Metal Additive Manufacturing
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Lecture-25
In-situ Control System

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Welcome to the next lecture in In-situ Control Systems. Previous lecture, we try to cover various monitoring sensors, which can be used to control the process. Here, we will try to see in situ, that is during the process, what are all the control systems which are used in additive metal additive manufacturing.

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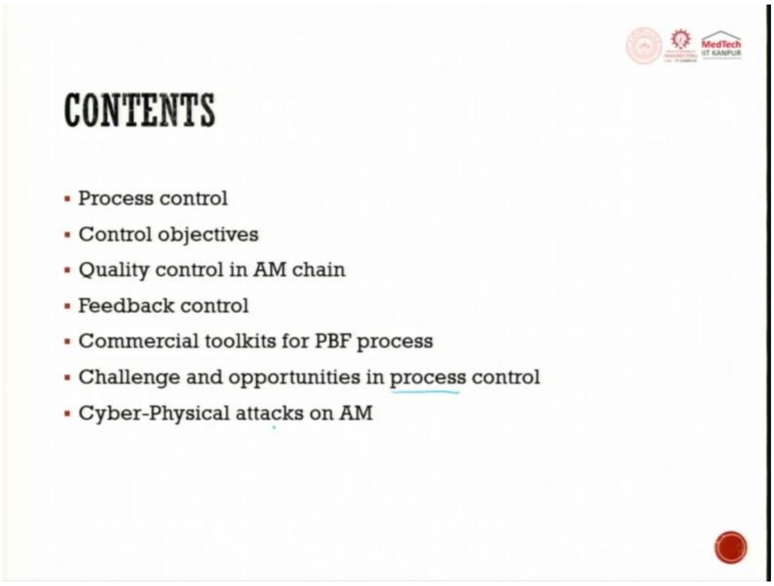

In this lecture, we will try to see process control, then control objectives, then quality control in additive manufacturing chain, feedback control, then commercial toolkits for powder bed fusion process which are all available, then challenges and opportunities in process control. And finally, we will try to see cyber physical attacks which are going on additive manufacturing.

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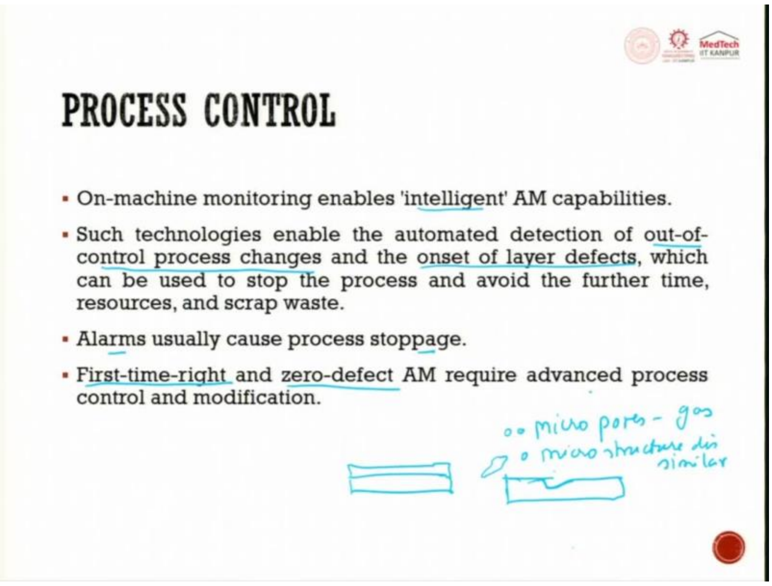

So, when we talk about process control or machine monitoring enables intelligent additive manufacturing capability. Today, we are looking for intelligent systems. Intelligent Systems are those systems, which works on the data and tries to take a decision on spot and try to produce a good quality output. Such technologies enable the automated deduction of out of control process changes and the onset of layer defects, which can be used to stop the process and avoid the further time resource and scrap waste.

So, here during the process of layer by layer fabrication, if you find out that there is a defect which has happened, now, the next layer itself will not happen. So, this will be tried to take an intelligent approach, intelligent means it has a deeper understanding with the data and the data which is collected from the process during the process and next is the previous data's which is already available with it.

So, with that they try to find out what is the best process of possible parameters or looking into that defect, they will try to stop it. So, that is what I said here, the out of control process changes and the onset of layer defects, this is a layer defect pores, micro pores because of gas because of the improper solidification or difference in solidification we tried to create micro structural dissimilarity that means to say we are trying to create your random pore, this is a circular pore, micro pore because of gas.

So, these are defects, which is by onset of the defects, which can be used to stop the process and avoid the further time resource and scrap waste is done. Alarms usually cause the process stoppage generally that is how it is done in even a factory where there are a series of CNC machines, if there is a defective part getting generated, it raises an alarm and stops the machine.

The same is done here also first time right and zero defect is the talk of the town today, first time whatever part is produced for the first time you produce the best product second time whatever you produce, it is defect less, so, it is zero defect additive manufacturing, which requires advanced process control and modification.

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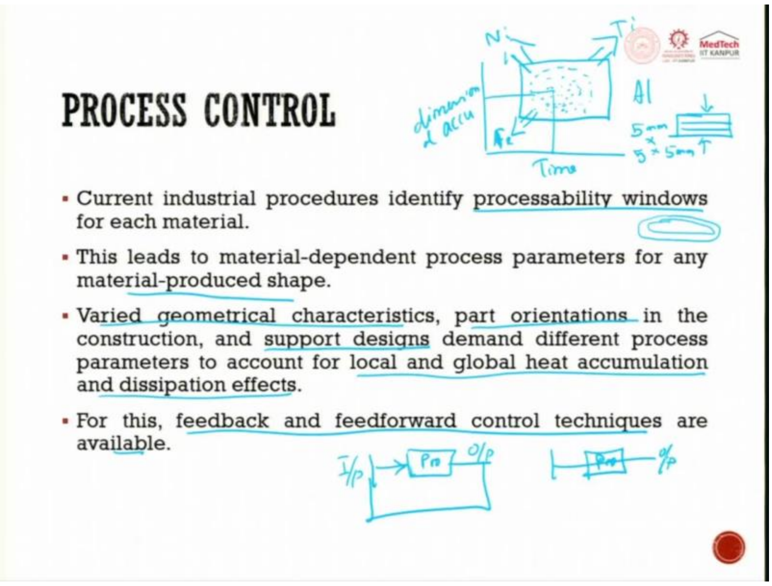

The current industrial procedure identify processability window for each material that means to say we let us assume pressure versus velocity or let us try to take pressure versus time and let me convert the pressure also into some dimensional accuracy. So, maybe what will happen is you will see lot of things are getting done here as a right part, all the parts which are produced here are good. So, maybe then what you do is you try to say this is the process window with which you operate such that you get the dimensional accuracy provided you do this time for solidification or this time for layer thickness whatever it is.

So, you try to this is called as the process window. So, the processability window is this, the safe thing where in which anywhere within the window you produce, it gives you a sound quality output. So, current industrial procedures are identifying the process ability window this is a process ability window, it is not a point it is a big area, in this area anywhere you do, you will try to get a highly dimensional controlled part. So, this leads to material dependent process parameter for any material produced space.

So, this can be for aluminium, there can be a shift when you talk about titanium, it can there can be shift when we talk about ferrous, it can shift anywhere and this side it can shift for nickel alloy, this window itself will shift and the window size can shrink or expand that is what is processability window. For metal forming process you can see that there is a process window where in which it can produce a sound quality output, almost a similar concept is used here to produce sound quality output this leads to material dependent process parameters for any material produced shape.

So, this is only for one particular say for example, if I want to build your block with 10 layers of dimension 5 millimeter, 5 mm x 5 mm x 5 mm, if I want to build so, then this is good. Suppose I tried to make the same area, but I tried to do it like a void in between the same volume, but the shape is different, then the window is going to be different. So, for every size you produce to a large extent, you will have a process window, which goes around. Varied geometrical characteristics, part orientation in the construction and support design demands different process parameters to account for local and global heat accumulation and dissipation effect.

So, that is what, I have very clear said at varying geometric characteristics, varying orientation of the part and support design all these things play a very very important role in deciding the local and global heat accumulation and dissipation device. In additive manufacturing, the heat the management system, while developing a product or a part is very, very important. People use today pulsating heat source, people use today external heating, infrared heating source, induction heating source, people try all sorts of tricks, so that they produce a sound quality output for this feedback and feed forward control techniques are available today, these techniques are available today, but the data to fit in from the material and for the shape is not available, today, we have feedback and feed forward technique.

Feedback is you have a process then this process comes back and this becomes your input and this is your output, this is the process. So, input process output, this is a feedback system which goes and the feed forward system is you have only this you have a process here and there is no output coming back.

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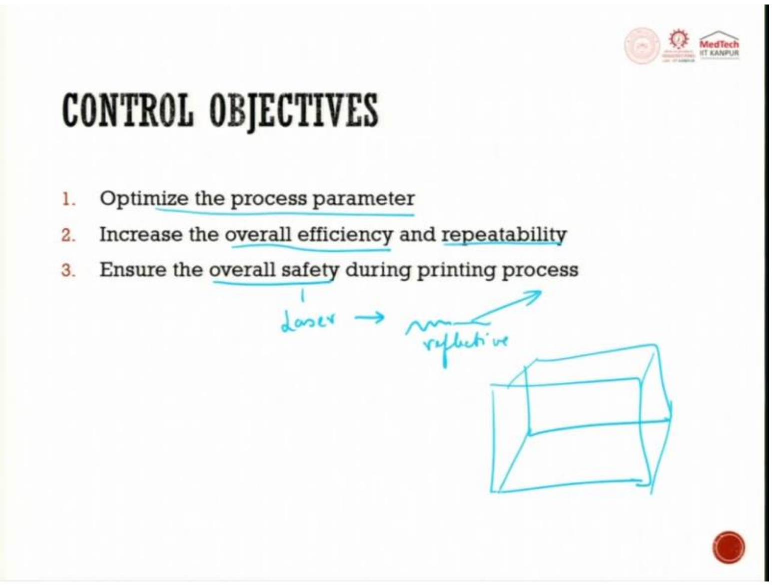

So, when we talk about control objectives, there are three types of objectives, one is called as optimize the process parameter. The next one is increase. When you optimize the process parameter that does not mean that you are trying to have a higher efficiency in the process or you are trying to have a better accuracy or repeatability.

The next control objective can be increase the overall efficiency and the repeatability. The last one is ensure the overall safety during printing process, safety is also very important, safety in terms of fumes coming out, safety in terms of the blasting of the small powder which comes out rejects out because of recoil pressure which exits out from the space that also is very important to be noted down and sometimes when you start working with magnesium and if there is an oxide layer getting formed or when there is a presence of oxidation, it leads you to a disastoric process. So, it tries to burn or it tries to blast so you have to be careful with whatever comes out of it. And the other thing is laser.

Laser when it tries to hit a reflecting surface, you can see the light coming out. This light should be made sure that it is confined inside the machine block. If you do it on open source, it is going to create a problem.

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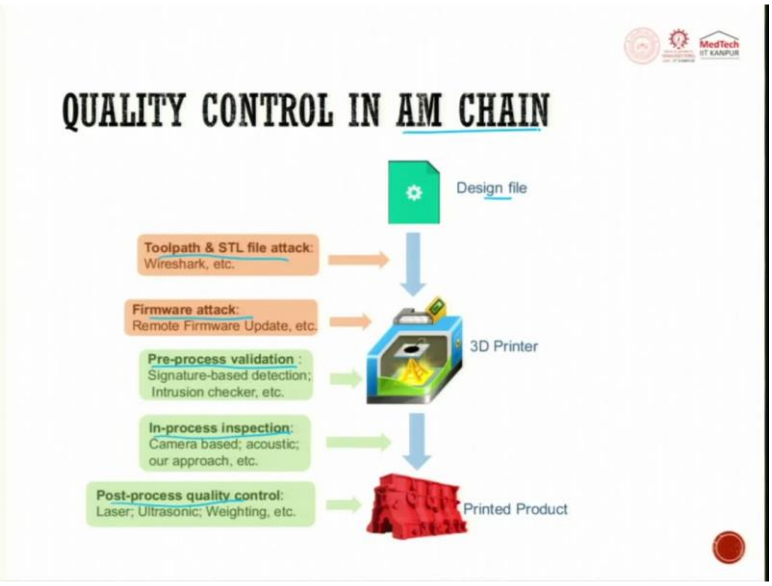

So, quality control in additive manufacturing chain, there is a design file then tool path an STL file attack, so, wire shark etcetera are brought in here. So, this one is going to be it talks about tool path and STL file, then it is firmware attack it talks about remote firmware update etcetera. So, these are some of the updates with them, these are the wire shocks which happens to, which hinders the process then you have pre-process validation, where the signature based detection, intrusion checkers etcetera. are done here.

Then in process inspection, camera based acoustic stick approach etcetera. are being discussed here. And finally, you have post process quality control which talks about laser, ultrasonic weighing etcetera. So, you will have design thinking, these are all the quality chain, Design Thinking toolpath and STL which is done then firmware which tries to convert the slicing layer then pre-process validation which is done in the simulation, then in process inspection while the process is developed, you see and then finally is the post process quality control. So, these are all some of the quality control checks, which are used in additive manufacturing chain.

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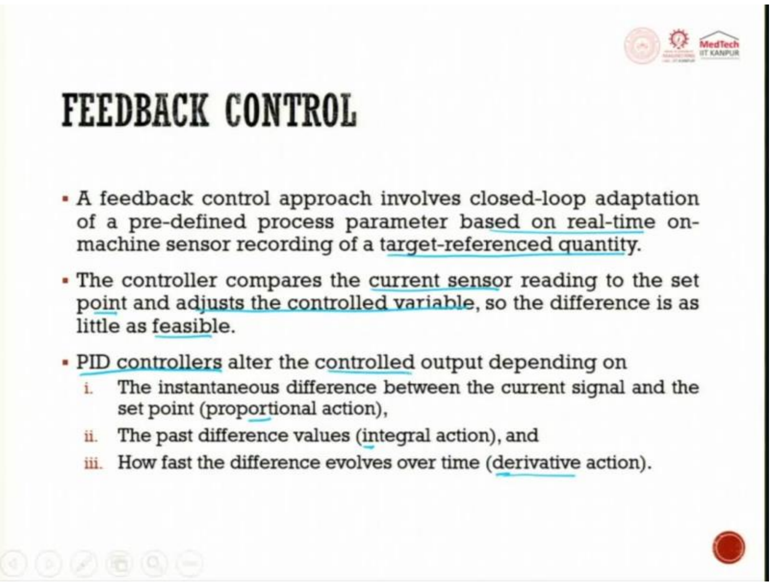

When we talk about feedback control, a feedback control approach involves closed loop adoption of your pre-defined process parameter based on real time on machine sensor recording of your target referred quantity, the controller compares the current sensor reading to the set point and adjust the controlled variable. So that the difference is as little or less feasible, we always try to use PID controller alerts the controlled output depends on instantaneous difference between the current signal and the set point which is proportional action.

So, then the past difference value is the integrated action then how fast the difference evolves over time is the derivative action. So PID. So, proportional integral or proportionate integral derivative control PID. So, you see that instantaneous difference between the current signal and the set point you have a proportional action. Then it is past difference value, the previous value integrated action, then how fast the difference evolves over time is the derivative action. So, these things are done in a controller to change the output.

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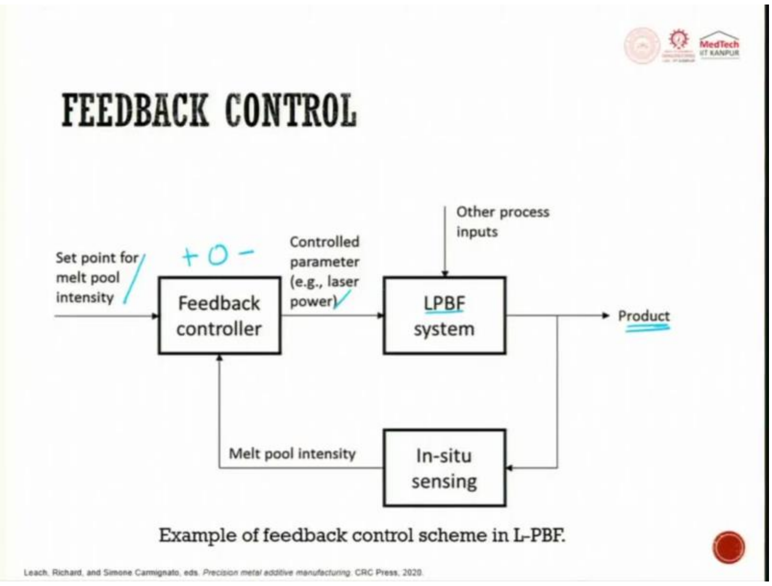

So, if you look at a block diagram, what we have you can see here the set point for melt pool intensity is given to a feedback controller, then this feedback controller controls the path which is laser power, then it gives us laser powder bed fusion system, then it tries to make a product out then we have products. Now from the products we try to have In-situ sensing we have In-situ sensing, then this In-situ sensing will move to melt pool intensity, it will go to feedback controller.

So, whatever is the point set here, it is checked from the melt pool intensity whatever comes out and if there is a plus zero or minus signal to be given, it is given to the feedback controller and this feedback whatever is given the controller gives the parameters to LPBF, and then finally, you get the product out. So, this loop is a very complex loop to be controlled. Here we are only talking about laser and power, but in reality, you also have the feed rate overlapping of spot diameter, then hatch pattern and then spacing between the hatch pattern all these things are discussed here. So, it is a multi-objective optimization has to be done. So then you try to get the required output.

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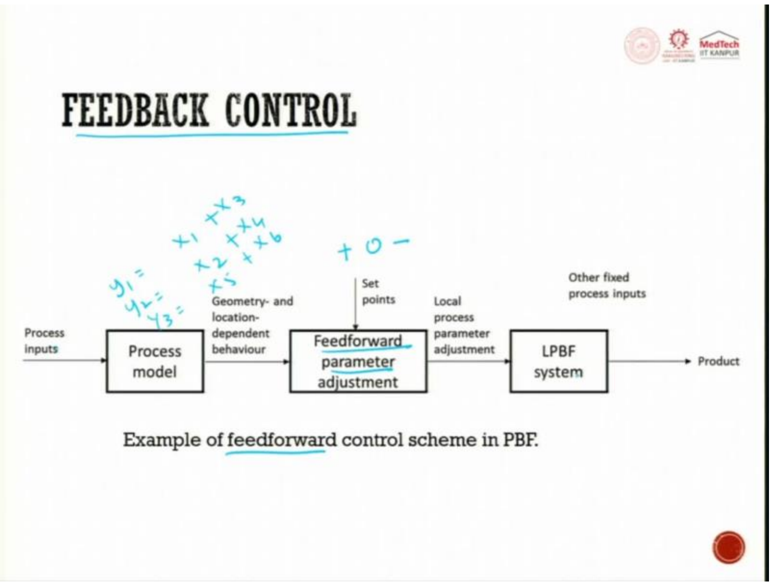

So, this is called as a feedback control scheme which is available in laser powder bed fusion method. This is a feed forward as I told you process input is given to a process model. Again here, it has multiple objectives y 1, y 2, y 3. These are all different different objectives, where we do it with x 1, x 2, for example x 3, here we talk about x 4, x 5, x 6. So, these are all varying parameters, you can try to have their influence on outputs. So, these are all models which we generate here. Now, with this model whatever we get generated, we try to look at geometric and locational dependent behavior, geometric and location.

So, we try to do that and then this is given us feed forward parametric adjustment, the set points are here. So, the feed forward parametric adjustment is done here, then it is moved to local process parameter adjustment, then finally, you get as LPBF system and then you get a product. So, the other fixed process inputs are this. So, you will have a feedback controller process input product then you have a feed model. Feed forward parameter adjustment which is a set point. So, again here you have a negative, 0, positive, so it tries to compare and it tries to adjust. Positive means it is greater produce. It has increased, reduced and maintained the same. So, local process parameter is adjusted and then it has given to the LPBF.

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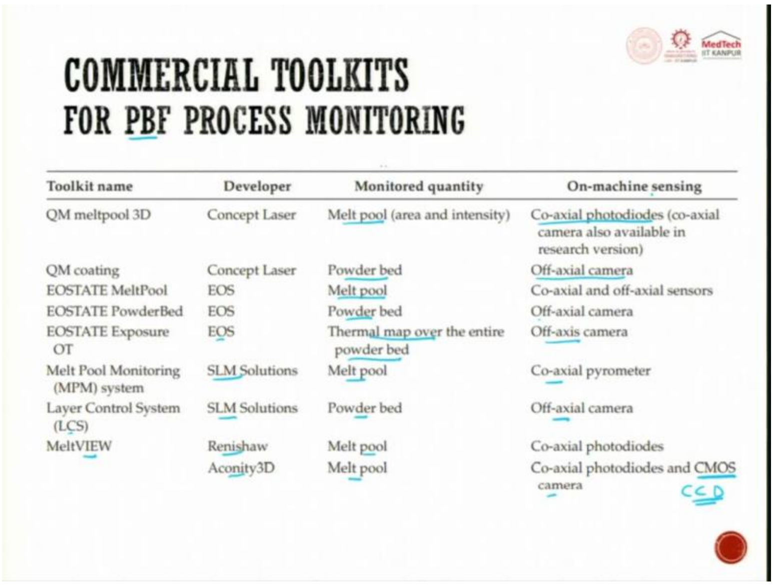

COMMERCIAL TOOLKITS FOR PBF PROCESS MONITORING

Toolkit name	Developer	Monitored quantity	On-machine sensing
QM meltpool 3D	Concept Laser	Melt pool (area and intensity)	Co-axial photodiodes (co-axial camera also available in research version)
QM coating	Concept Laser	Powder bed	Off-axial camera
EOSTATE MeltPool	EOS	Melt pool	Co-axial and off-axial sensors
EOSTATE PowderBed	EOS	Powder bed	Off-axial camera
EOSTATE Exposure OT	EOS	Thermal map over the entire powder bed	Off-axis camera
Melt Pool Monitoring (MPM) system	SLM Solutions	Melt pool	Co-axial pyrometer
Layer Control System (LCS)	SLM Solutions	Powder bed	Off-axial camera
MeltVIEW	Renishaw	Melt pool	Co-axial photodiodes
	Aconity3D	Melt pool	Co-axial photodiodes and CMOS camera

When we look at commercial toolkits for powder bed fusion process monitoring, which is available in the market today, you have QM melt pool 3d, which is developed by concept laser and then it monitors quality like melt pool area and intensity, then on machine sensing is coaxial photodiode, I have discussed in the last class, then you have QM coating, where concept laser is again the developer we do it monitoring control is on a powder bed, so it is off axis axial camera. So, it is co axial photodiode it is off axial camera, then EOSTATE melt pool which is developed by EOS. They try to monitor the melt pool.

So, it is coaxial and off axial sensors are used. Then EOSTATE powder bed we have EOS as developed. So, you have powder bed will be the monitoring quality. Then you have an off axis camera, EOSTATE exposure OT developed by EOS company concept laser is one, there are 2 big giant companies. They look at thermal map over the entire powder bed and they use off axis camera if you look into it, majority of them has used vision and infrared. So melt pool monitoring system is going to be which is developed by SLM solutions, which looks into the melt pool, it works on coaxial pyrometer.

The next one is Layer Control System LCS, which is developed by SLM solutions, which talks about monitoring qualities about the powder bed, it does an off-axial camera when we talk about melt food, which was developed by Renishaw, which is a for melt pool and aconity3D is also done for melt pool. Coaxial photo diodes are used, coaxial photo diodes and CMOS cameras are used for measuring, we discussed last time what are the different types of CCD cameras and CMOS cameras, today in the cell phone we use CMOS cameras.

So, you can read about it for your understanding. So, these are the cameras which are used and in CCD and all you should be doubly sure that the camera does not saturate with respect to the emissivity whatever comes on machine sensing is these are the things which are done today.

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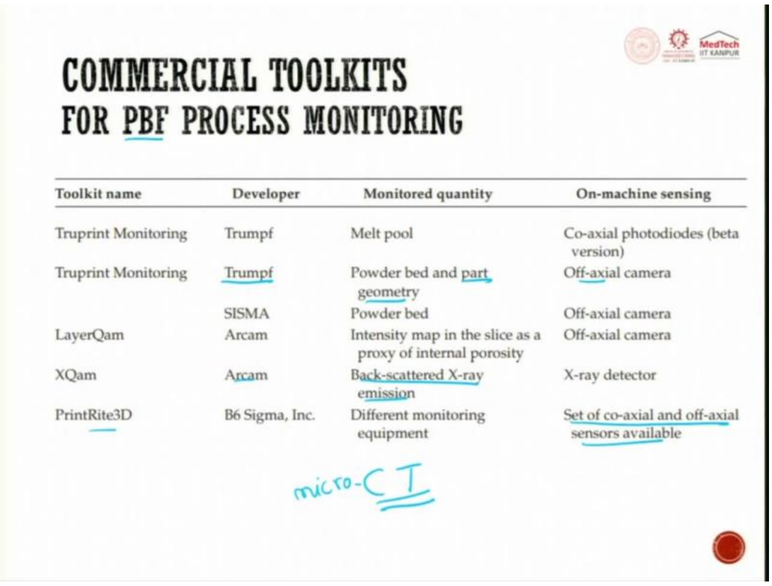

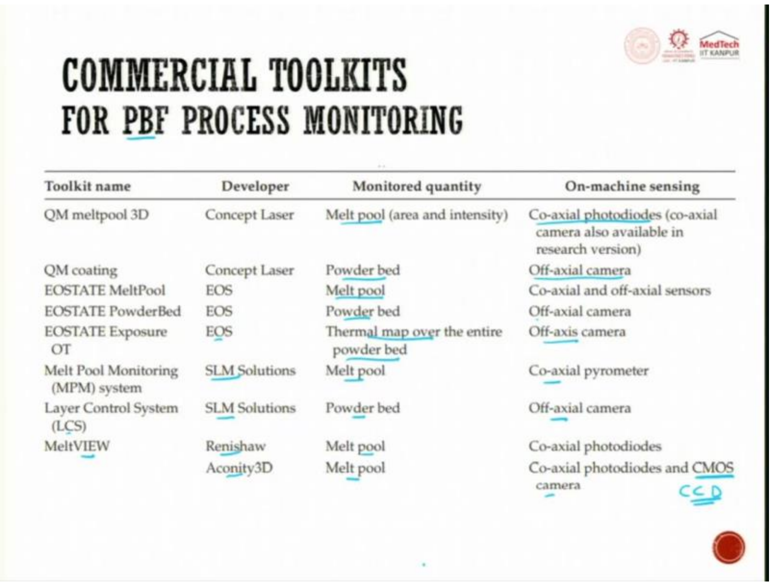

When we look at some more for powder bed fusion process monitoring you have Truprint monitoring, which is Trumpf which is developed by Melt pool, coaxial photodiodes are used. Truprint monitoring which is done by Trumpf which is powder bed and part geometry it also checks, the part geometry is very important. Then it is off axial camera is used layer one is nothing but SISMA, Arcam powder bed is used or intensity mapping in the slice as a proxy of internal porosity is done of axial camera, then XQam is Arcam is the developer and back-scatter X ray look at back-scatter X ray is used. X ray is CT Computer Tomography, which we do for a human.

We have micro CTS which are used today. Then different monitoring equipment are used for monitoring. So set for coaxial and off axial sensor available. So, this is PrintRite3D is a toolkit which is used. So, if you look at it so and the concept laser EOS are the standard companies which produces 3D metal additive manufacturing machines.

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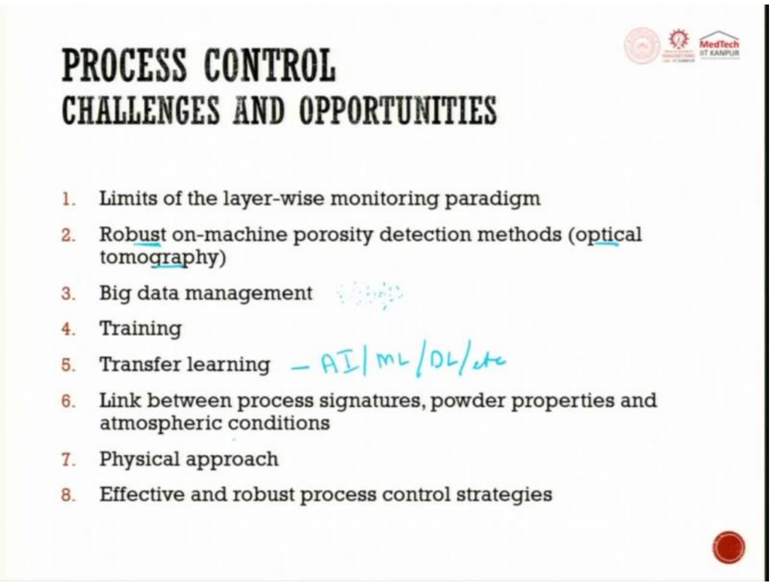

So, some of the process control challenges and opportunities, it limits of the layer wise monitoring paradigm, it is only there if you want to have 3 - 4 layers together and if you want to monitor them, it is very difficult. It limits of the layer wise monitoring paradigm robust on machine porosity deduction method robust so optical tomography can be used. Big Data Management is a big challenge, because when we try to take a thermal image, what you get is only a point cloud data, this point cloud data has to be processed for surface, then the process to surface has to be processed for temperature profile.

So, this makes a big challenge. So, big data management is a big challenge, which is there in front of us then training in using these advanced machines and developing good quality output training is very important, then transfer learning today, not many people have learned metal additive manufacturing in particular in a big way. So, whatever a few people have learned, the transfer of learning is not happening. So here we are now using exhaustively AI, ml, DL etcetera. For our understanding and transfer of learning and training.

Link between process signature, powder properties and atmospheric conditions are even today not established process signature process parameters, which are not even today established the powder properties and atmospheric conditions. Physical approach is a major challenge. Effective and robust process control strategies are even today trying to be explained or developed for strategic applications.

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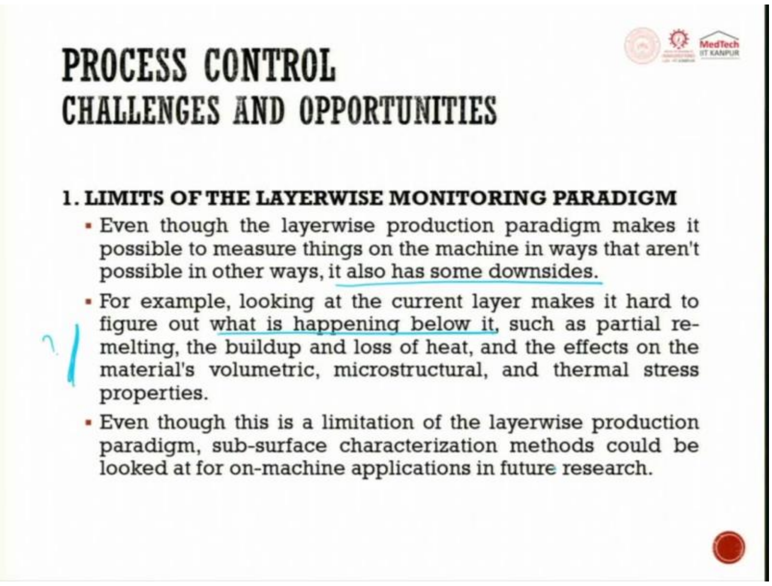

So, when we look into limit of the layer vise monitoring paradigm, even though the layer wise production paradigm makes it possible to measure things on the machine in ways that are not possible, in other ways, it also has some downside. For example, we are looking at a current layer makes it hard to figure out what is happening below this is what I said when you look at the top layer what happens in the below we do not know. Such a partial remelt and built up and loose of heat and the effect on which the material volumetric, micro structural and thermal stresses properties or thermal properties come into existence.

So, this is a challenge. So, here when we talk about layer wise production paradigm, we are trying to look at what happens below it top layer bottom layer what happens below it that is what is very important and when you do it, there is something called as partial re-melt. Even though this is a limitation of the layer based production paradigm, several surface characterization methods have been developed today to look at on machine application.

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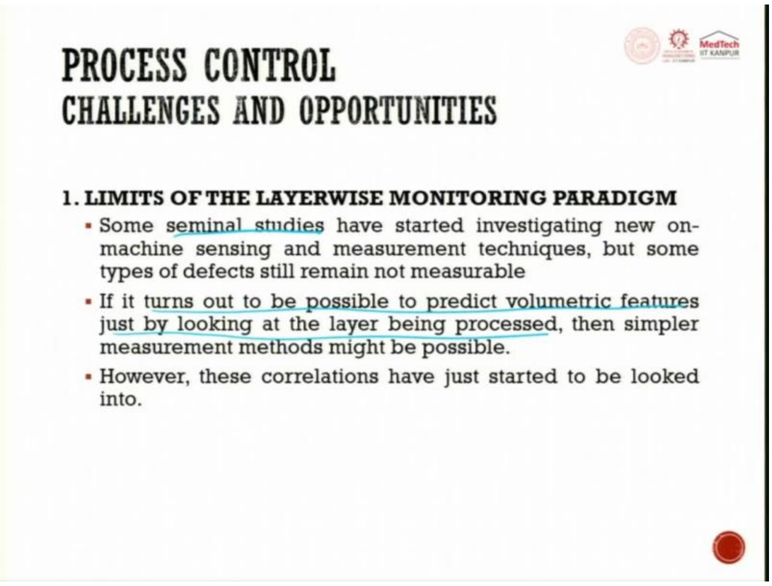

Some seminal studies have started investigation, new on machine sensing and measurement techniques. So, it is turned out to be possible to predict volumetric features just by looking at the layer being processed. Now, the techniques are also introducing the studies. However, these correlations have just started to be looked into.

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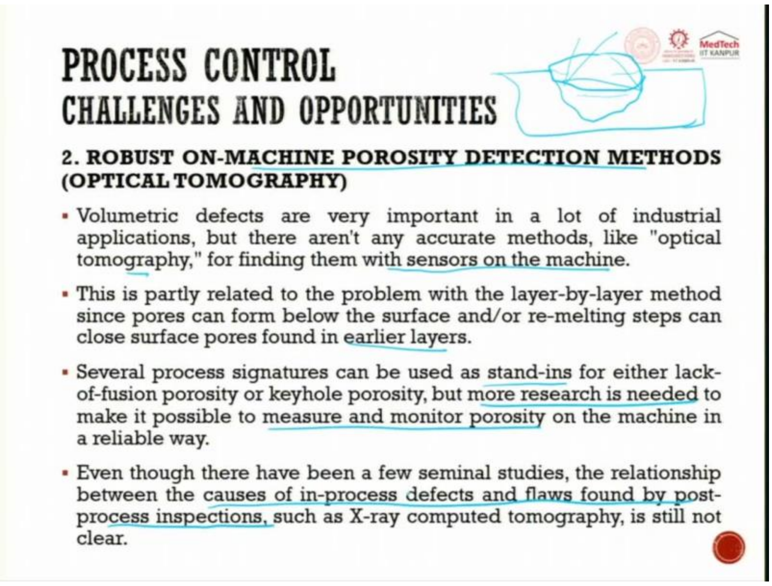

Using these machines, like a dumb box does not mean anything. Buying a metal additive manufacturing machine and understanding each and every process, its parameter understanding the process parameter influence on the sound quality output, all this knowledge is very important. Once you have your big set of data or big set of knowledge, then you are mastering the process and you are trying to develop sound quality output otherwise, people are even today using it just like a machine a black box, you fit in the drawing, you get the output whatever you want and then you keep going. Moment there is a defect, they redo it, but that is not the way that we are looking forward through you.

So, robust on machine porosity detection methods are getting developed today. For example, if you have your 3 dimensional picture on top of a layer or on an inner layer, suppose let us assume that you have a pit like this. Now, how do you characterize it? What are all the characterization tools which are available to do it, if you do it in contact, you will try to scribe over one surface but what you have here is your area, then when you try to scribe it is also you try to scribe only one layer of information which is there that can be here on the top or that can be at the bottom. So, this is a big challenge for us to develop.

So, here volumetric defects are very important in a lot of industrial applications volumetric efficient. So, if you try and take a photo also it is very difficult, because this photo of light will get reflected. It will get internally reflected. So trying to get the entire detail through an optical tomography is a challenge. So, volumetric defects are very important in a lot of industrial applications, but there are not any accurate method like optical tomography for finding out with sensors on the machine, but optical also has its limitation, if you try to do X ray, so, then it is very difficult for you to do layer by layer.

Once the process or the core part is made, then you can go for X ray, but during the process optical tomography is the most acceptable technique, this is partially related to the problem with the layer by layer method, since pores can form below the surface or remelting step and can close the surface pores found in the earlier layer. So, this is where we are stuck one layer might have a pore the subsequent layer might not have a pore.

So, then we are stuck with the technique, several process signatures can be used as stand ins for lack of fusion porosities or key hole porosities. But more research is needed to make it possible to measure and monitor porosities it is very important more research has to be done it is not that like a thermometer what you push it into a person you measure the temperature it is not like that, like a pulse oximeter what you put in your finger it is not like that. Here, it needs still needs a lot of development lot of data, we do not have a lot of data also nowadays and people have just started sharing data.

In fact, if we wanted to have an additive manufacturing standard for Indian standard, we do not have it we know currently ASTM has started or ASME has started and then subsequently

Japan has started Euro has started now they are all looking for what are the standard parameters, standard testing devices or standards to be followed we are now looking forward because it is a growing area and the lack of fusion porosity or keyhole porosity is very important.

Even though there have been a few seminal studies the relationship between the costs in the process defect and the flaw found in the post processing inspection can be such as X ray tomography is still not very clear. During the process measurement and after the product is measured through an x ray CT, we are still not able to correlate what is this with respect to that coming.

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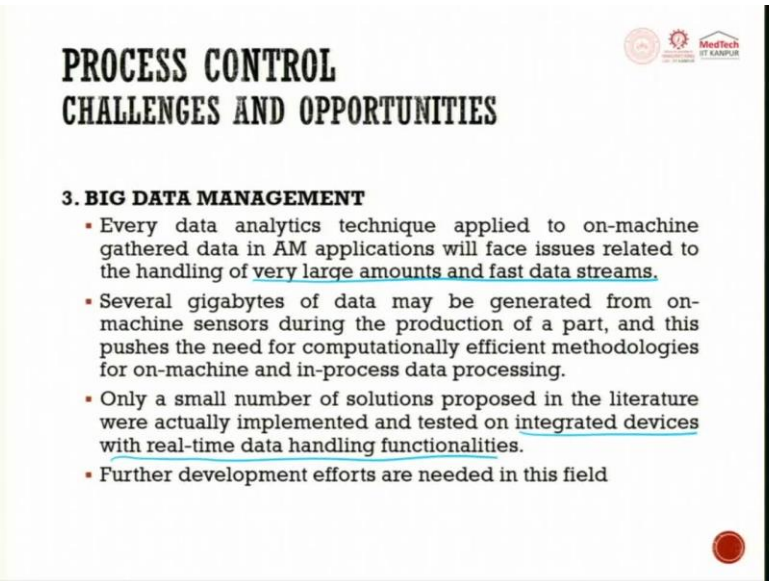

Big Data Management every data analytical technique applied to on machine gather data will face issues related to handling of a very large and very fast stream data. If you are trying to look at spatial resolution, we look at time and we also look at space. So fast space streams is there several giga bytes of data may be generated from one machine sensor during the production of the part only a small number of solution proposed in the literature were actually implemented and tested on integrated device with real time data handling system there is a lot of development, which has to happen in the big data.

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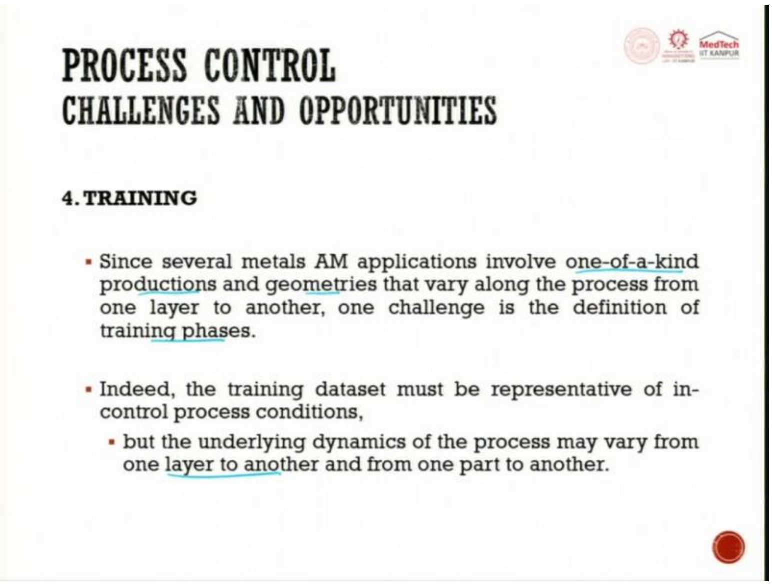

Since several metal additive manufacturing applications involve one of a kind production and geometries that vary along the process from one layer to the one challenge is the definition of training phase. That is what I told you. So, you have one of a kind production one geometry, suppose you produce 100 parts, then you can try to establish your empirical rule. If you are trying to produce one of its kind, then it is very difficult for you to take that knowledge and transfer it to some other shape. Indeed, the training database must be represented in control process condition, but the underlying dynamics of the process may vary from one layer to the other from one part to another.

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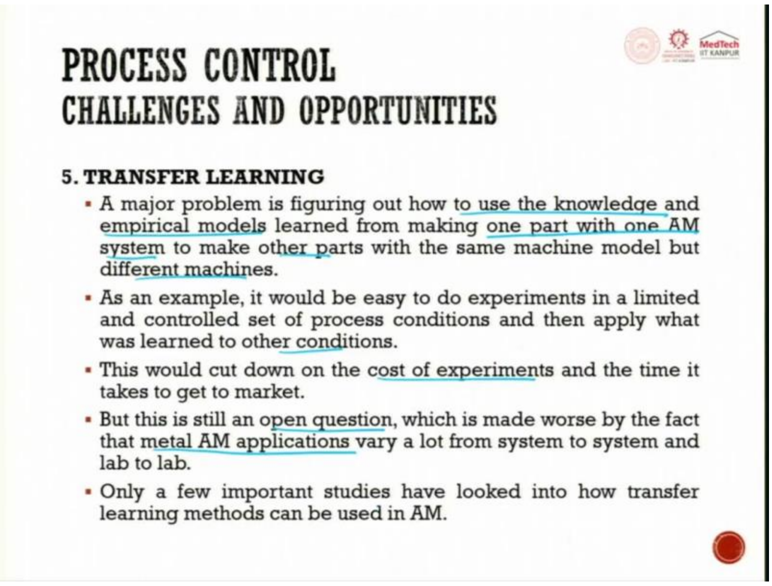

The transfer learning major problem is figuring out how to use the knowledge and empirical models learned from making one part with one additive manufacturing system to another part with the same machine model but different machine. So, this is what use of knowledge and empirical model transfer making one part with one am system to another part in the same machine model but a different machine.

As an example, it would be easy to do experiments in limited uncontrolled setup process conditions as they apply what was learned from the other condition. This would cut down the cost of experiments, but this is still an open question, which is made worse by the fact of metal additive manufacturing application. Only a few important studies have looked into and how transfer of learning methods can be done in AM.

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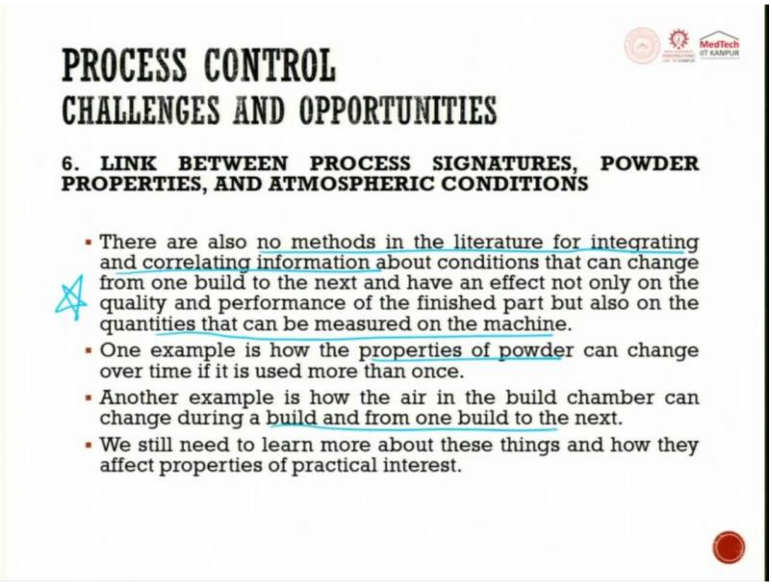

Link between process signature powder properties atmospheric condition. There is no method in the literature for integrating and correlating information about conditions that can change from one build to the next and have an effect not only on the quality and performance of the finished part, but also on the quantities that can be measured on the machine, very important point.

One example is how the properties of powder can change over time, that is true, when you used properties of powder, what happens is when you use it once, and then you try to suck it, then next time you use the same powder, then you remove all the powders which have not used. So, when you do it multiple times the property of the powder changes, though the powder particle was not involved in sintering, but the heat transfer would have happened in the powder bed. So, the property of the powder changes. Another example is how the air in the bed chamber can change during the build from one build to the other, we still need to learn about these things, how they affect the properties.

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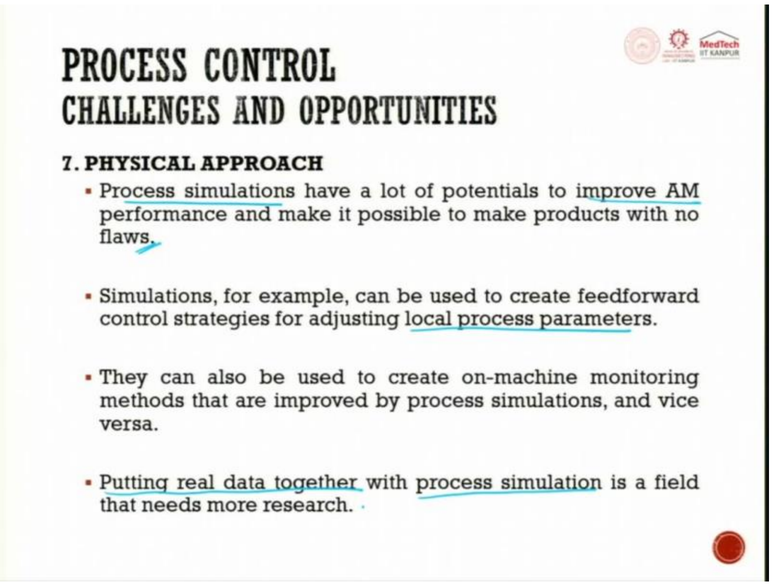

Physical approach, process simulation have a lot of potential to improve AM performance and make it possible to make products with low flaw. So, that is why we do process simulation in many of the process simulation whatever is available today, we try to simulate and see how the hatch patterns is happening, how much time will it take to build all those things, but we are still not in a position to simulate and see what happens to the metal powder for this response over a large area.

Molecular dynamics simulations are also exhaustively used to do process simulation during the process, but it is still a long way to go simulations for example, can be used to create feed forward control strategies for adjusting local process parameters. They can also be used to create on mission monitoring method that are improved by process simulation and vice versa. Putting real time data together with process simulation is a field putting real time data together with process simulation is a field that needs to be researched.

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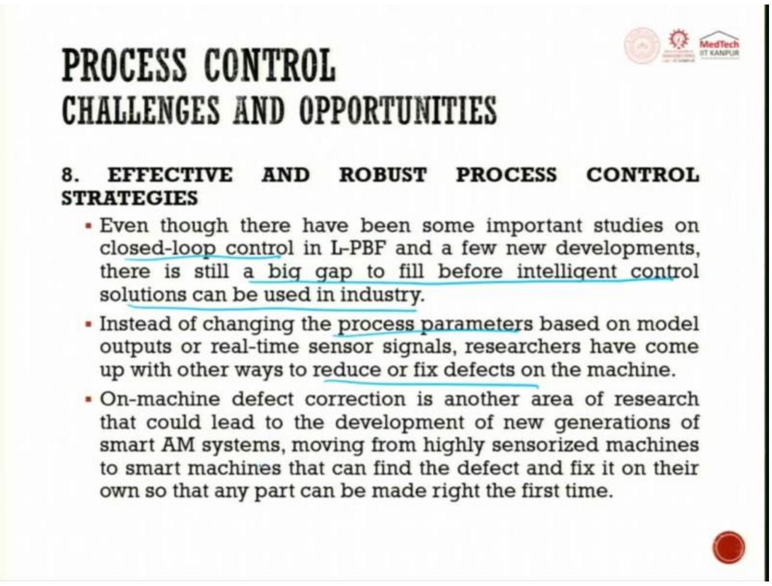

Why am I giving so much of importance to all these in process and other things is because people always think once you finish your CAD you dump it into the machine, you will get what you want sorry, it is very difficult what you think and what you get is the same, you have to understand the process, you have to tweak the process parameters such that the best out of the machine can be taken out. Effective and robust process control strategies.

Even though there have been some important studies of closed loop control a few new developments are still a big gap to fill between before intelligent control system can be used in industry, instead of changing the process parameters which is always thought of based on the model output real time sensor signals researchers have come up with other way to reduce and fix the defects on machine defect control is another area of research which could lead to the development of new generation of smart additive manufacturing.

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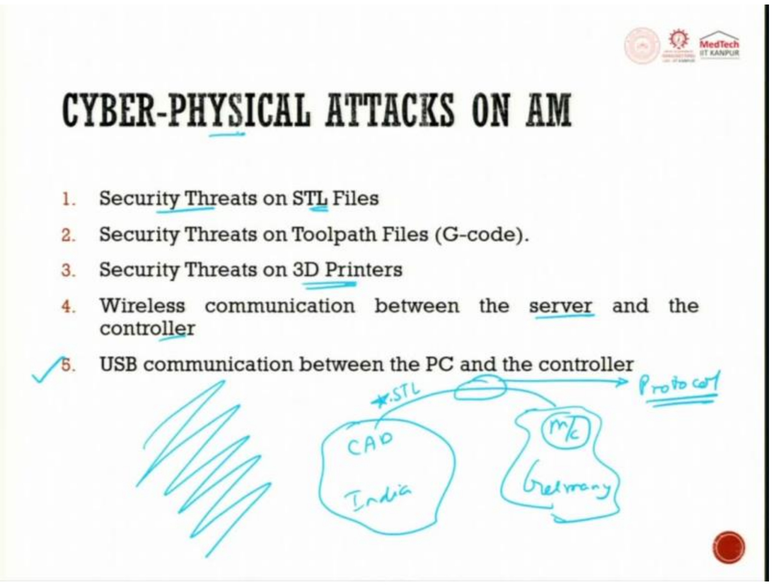

Some of the cyber physical attacks which are happening on additive manufacturing security threat on STL files, when we are trying to transfer the CAD drawing along with a neutral file, there is a breach of trust and people can start tampering with the STL file moment you tamper with the STL file whatever the file gets communicated to the machine, we still have a problem what are we talking about say for example, you have a country like India. So, India, so where they do India, where they do a CAD.

So, suppose let us try to take another country maybe Germany, where they have this machine. Today what we are talking about this transferring data from here to here after you make CAD you make an STL file star dot STL and then you transfer the data the machine is available here the machine will be running 24 by 7 this data transfer happens here currently when we are transferring it we do not have a clear policy clear protocol to protect the tampering of the data or the truthfulness of the data is converted to is carried to the machine. So there can be a security threat on STL file transfer there can be threat on tool path file.

So, tool path file is the way you are trying to move inside our layer then threat on 3D printer itself. So, they tried whatever data you give they try to tamper it wireless communication between the server and the controller. Today we try to use RS 232C the latest version. But we are now trying to see how can we wirelessly communicate between the server and the controller.

Then USB communication between the PC and the controller, this to a large extent is happening today, where there are several IEEE standards available today which are working on this, there is a big research group across the globe who are trying to work on cyber security threat of STL files, there is a big difference between the STL file getting transferred and their normal high voluminous binary data for getting transferred here you have more number of headers, footers and connecting statements and other details, but that is not there in a normal Word format which gets more so, this is the major challenge for the cyber physical attack on AM.

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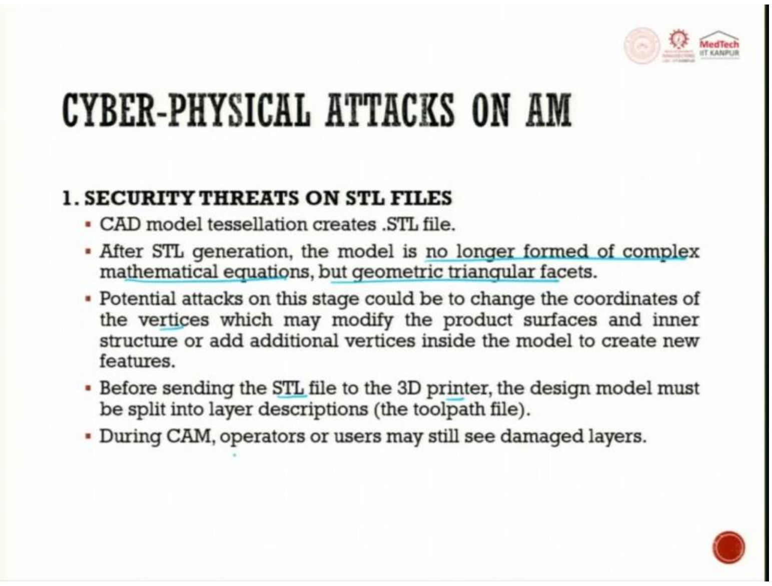

The security is CAD model tessellation creates STL file after STL file generation the model is no longer form of complex mathematical equation but geometrical triangles. So, this is what I said it is no more a mathematical equation it has geometry, the potential attack on this stage can be to change the coordinates and the vertices before the sending the STL file to 3D printer. The Design Modeler must be split into layer description for the toolpath during camp operations and the users may still see damaged layer.

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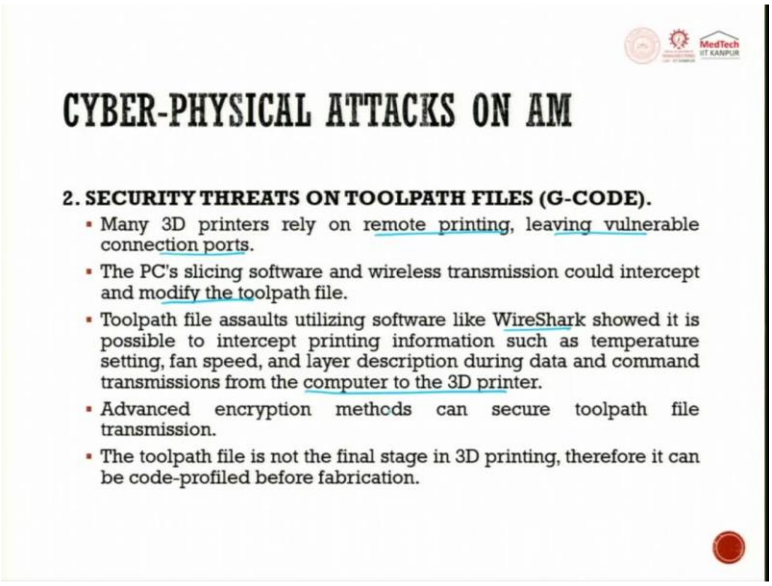

Security threat on toolpath file. So, this is remote printing leaving vulnerable connection ports. So, the PC slicing software and the wireless transmission could interpret and modify the toolpath. The toolpath file assaults utilizing software like Wireshark showed it is possible to interpret printing information such as temperature setting, fan speed layer description, during the data and command transmission from the computer to 3D printing. advanced encryption methods are thought of at this stage.

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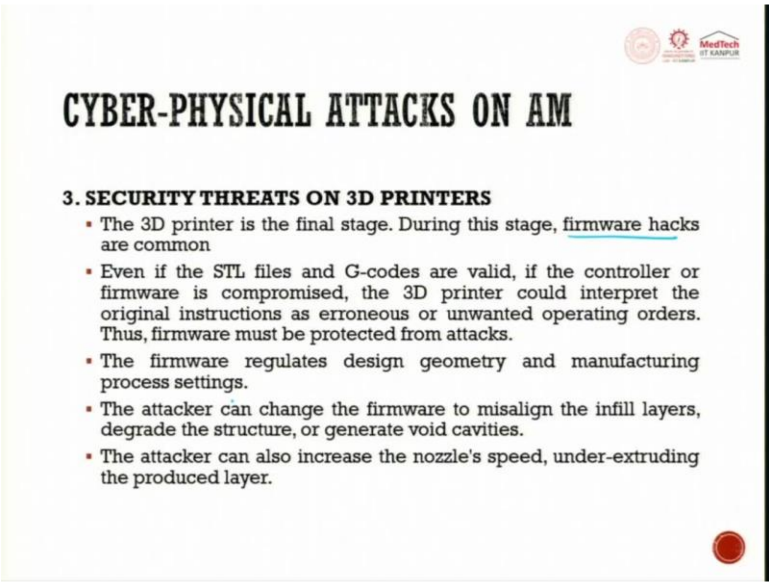

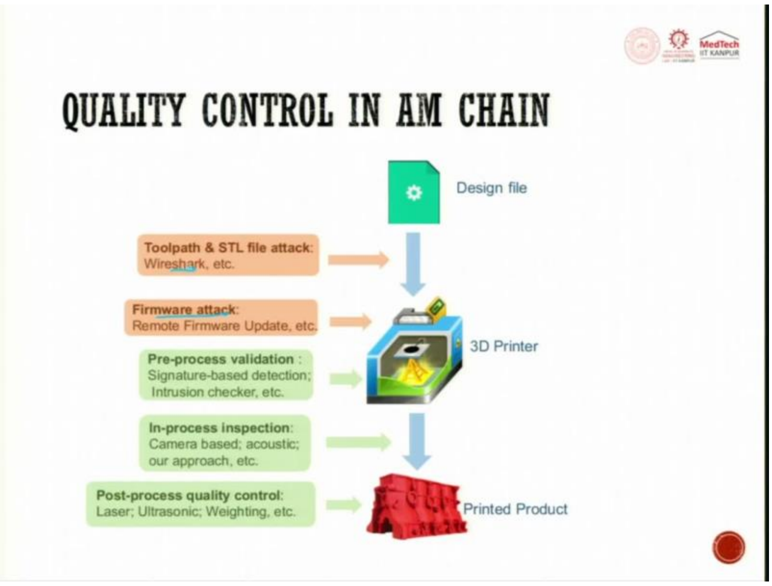

When we are trying to talk about threat to 3D printer, a 3D printer is the final stage. During this stage firmware hacks are common. We saw that all these things, so if you are able to recollect to our previous thing.

So, we said here you can see firmware attack, Wireshark so, all these things have said here. So, these are the cyber security threat which are available today. So, even if the STL file and the G codes are valid, if the controller or the firmware is compromised, the 3D printer could interpret the original instruction as unwanted operating orders. Thus, firmware must be protected from attacked. The firmware regulates design geometry and the manufacturing process setting.

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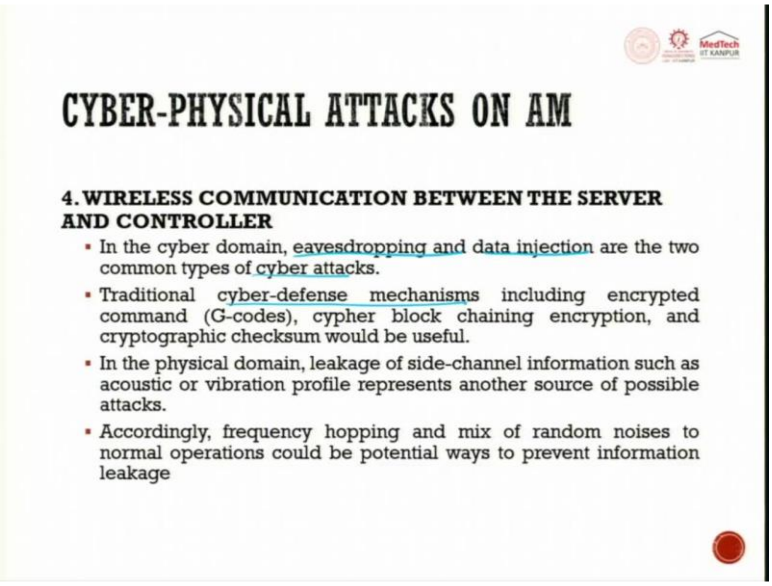

When we are looking at Wi Fi. So, in the cyber domain eavesdropping and data injection are 2 common types of cyber attack. So, traditional cyber defense mechanism including encrypted code Cyper, Blockchain encryption and cryptographic checksum would be used in the traditional cyber mechanisms. In the physical domain leakage of side channel information must such as acoustic and vibration provide represents another source of possibility accordingly, frequency hopping and mix of random noises to normal operation could be the potential way to prevent the information getting used.

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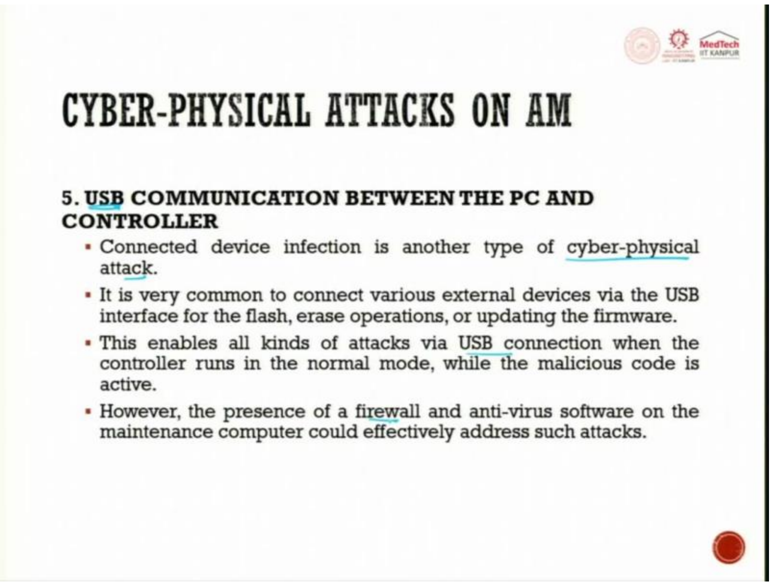

So, connected device infection is another type of cyber physical attack. So, when we use a USB, USB has a virus injected to it. So, it is very common to connect various external devices via USB, this enables all kinds of attack via USB connection. However, the presence of firewall and the anti-virus software on the maintenance of computer to set effectively.

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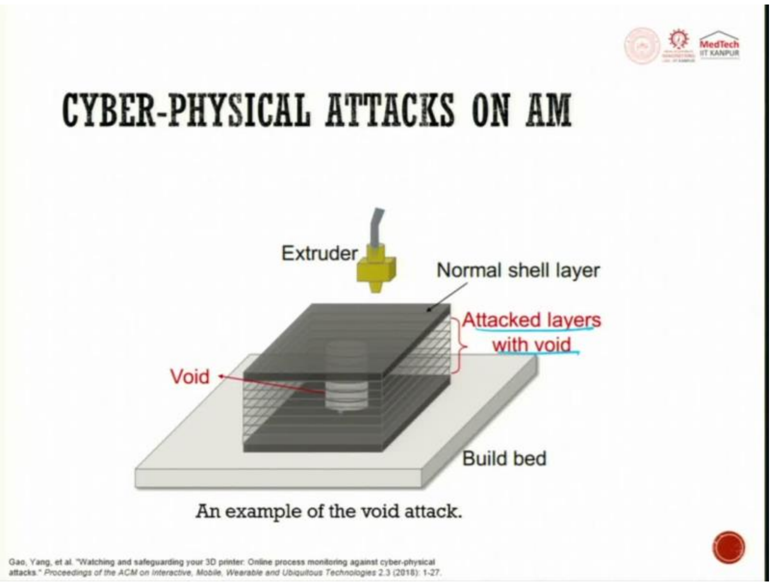

This is the cyber physical attack on AM so you have additive manufacturing. So, this is extruded, this is a normal shell layer, these are the attacked layers with wire which was not there in the original part. So, this is a cyber attack which is created.

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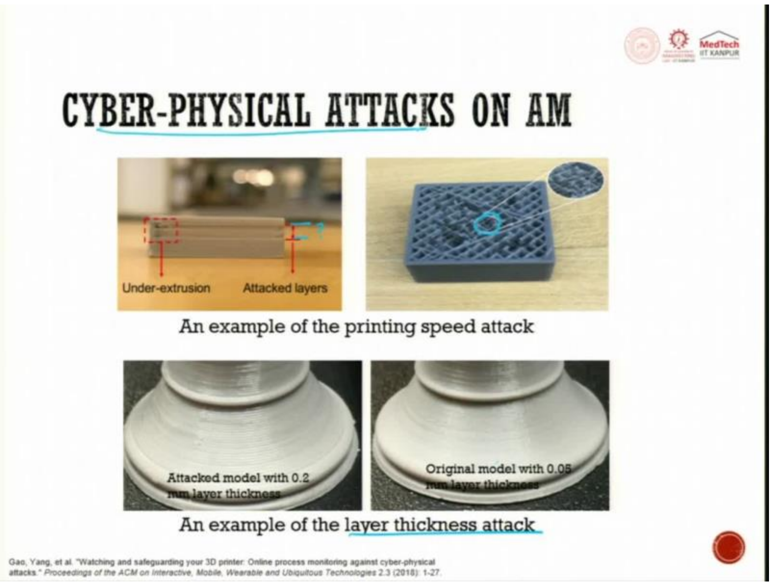

So, an example for printing speed attack. So, you see here under extrusion has happened here. So, you see here, there is a print attack which has happened here attack model with point 2 millimeter layer thickness, this is 0.05 layer millimeter thickness. So, we wanted 0.05 we got at 0.2 or we wanted 0.2 we got at 0.05. So, the layer thickness attack has happened here, the attack layer you see here it is the attack layer. So, here you can see there is an attack layer. So, these are all cyber physical attack which is created on AM.

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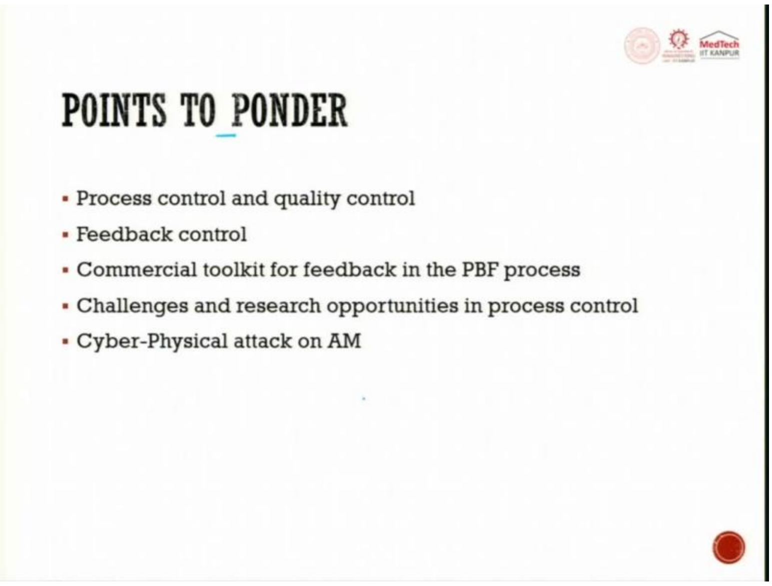

So, what did we cover in this lecture points to ponder the process control and quality control was discussed. Then feedback control was discussed commercial toolkits which are available for feedback in powder bed fusion process was done. Challenges and research opportunities in process control and cyber physical attack on AM was discussed.

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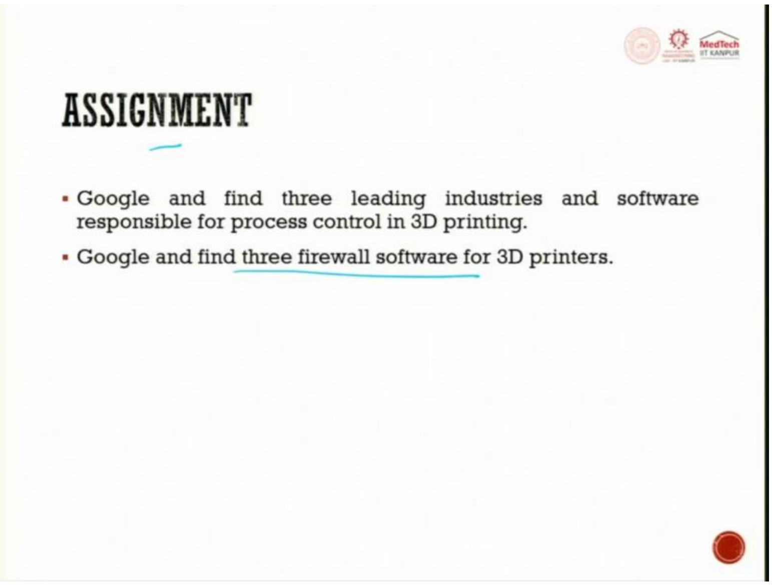

So, assignment, Google and find 3 leading industries and software responsible for process control in 3D printing, Google and find the 3 firewall software for 3D printing please do this. So, this when you start doing it, you will try to know the name and you will try to see the features which are available that will try to give you more understanding on this lecture whatever we discussed, with that, I would like to thank you all for listening to this lecture. Thank you very much.