



IN-SITU CONTROL SYSTEM

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CONTENTS

- Process control
- Control objectives
- Quality control in AM chain
- Feedback control
- Commercial toolkits for PBF process
- Challenge and opportunities in process control
- Cyber-Physical attacks on AM



PROCESS CONTROL

- On-machine monitoring enables 'intelligent' AM capabilities.
- Such technologies enable the automated detection 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, resources, and scrap waste.
- Alarms usually cause process stoppage.
- First-time-right and zero-defect AM require advanced process control and modification.



PROCESS CONTROL

- Current industrial procedures identify processability windows for each material.
- This leads to material-dependent process parameters for any material-produced shape.
- Varied geometrical characteristics, part orientations in the construction, and support designs demand different process parameters to account for local and global heat accumulation and dissipation effects.
- For this, feedback and feedforward control techniques are available.

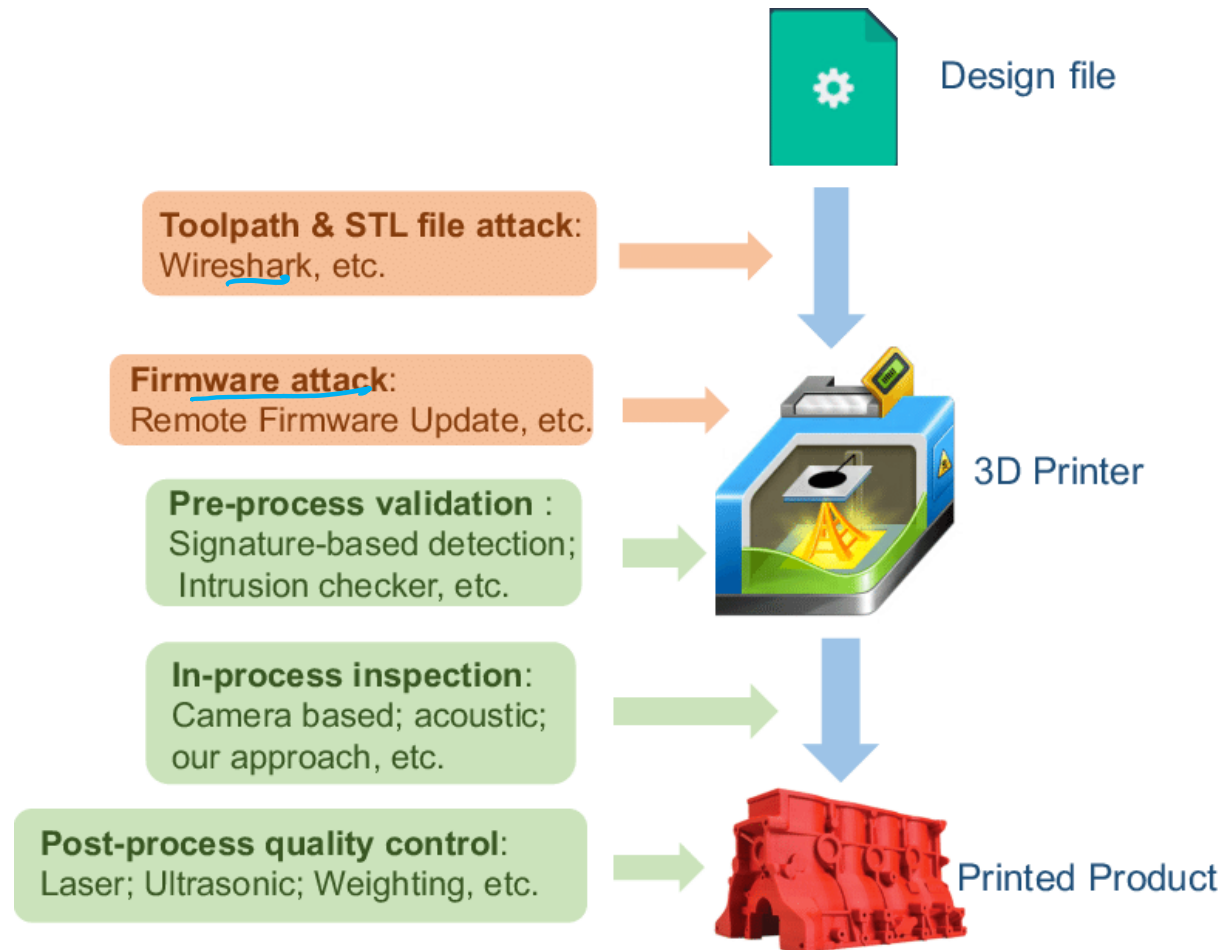


CONTROL OBJECTIVES

1. Optimize the process parameter
2. Increase the overall efficiency and repeatability
3. Ensure the overall safety during printing process



QUALITY CONTROL IN AM CHAIN

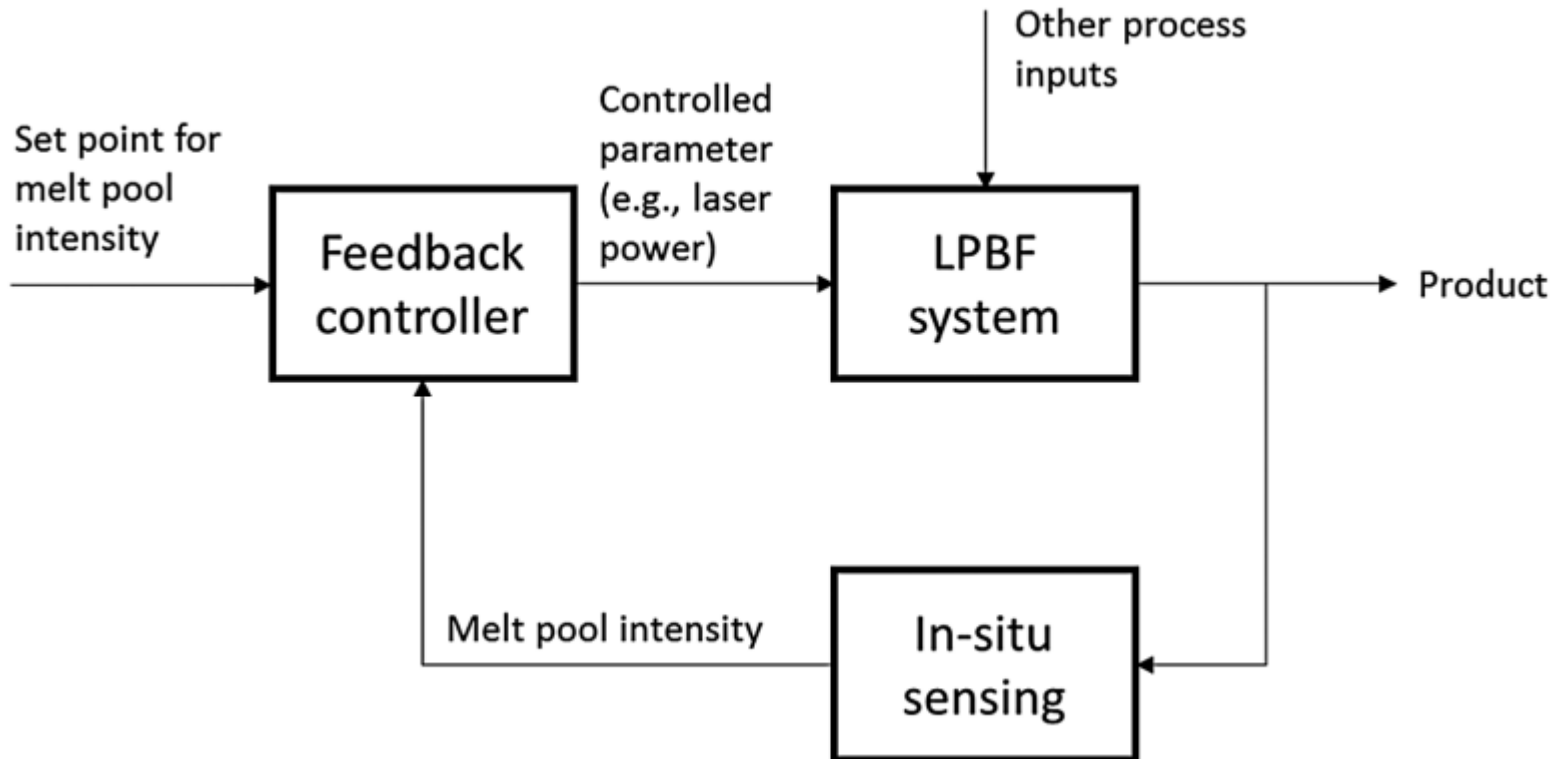


FEEDBACK CONTROL

- A feedback control approach involves closed-loop adaptation of a pre-defined process parameter based on real-time on-machine sensor recording of a target-referenced quantity.
- The controller compares the current sensor reading to the set point and adjusts the controlled variable, so the difference is as little as feasible.
- PID controllers alter the controlled output depending on
 - i. The instantaneous difference between the current signal and the set point (proportional action),
 - ii. The past difference values (integral action), and
 - iii. How fast the difference evolves over time (derivative action).



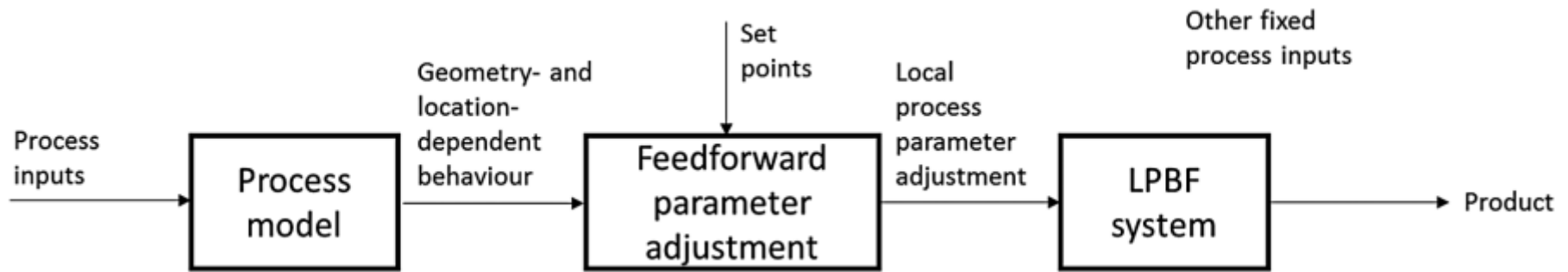
FEEDBACK CONTROL



Example of feedback control scheme in L-PBF.



FEEDBACK CONTROL



Example of feedforward control scheme in PBF.



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



COMMERCIAL TOOLKITS FOR PBF PROCESS MONITORING

Toolkit name	Developer	Monitored quantity	On-machine sensing
Truprint Monitoring	Trumpf	Melt pool	Co-axial photodiodes (beta version)
Truprint Monitoring	Trumpf	Powder bed and part geometry	Off-axial camera
LayerQam	SISMA	Powder bed	Off-axial camera
	Arcam	Intensity map in the slice as a proxy of internal porosity	Off-axial camera
XQam	Arcam	Back-scattered X-ray emission	X-ray detector
PrintRite3D	B6 Sigma, Inc.	Different monitoring equipment	Set of co-axial and off-axial sensors available



PROCESS CONTROL CHALLENGES AND OPPORTUNITIES

1. Limits of the layer-wise monitoring paradigm
2. Robust on-machine porosity detection methods (optical tomography)
3. Big data management
4. Training
5. Transfer learning
6. Link between process signatures, powder properties and atmospheric conditions
7. Physical approach
8. Effective and robust process control strategies



PROCESS CONTROL CHALLENGES AND OPPORTUNITIES

1. LIMITS OF THE LAYERWISE MONITORING PARADIGM

- Even though the layerwise production paradigm makes it possible to measure things on the machine in ways that aren't possible in other ways, it also has some downsides.
- For example, looking at the current layer makes it hard to figure out what is happening below it, such as partial re-melting, the buildup and loss of heat, and the effects on the material's volumetric, microstructural, and thermal stress properties.
- Even though this is a limitation of the layerwise production paradigm, sub-surface characterization methods could be looked at for on-machine applications in future research.



PROCESS CONTROL CHALLENGES AND OPPORTUNITIES

1. LIMITS OF THE LAYERWISE MONITORING PARADIGM

- Some seminal studies have started investigating new on-machine sensing and measurement techniques, but some types of defects still remain not measurable
- If it turns out to be possible to predict volumetric features just by looking at the layer being processed, then simpler measurement methods might be possible.
- However, these correlations have just started to be looked into.



PROCESS CONTROL CHALLENGES AND OPPORTUNITIES

2. ROBUST ON-MACHINE POROSITY DETECTION METHODS (OPTICAL TOMOGRAPHY)

- Volumetric defects are very important in a lot of industrial applications, but there aren't any accurate methods, like "optical tomography," for finding them with sensors on the machine.
- This is partly related to the problem with the layer-by-layer method since pores can form below the surface and/or re-melting steps can close surface pores found in earlier layers.
- Several process signatures can be used as stand-ins for either lack-of-fusion porosity or keyhole porosity, but more research is needed to make it possible to measure and monitor porosity on the machine in a reliable way.
- Even though there have been a few seminal studies, the relationship between the causes of in-process defects and flaws found by post-process inspections, such as X-ray computed tomography, is still not clear.



PROCESS CONTROL

CHALLENGES AND OPPORTUNITIES

3. BIG DATA MANAGEMENT

- Every data analytics technique applied to on-machine gathered data in AM applications will face issues related to the handling of very large amounts and fast data streams.
- Several gigabytes of data may be generated from on-machine sensors during the production of a part, and this pushes the need for computationally efficient methodologies for on-machine and in-process data processing.
- Only a small number of solutions proposed in the literature were actually implemented and tested on integrated devices with real-time data handling functionalities.
- Further development efforts are needed in this field



PROCESS CONTROL CHALLENGES AND OPPORTUNITIES

4. TRAINING

- Since several metals AM applications involve one-of-a-kind productions and geometries that vary along the process from one layer to another, one challenge is the definition of training phases.
- Indeed, the training dataset must be representative of in-control process conditions,
 - but the underlying dynamics of the process may vary from one layer to another and from one part to another.



PROCESS CONTROL CHALLENGES AND OPPORTUNITIES

5. TRANSFER LEARNING

- A major problem is figuring out how to use the knowledge and empirical models learned from making one part with one AM system to make other parts with the same machine model but different machines.
- As an example, it would be easy to do experiments in a limited and controlled set of process conditions and then apply what was learned to other conditions.
- This would cut down on the cost of experiments and the time it takes to get to market.
- But this is still an open question, which is made worse by the fact that metal AM applications vary a lot from system to system and lab to lab.
- Only a few important studies have looked into how transfer learning methods can be used in AM.



PROCESS CONTROL

CHALLENGES AND OPPORTUNITIES

6. LINK BETWEEN PROCESS SIGNATURES, POWDER PROPERTIES, AND ATMOSPHERIC CONDITIONS

- There are also no methods 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.
- One example is how the properties of powder can change over time if it is used more than once.
- Another example is how the air in the build chamber can change during a build and from one build to the next.
- We still need to learn more about these things and how they affect properties of practical interest.



PROCESS CONTROL CHALLENGES AND OPPORTUNITIES

7. PHYSICAL APPROACH

- Process simulations have a lot of potentials to improve AM performance and make it possible to make products with no flaws.
- Simulations, for example, can be used to create feedforward control strategies for adjusting local process parameters.
- They can also be used to create on-machine monitoring methods that are improved by process simulations, and vice versa.
- Putting real data together with process simulation is a field that needs more research.



PROCESS CONTROL CHALLENGES AND OPPORTUNITIES

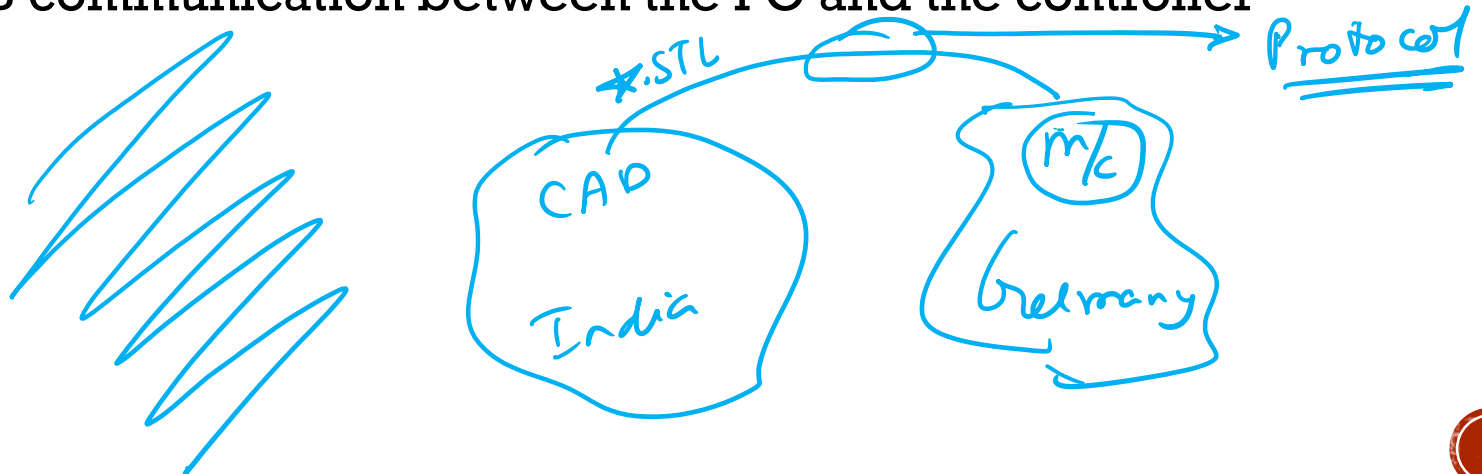
8. EFFECTIVE AND ROBUST PROCESS CONTROL STRATEGIES

- Even though there have been some important studies on closed-loop control in L-PBF and a few new developments, there is still a big gap to fill before intelligent control solutions can be used in industry.
- Instead of changing the process parameters based on model outputs or real-time sensor signals, researchers have come up with other ways to reduce or fix defects on the machine.
- On-machine defect correction is another area of research that could lead to the development of new generations of smart AM systems, moving from highly sensorized machines to smart machines that can find the defect and fix it on their own so that any part can be made right the first time.



CYBER-PHYSICAL ATTACKS ON AM

1. Security Threats on STL Files
2. Security Threats on Toolpath Files (G-code).
3. Security Threats on 3D Printers
4. Wireless communication between the server and the controller
- ✓ 5. USB communication between the PC and the controller



CYBER-PHYSICAL ATTACKS ON AM

1. SECURITY THREATS ON STL FILES

- CAD model tessellation creates .STL file.
- After STL generation, the model is no longer formed of complex mathematical equations, but geometric triangular facets.
- Potential attacks on this stage could be to change the coordinates of the vertices which may modify the product surfaces and inner structure or add additional vertices inside the model to create new features.
- Before sending the STL file to the 3D printer, the design model must be split into layer descriptions (the toolpath file).
- During CAM, operators or users may still see damaged layers.



CYBER-PHYSICAL ATTACKS ON AM

2. SECURITY THREATS ON TOOLPATH FILES (G-CODE).

- Many 3D printers rely on remote printing, leaving vulnerable connection ports.
- The PC's slicing software and wireless transmission could intercept and modify the toolpath file.
- Toolpath file assaults utilizing software like WireShark showed it is possible to intercept printing information such as temperature setting, fan speed, and layer description during data and command transmissions from the computer to the 3D printer.
- Advanced encryption methods can secure toolpath file transmission.
- The toolpath file is not the final stage in 3D printing, therefore it can be code-profiled before fabrication.



CYBER-PHYSICAL ATTACKS ON AM

3. SECURITY THREATS ON 3D PRINTERS

- The 3D printer is the final stage. During this stage, firmware hacks are common
- Even if the STL files and G-codes are valid, if the controller or firmware is compromised, the 3D printer could interpret the original instructions as erroneous or unwanted operating orders. Thus, firmware must be protected from attacks.
- The firmware regulates design geometry and manufacturing process settings.
- The attacker can change the firmware to misalign the infill layers, degrade the structure, or generate void cavities.
- The attacker can also increase the nozzle's speed, under-extruding the produced layer.



CYBER-PHYSICAL ATTACKS ON AM

4. WIRELESS COMMUNICATION BETWEEN THE SERVER AND CONTROLLER

- In the cyber domain, eavesdropping and data injection are the two common types of cyber attacks.
- Traditional cyber-defense mechanisms including encrypted command (G-codes), cypher block chaining encryption, and cryptographic checksum would be useful.
- In the physical domain, leakage of side-channel information such as acoustic or vibration profile represents another source of possible attacks.
- Accordingly, frequency hopping and mix of random noises to normal operations could be potential ways to prevent information leakage



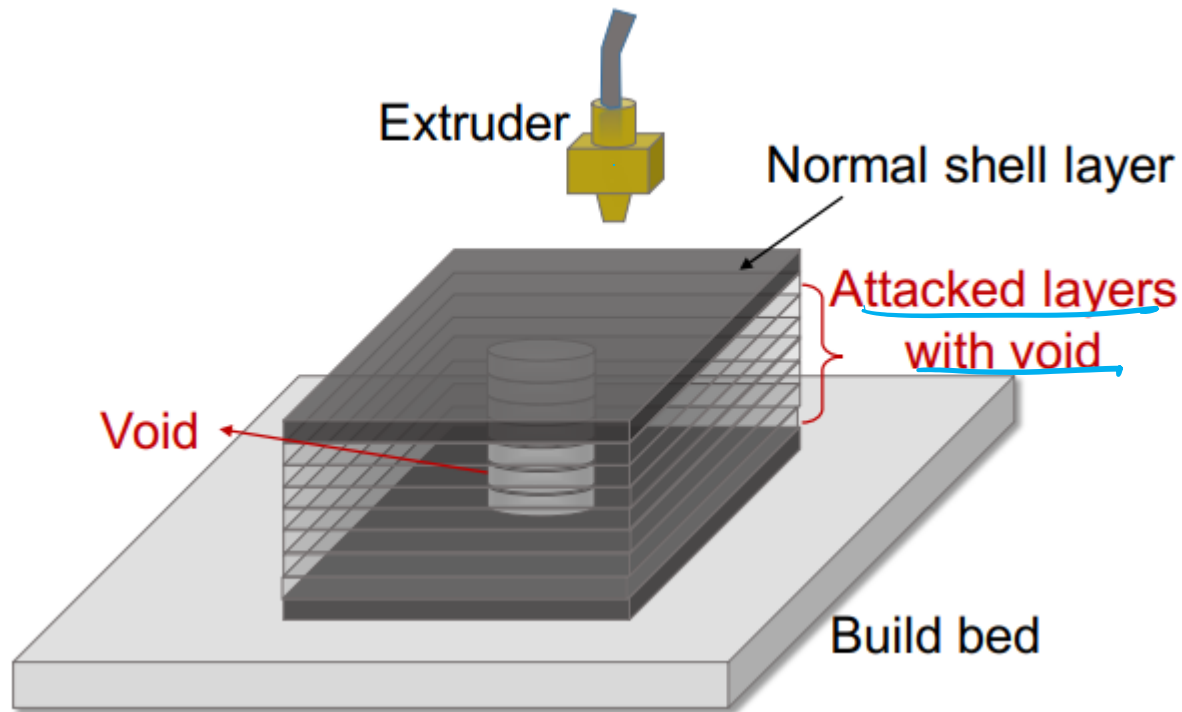
CYBER-PHYSICAL ATTACKS ON AM

5. USB COMMUNICATION BETWEEN THE PC AND CONTROLLER

- Connected device infection is another type of cyber-physical attack.
- It is very common to connect various external devices via the USB interface for the flash, erase operations, or updating the firmware.
- This enables all kinds of attacks via USB connection when the controller runs in the normal mode, while the malicious code is active.
- However, the presence of a firewall and anti-virus software on the maintenance computer could effectively address such attacks.



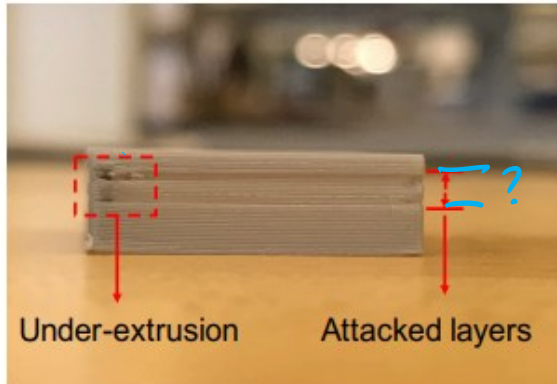
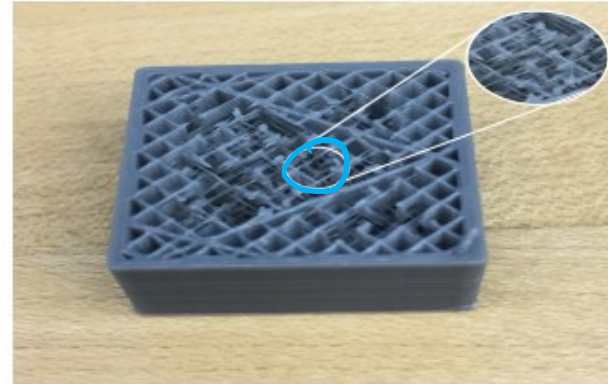
CYBER-PHYSICAL ATTACKS ON AM



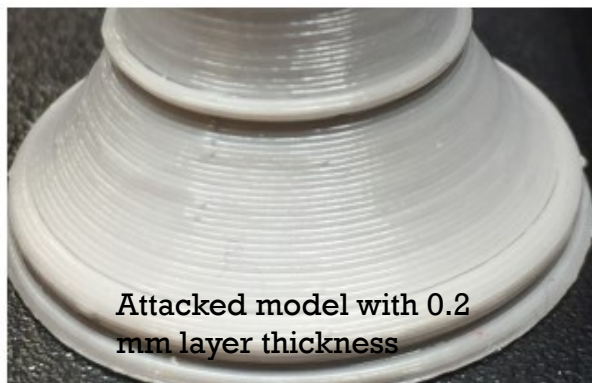
An example of the void attack.



CYBER-PHYSICAL ATTACKS ON AM



An example of the printing speed attack



An example of the layer thickness attack



POINTS TO PONDER

- Process control and quality control
- Feedback control
- Commercial toolkit for feedback in the PBF process
- Challenges and research opportunities in process control
- Cyber-Physical attack on AM



ASSIGNMENT

- Google and find three leading industries and software responsible for process control in 3D printing.
- Google and find three firewall software for 3D printers.



THANK YOU

