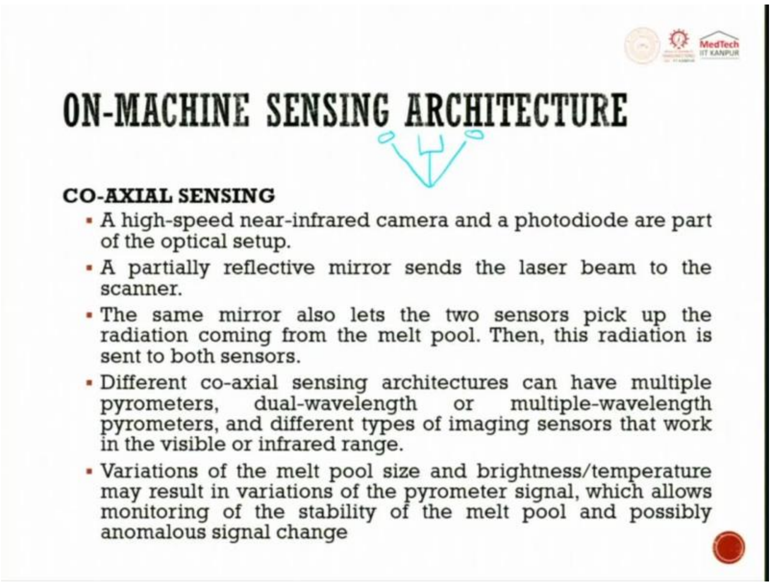

When we talk about co axial sensing, your high speed near infrared camera and your photodiode are part of the optical setup. A partially reflective mirror which sends the laser beam to the scanner the same mirror also lets the 2 sensor pick up the radiation coming from the melt pool then the radiation is sent to both the sensors, so difference of both the sensors laser coming. Different co axial sensing architectures can have multiple pyrometer dual length or multiple wavelength pyrometer and different types of imaging sensors that work in visible or an infrared image. The variation of the melt pool size and the brightness temperature may result in variation of the pyrometer signal which allows monitoring of the stability of the melt pool and possible anonymous signal change.

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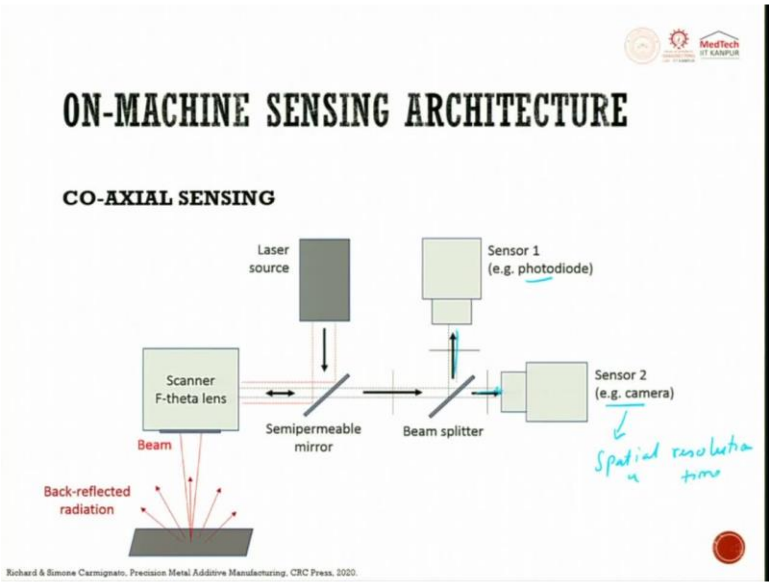

So this is a typical co axial sensing in typical co axial sensing you have a laser source, you have a scanner you have a f-theta lens, this f-theta lens strikes to hit at the powder bed from the powder bed that is a reflection of radiation. So now, from here what they do is they put a beam splitter, so it goes to photodiode 1 and it goes to camera. So now by this combination rebuilt it generates a fringe patterns. Now they count different patterns and convert it into some signals. So you have a photodiode sensor and you have a camera sensor, camera tries to measure with spatial resolution high as well as special time.

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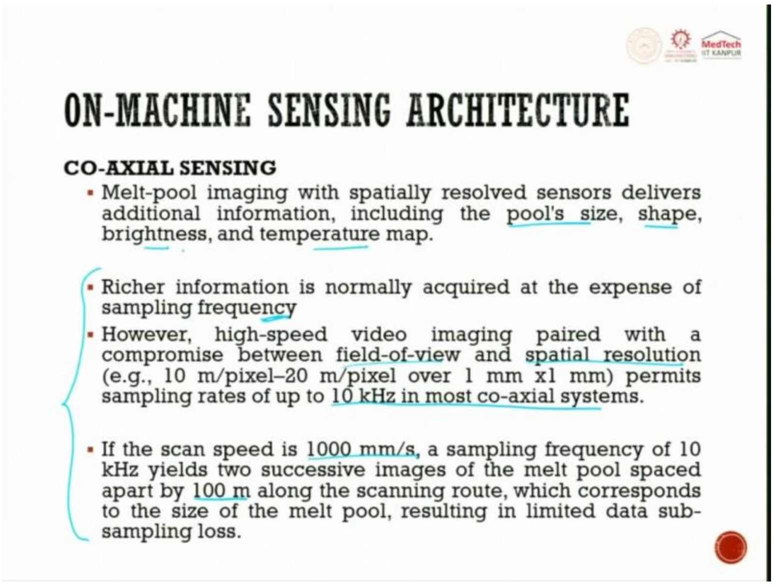

When we talk about this co axial sensing melt pool imaging with spatially resolved the sensor delivers additional information including pool size, pool shape, brightness and temperature mapping. Richer information is normally acquired at the expense of sampling frequency. Moment you have a higher sampling frequency you have lot of information a lot of information means lot of data, this data has to be processed so that is where is that difficulty.

However, high speed video imaging paired with a compromise between the field of view and spatial resolution permits the sampling rate to be from 10 kilohertz in most co axial systems. If the scanning speed is 100 millimeter per second your sampling frequency of 10 kilohertz yield 2 successive images of the melt pool spaced apart by 100 microns along the sampling route which corresponds to the size of the melt pool resulting in limited data sub sample losses. So this is very important information you should be careful while using it. So here it talks about melt pool size, shape, brightness and temperature mapping.

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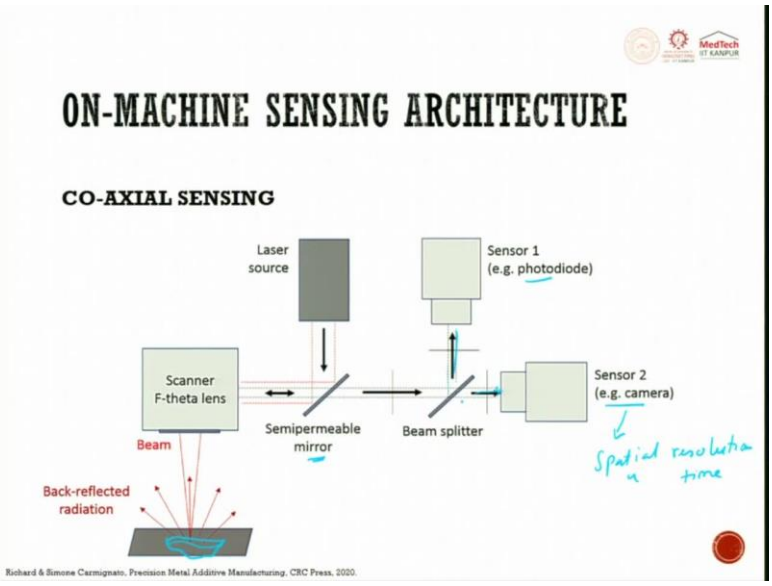

So here it talks about the melt pool. So you can use the f-theta lens. So here you have a semi permeable mirror, so the light hits and the light transfers here. So you have a beam splitter which is there. So the beam splitter splits the light to the camera as well as and then it comes back and then it gets reconstructed. So this is all co-axial.

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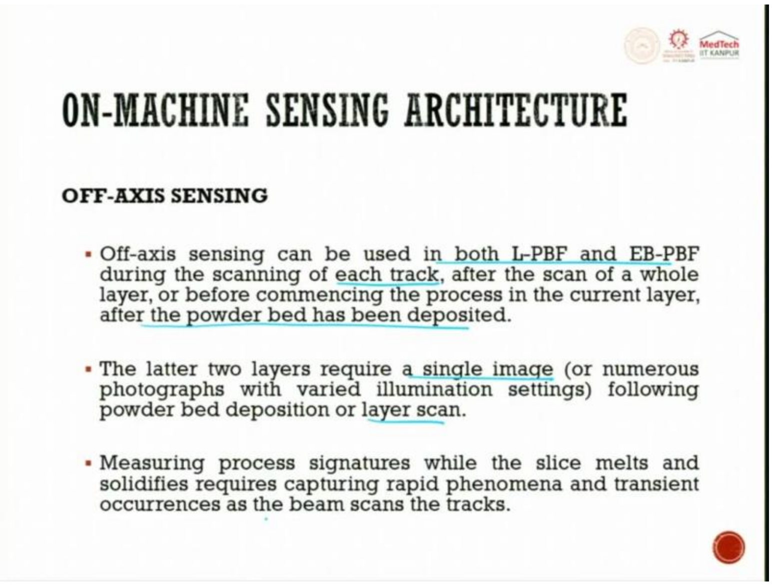

Next let us go to off axial sensing. Off axial sensing can be used in laser powder bed fusion and electron beam powder bed fusion. During the scanning of each track after the scan of your hole layer or both commencing the process in the current layer after the powder bed has been deposited, it can be used in both this and this scanning of each track after the scanning of a whole layer, so here in the current layer it is done. The latter two layers require a single image following powder bed the position on layer scan. Measuring process signature while the slice melts and solidifies requires capturing rapid phenomena and transient occurrence as a beam scans and tracks.

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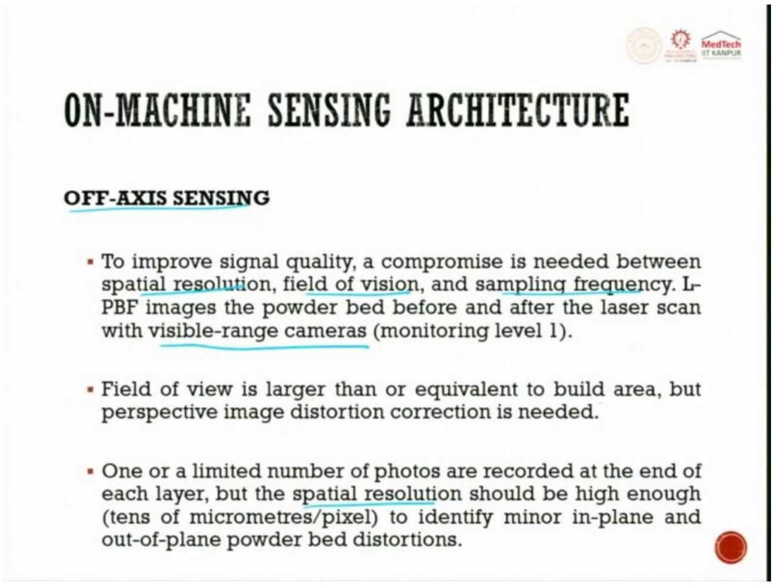

To improve signal quality your compromise is being made between the spatial resolution, field of view, scanning frequency. So the powder bed before and after the laser bed scanning visual range camera are used for doing it the field of view is very large, when we try to use off axis sensing then or equal into the building area, but the perceptive image distortion correction is also made. One or a limited number of photos are recorded at the end of each layer, but the spatial resolution should be as high as possible to get information in pixel level.

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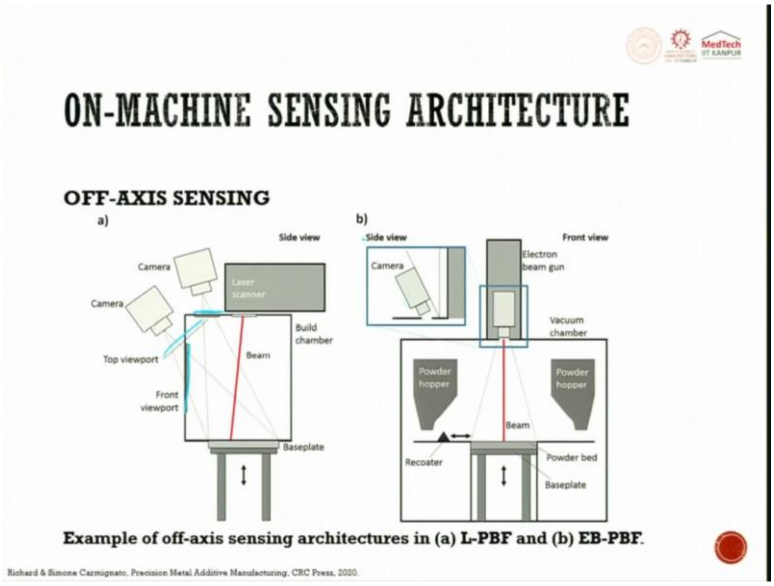

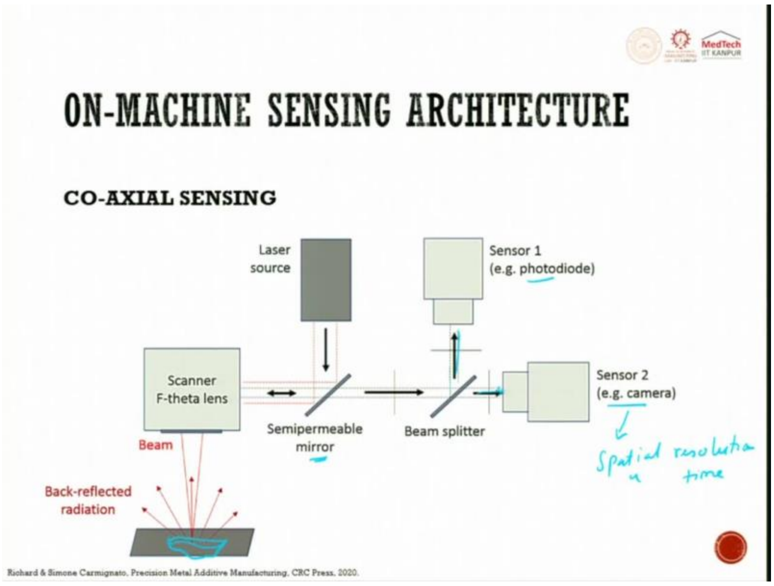

So this is called as the off axial sensing. In off axial sensing, you will have a camera you will have a laser scanner, this laser scanner beam passes through it you have a base table. So then you have one camera top view and then you have this front view this is top view and then you have a camera here. So you try to take the image from here front view from top view and then you try to reconstruct the image and get it done.

So when we are trying to do with electron beam, so you can see here the camera is placed and then this is how the viewing happens. So this is the electron gun, so the beam hits it, so you have a powder hopper, powder hopper, so your recoater is used and you can see your camera is placed here. So this is off axial sensing architecture. So this was open co axial this was co axial sensing. So co axial you can see two axis and here you see that it is an off axis. So off axis is used to for predominantly for EE beam powder bed fusion.

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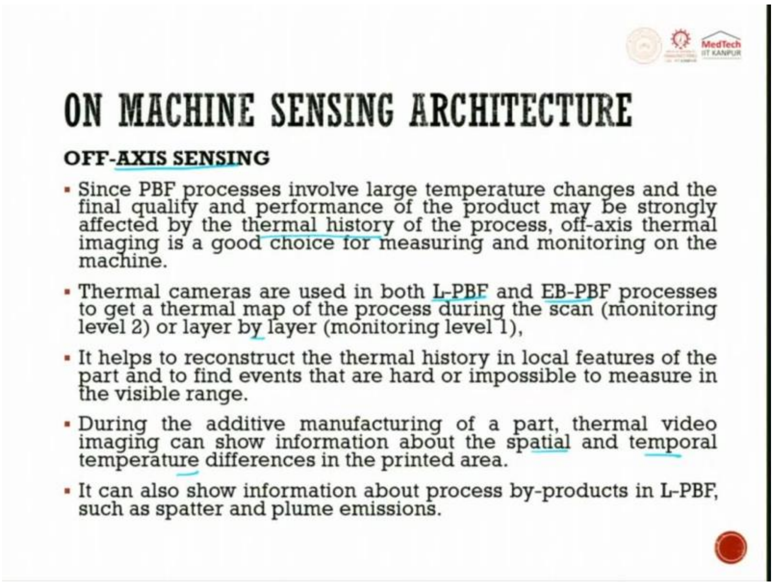

Since the powder bed fusion process involves large temperature change and final quality and performance of the product may be strongly affected by the thermal history of the process. The thermal camera are used for both this to get a thermal map of the process during the scanning or layer by layer. It helps to reconstruct the thermal history in local features of the part and find events that are hard or impossible to measure. During the additive manufacturing of a part thermal video imaging can show information about the spatial and temporal temperature difference in the print area. It can also show information about process by products in laser powder bed fusion, such as spatter and flume emission by using this off axis sensing. So you see off axis sensing how well it is used.

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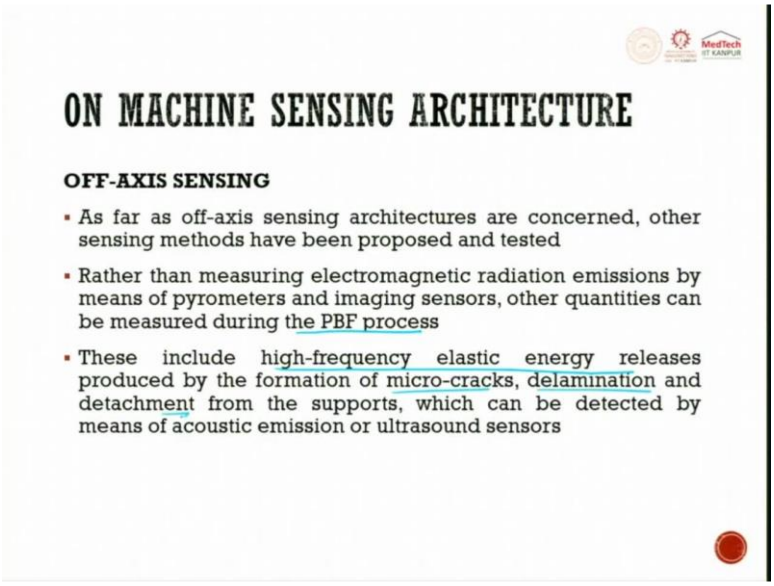

As far as the off axis sensing architecture are concerned, other sensing methods have been proposed and tested rather than measuring an electromagnetic radiation emission by means of pyrometer and image sensing other quantities can be measured during the powder bed fusion process. This includes high frequency elastic energy release produced by the formation of micro cracks, delamination and detachment from the support.

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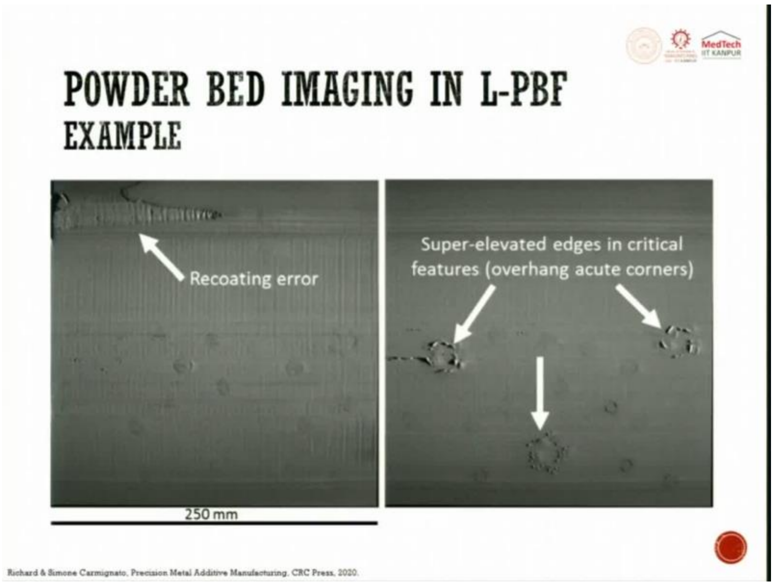

So this is powder bed imaging in laser powder bed fusion, you can see here recoater error, this is a recoater error and you can see here super evaluating yet just in critical features overhang acute corners.

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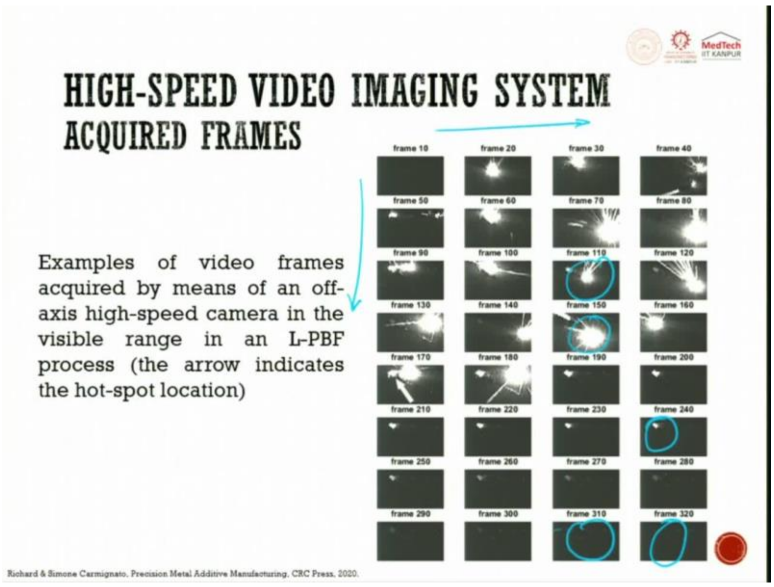

High speed video imaging system acquiring frames. So you can see 10, 20, 30 this is the frame increase and it can go keep increasing, this is the first 10 frames then when it is 20 then you can see at 110, how is it 150, then you see at 240, then you look at 310, then 320 frames per second. So the example of video frame acquired by means of access high speed camera in the visible range in an laser powder bed fusion is shown here. So this can be used for sensing or for measuring or imaging and then understanding the output.

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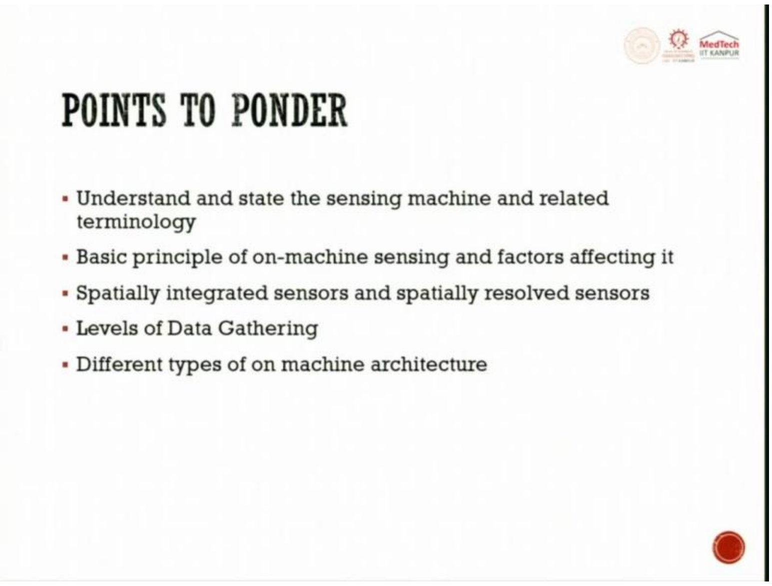

So points to ponder in this lecture what did we go through we went and understand the state, the sensing machine and related terminologies are. Basic principle of on machine sensing and factors, spatial integration sensor and spatially resolved sensors, levels of data gathering level 0, level 1, level 2, level 3 and different types of machine architecture of co axial and off axial machine architecture we saw.

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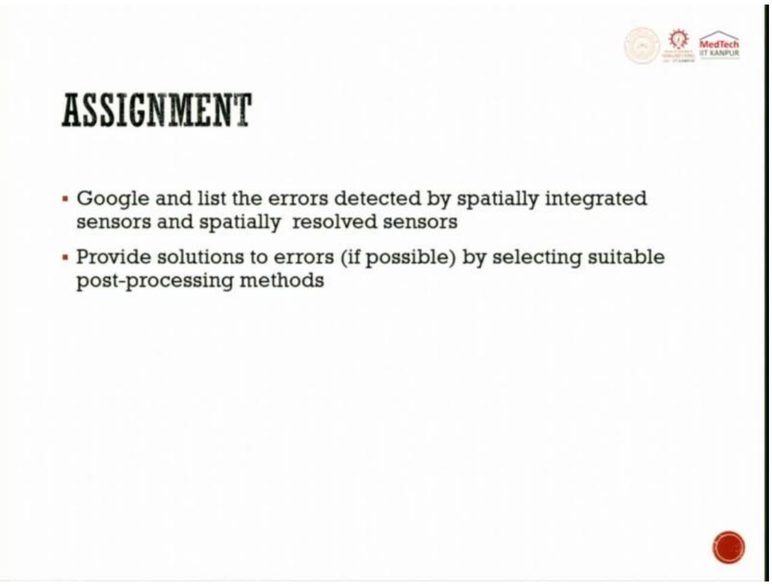

Google and list the errors detected by spatial integrated sensors and spatially resolved sensors, this will be assignment number 1, and assignment number 2 will be provide solutions to yours by selecting suitable post processing method. By looking into the error you are supposed to suggest your post processing method. With that, I thank you very much for your patient hearing in this lecture.