Defect	Causes	Size range	Effect	Frequency	Comments	References
					Warping for ABS can be small as 0.1mm for 40-100 layers [2] ABS has a coefficient of thermal expansion of ~90 um/m-k [3] PLA has a coefficient of thermal expansion of ~68 um/m-k [3]	
	Cooling issues --> warping	min 0.0756 mm		Very Common (ref. 5)	Defect small as 0.0756 mm - could be more **(I Calculated)**	1,2,3,5
	distance between print bed and nozzle not calibrated	SM		Not common - human error		1
Detachment	Vibration	SM or min 0.0756 mm		Not common		1,2,3
	This is from a partial collapse or a collapsed bridge (aka the structure of the printed object could not support itself)	0.4 mm - large		Common with complex prints	The defect size can only be as small as one layer thickness.	1,4
Deformed object	Nozzle misses the print bed	0.4 mm - large		Uncommon	May happen if someone tries to make an object too big for the printer or miscalibrate the printer	1,5
	Roll is empty	0 mm	print stops	Unlikely	Pursa i3 has a visible material coil	1,5
	Nozzle too close to the print bed - Material can't come out	0 mm	print stops	Uncommon		1,5
	Clogged/Blocked nozzle	0 mm	print atops	Somewhat - Common	can happen after changing spools or if the filament is stripped (not smooth)	1,5
	Snapped Filament	0 mm	print stops	Uncommon	The coil isnt usually messed with	1,5
	Spool could be low/empty		stops	Common	Extrusion stops midway - incomplete part	6
Missing Material Flows	Tangled filament		stops	Common		6
	First layer is messy	Not visible	prints normally	Sometimes	Happens if the nozzzle is too close or far from the print bed	1,5
	Gaps between infill and wall	0.4mm - large	looks bad			5
	Cracks between layers	0.1 mm - 1 mm	looks bad	Common	**Estimated from images**	5
	Misaligned layers	min? - 0.4 mm		Uncommon		5
Surface Errors	Stringy sides	0.1 mm - 0.4 mm		Uncommon	**Filament not retracting before moving**	5
	Print bowes out at the bottom (elephants foot)	0.1 mm - 1 mm		Common with large/heavy objects & heated bottoms	**DO we have a heated print base? Estimated from images**	5
	Infill is visible from the outside	min? - 0.4 mm			**Not sure the min size?**	5
	Object starts leaning	0.4mm - large		Sometimes	Hard to give a lower bound, beacuse once it starts leaning it will continue	5
	Waves/Ripple/echoes from vibrations	min? - 0.4 mm		Sometimes	It could technically be infinitely small - **how small do we care about?**	5
	Over-extrusion	0.4 mm			The nozzle is too far from the bed	5
Deviation from the Model	Holes i the top layer (top layer either didnt cool properly or is too thin)	0.4 mm - large		Common if top layer is thin		5
	Layers of material slowly lift off from each other -	>0.4 mm	Incomplete/ugly	Common	Extrustion temperature and sintering of material problem	6
Debonding/ Delamination	No stick between layers					
	No steady movement of nozzle - position out of place	>0.5 mm	Incomplete/ugly	Common	Physical parts of printer are not secure (loose grub screws on pulleys on X&Y motors, tightness of belts) - they affect nozzle positon	6
	Print head misses the bed				No lubrication of parts	
Layers Misalligned (layers do not line up or shifted)					Also, if printer is on a flat, sturdy surface	
					Dirty printer parts (debris) can affect print run	
	Caused by vibration or shock from moving parts of 3Dprinters	>0.3 mm	Bad surface finish	Somewhat	Surface is not sturdy, printer has no support	6
					Worn linear bearings	
Visual waves on print surface					No lubrication	

	Clogged
2	Detachment
1	Deformation
3	Missing MTRL flow

References	
1	https://www.researchgate.net/publication/303505955_Vision_based_error_detection_for_3D_printing_processes
2	https://link-springer-com.ezproxy.library.ubc.ca/content/pdf/10.1007/s00170-006-0556-9.pdf
3	https://www.simplify3d.com/support/materials-guide/properties-table/
4	https://blog.prusaprinters.org/everything-about-nozzles-with-a-different-diameter/#targetText=The%20default%20nozzle%20diameter%20for,bring%20a%20number%20of%20benefits.
5	https://all3dp.com/1/common-3d-printing-problems-troubleshooting-3d-printer-issues/
6	https://www.researchgate.net/publication/326146283_Common_FDM_3D_Printing_Defects
7	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5951346/

Sensor Name	Sensor Type	Price	Precision	Description	Comments	References
D-sight	Visual		Able to detect as low as 2% corrosion pillowing in aircraft structures	Involves a light source, a retroreflective screen and an EOL scanner. Defects are detected because of the difference in the EOL peaks received by the scanner when the light hits a defect is significant from when its on smooth/defect free surfaces.	Might be difficult to set up and will probably involve some motion around the print or ~ 4 different set ups	J.P. Korowski Double Pass Retroreflection.... Pg 74 https://www.researchgate.net/profile/Jerzy_Komorowski/publication/44047526_Double_Pass_Retroreflection_for_Corrosion_Detection_in_Aircraft_Structures/links/0c960528010e7ba00b000000/Double-Pass-Retroreflection-for-Corrosion-Detection-in-Aircraft-Structures.pdf#page=74
Web cam & aux thresholding algorithm (single side).	Optical		During the testing, this set up sucessfully detectected 80% of material flow failures and 60% of object detachement failures.	Great detail is taken to identifying the edges of the printed object initially. Then images are taken with a frame rate of 25 frames per second. 3 consecutive frames are then formed into a differential image for comparison. If no error is present the images should only indicate object movement in the z direction (as more layers are added). If movement occurs in either the x or y directions, it is an indication to the user that a mis-print is in progress.	Process still needs improvement in terms of resilience against lighting changes and marker mis detection.	https://www.researchgate.net/publication/303505965_Vision_based_error_detection_for_3D_printing_processes
Cameras taking 2D images compared to 2D image of 3D model object (single side)	Optical		Can detect errors of 5% and more between model object and printer object to an accuracy of 100%. Can detect errors such as incomplete object (missing material flow) & printed object (with manual measurement).	**Single Camera:** 2D image of the 3D object is taken (CamearImage) for the part being printed. The printed part is then compared to 2D shape model (STLImage). To create this STL image, a rendered 3D model from OpenSCAD is converted to an stl file (STLImage) then saved as a PNG file on the X-Y plane. Some rectification occurs and then comparison occurs by "subtracting the simulated 3D object image from the actual image. If the difference of subtraction is greater than 5%, there is an error; otherwise, there is no error flagged". **Double Camera:** Same method of operation as for the single camera, however special care must be taken to match the 3D space between the 2 cameras. Additonal models- Scale invariant feature transform (SIFT) and Random Sample Consensus (RANSAC) are employed for this purpose.	"The size error percentage of two cameras is less than the shape error percentage of single camera. However, the calculation time of two cameras setup is greater than that of the single camera setup as the two-camera setup provided the width and height error. There are more error details for the double-camera setup than the single camera that provided only the total shape error."	https://link.springer.com/article/10.1007/s40964-017-0027-x
Optical sensors have to do with light and can involve visible, laser, UV, IR... most of which will likely be too expensive for us... Will be limited to visible light I think...						
IR	Thermal			Use visual device: IR camera but the information collected is computed as thermography		
	Thermal			There are seven types of thermal sensors. Most of them need to be in contact with the object we want to measure the temperature of. The best option would be infrared cameras.	Infrered cameras are mostly used for research, to know what is the ideal temperature to print different materials.	http://movitherm.com/knowledgebase/3d-printing-and-the-advantages-of-thermal-monitoring/
Model MD	Acoustic Emission		AE sensor is a differential wide-band sensor with operating frequency response range of 100-900kHz. Detected first layer, which was printed at 100 micro-meters	FDM machine used is Model E5 Engine made by HYREL3D and printing material is ABS. AE sensor continuously detects the stress waves emitted from the sources: the extruder and the printed part specifically in the FDM machine. Sampling rate was set at 5 M samples per second. AE signal is processed and stored as a series of AE hits. Processing hits is more efficient than processing original sensing data . Use the total number of AE hits as an indicator for process failure detection. If the number of AE hits significantly increases suddenly, immediate reactions such as job abort or human inspection must be taken	Paper looks solely at the first layer being deposited. Would this be applicable for multiple layers?	https://www.researchgate.net/profile/Yan_Wang468/publication/308706605_A_New_Approach_for_Online_Monitoring_of_Additive_Manufacturing_Based_on_Acoustic_Emission/links/5a83a8cf0f7e9bda86a46401/A-New-Approach-for-Online-Monitoring-of-Additive-Manufacturing-Based-on-Acoustic-Emission.pdf
Microsoft Azure Kinect	Infrared	$399 USD	1-MP time-of-flight depth camera, 7-microphone array, 12-MP RGB camera and IMU.	Developer kit with advanced AI sensors that provide sophisticated computer vision and speech models. Contains depth sensor, spatial microphone array with video camera, orientation sensor	In the Logistics and manufacturing industry: improve quality assurance with part identification and anomaly detection. But centralized around larger objects. For the specs of the defects, would be more worthwhile to use a camera with better dimensions. Greatest advantage to this sensor is depth camera	https://azure.microsoft.com/en-ca/services/kinect-dk/
	Sonar			An ultrasonic sensor uses a single ultrasonic element for both emission and reception. In a reflective model ultrasonic sensor, a single oscillator emits and receives ultrasonic waves alternately. This enables miniaturization of the sensor head	Depending on the shape, waves can be deflected and the sensor might not be able to sense the object	http://cmra.rec.ri.cmu.edu/content/electronics/boe/ultrasonic_sensor/1.html